

Assessment & Mitigation Proposal in case of major tsunami impact

How to reduce the impact of a tsunami in Iquique,
Chile

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ASSESSMENT & MITIGATION PROPOSAL IN CASE OF MAJOR TSUNAMI IMPACT

by

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ABSTRACT

Iquique is an important city in the northern of Chile. For the coast of Iquique a seismic gap with a return period of 111 ± 33 years is present. Since the last big event in 1877 only 20 % of the accumulated seismic slip is released. The configuration of Iquique is such that a large future earthquake and subsequent tsunami would generate a serious impact in terms of loss of life, economical and material damage and post-event disruption of the society.

In this research an answer is given to the question how to reduce the impact of a major tsunami. First the size of the impact is assessed with a high resolution numerical model, NEOWAVE. Various possible scenarios are analysed. Governing parameters are flow depth, flow velocity and the arrival time of the wave in city. The worst case tsunami scenario predicts significant inundation on three locations, the port, the commercial centre Zofri and the popular Cavanca region. The port is outside of the scope of this research. Detailed analysis of the Zofri and Cavanca areas give relevant information for future disaster mitigation.

In Zofri, the natural barrier at the shore is overtopped, after which the hinterland, including the Zofri mall, is inundated. The topography of this area shows a hollow profile therefore a 'bathtub' effect is present. After 60 minutes 50 % of the area is inundated with a maximum of flow depth 2,5 meters and a runup of 4.7 meters. The total inundated area is 760.000 m^2

In the Cavanca region the water enters 17 minutes after the earthquake event, mainly from the north side, inundating the hinterland. After 5 additional minutes, the Cavanca peninsula is cut off, creating an island. The numerical results give a maximum flow depth of 5 m and flow velocities between the 3 and 5 m/s and the runup reaches 6.8 meters. The total inundated area is 700.000 m^2 .

As the size of the impact is determined, the mitigation of the impact is assessed. A method of developing and assessing mitigation measures is put forward. Essential to this method is the framework, in which elements of existing calamity frameworks are captured. The used framework addresses the phase to which the disaster has evolved (*strategies*), techniques that can be applied with respect the the event (*methods*) and the concept of safety ensured on multiple *levels*. The use of the framework ensures the development of a multi-lateral complex solution.

Sub-research questions corresponding to the stages of analysis, design and validation are introduced to guide the process of obtaining the answer to the main research question.

In the analysis stage a short list of mitigation measures, specifically suited for the Iquique areas, is derived. In the subsequent design stage, the methods, derived in the framework, are used to compose three possible systems of mitigation.

The first system focusses on *retaining water* at the coastline, preventing the hinterland from being inundated by the use of a Dyneema tsunami barrier. In order to secure safety, mitigation measures related to *escaping the water* are implemented. Since the system also has to reduce impact related to possible post-disaster disruption, also the method *preparing for the aftermath* is employed. The second system evolves around the concepts of *delaying and diverting* the incoming water. In order to do this, an submerged breakwater and flow channels integrated in existing infrastructure are introduced. Similar to the first system, this system makes use of measures related to escaping the water and preparing for the aftermath. The third system focusses completely on the concepts of escaping the water and preparing for the aftermath. A new evacuation protocol and the design of a public vertical evacuation building are proposed.

The systems are validated on their effectiveness and their side effects are evaluated.

At this point, the three complex solutions are evaluated on the impact criteria. All the systems can be implemented in Iquique and will reduce the impact of a future tsunami. When mitigation measures for Iquique are considered the systems proposed in this report are a guidance for the possibilities and scale of impact reduction.

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When the first plans for a multidisciplinary project abroad took shape in Januari 2014, we could not have dreamed of the amazing experience that awaited. Our demands for the project were simple: we wanted to learn something new within our civil engineering discipline and go abroad to experience a new culture. In November, we packed our backs to start our two month research project on the impact of a tsunami at the Universidad Catolica de la Santisima Concepción, Chile.

Due to our Dutch background, we had very little experience with the source of earthquakes (with the exception of the self-induced terremoto-cita's) and possible subsequent tsunami's. Upon arriving in Chile, we could not have been received with more welcome. We were shown to our spacious office and received a earthquake/ tsunami crash-course to get us up to speed. During our very first *once* (eleven o'clock good-coffee break) our supervisor introduced us to *the* Chilean key-word: *weón* (big egg). Also we discovered a curious Chilean dish we could not quite identify but is sold under the name *pan Holandes*.

Our day of arrival was the first of many fun and interesting days in -and outside of - Concepción. We learned a lot, on the subject of our research and on the country itself.

We would like to express our appreciation to all who provided us with the possibility to perform our research. First of all our gratitude goes out to our supervisor at the universidad, Rafael Aranguiz. He made this project possible and supported us during our stay; supplying us with expert knowledge on the subject, arranging the field survey and ever willing to show us his top-notch barbecue tricks. Many thanks go to Luisa Urra for helping us with the NEOWAVE modelling of the tsunami impact. The NEOWAVE model was unknown territory and her expertise was crucial for us to obtain reliable results. Also Juan González Carrasco was very kind to supply the updated earthquake scenarios, helping us along in the research. For the - much needed - logistical assistance we would like to thank Caitlin Jurgensen and Mary Hayes, especially for their help in finding our wonderful house - and perhaps some weekend trip reservations in the viñas.

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INTRODUCTION TO THE PROJECT

INTRODUCTION

THE PROJECT

This report contains the results and conclusions as found by multidisciplinary group *Project Iquique* of the Delft University of Technology. A research project has been designed to bring together various branches of civil engineering to deal with the globally relevant subject of tsunami risk mitigation. The research objective is twofold; initially the aim is to analyse the various impact scenario's of a tsunami following an earthquake occurring for the coast of the Chilean port city of Iquique. Subsequently, measures shall be proposed to mitigate the tsunami impact on Iquique taking into account the local situation and socio-economical restrictions.

STAKEHOLDERS IN THE RESEARCH

The research is conducted within the University Católica de la Santísima in Concepción, Chile. University researchers are connected to CIGIDEN, the national research center for integrated natural disaster management in Chile (CIGIDEN [3]). Together they take part in a larger project to study effective countermeasures to natural disasters such as tsunamis and earthquakes in Chile. The overall name of the project is the Research Project on Enhancement of Technology to Develop Tsunami-resilient Community and is classified as a SATREPS project. SATREPS is an initiative lead by JICA and JST. JICA is an international cooperation agency that organises various world wide activities based on the pillars of a field-oriented approach, human security, and enhanced effectiveness, efficiency, and speed (JICA [4]). JST is a government based Japanese Science and Technology agency, occupied with the implementation of policies and raising awareness related to science and technology issues(?). This report can be seen as a contribution to the JICA-SATREPS project.

PROJECT FOCUS

Chile's exceptionally long coastline runs more or less parallel to the active Nazca subduction zone (as can be seen in figure 8).

The ongoing subduction of the Nazca plate underneath the Southamerican continental crust makes Chile, with an average of 20 earthquakes per day, one of the most seismically active countries in the world and therefore prone to undergo a tsunami(de Chile [5]).

The focus of the research lies in the north of Chile, on the city of Iquique. The location next to the Pacific ocean and the relative low ground elevation put the city at risk when a tsunami would strike. To the east the city is enclosed by the Andes Mountains. The coastal city is considered an economically important region due to its tourism, commercial and shopping areas and the presence of one of Chile's two free ports. In the greater Iquique region live around 280 thousand people, about 1,5 percent of the Chilean population (Worldbank [6]).



Figure 1: Plate Boundaries in South American Region

RELEVANCE OF TSUNAMI RESEARCH IN IQUIQUE

The relevance of this research for the city of Iquique is discussed in this section.

HISTORY OF SEISMICITY IN CHILE

Chile has a long history of earthquakes and subsequent tsunamis. Records of these events go back to the early Spanish occupation in the 16th century. A few large events are mentioned here.

In 1877, the north region of Chile was hit by an event of a magnitude $M_w \sim 8,5-8,8$. Soloviev et al note that in the city of Iquique a water rise of 4,8 to 6 m was reported. According to official accounts 30 people in the town died (Soloviev and Chi [7]).

In 1960 the largest earthquake ever recorded took place with a magnitude of 9,5 on the Richter scale, causing devastation not only in near the epicentre in central Chile but also in pacific coastal zones of Japan, Hawaii, the Philippines and the United States. The evoked tsunami reached a maximum waterheight of 25 m and took more than 1200 lives in the affected areas (Soloviev and Chi [7]).

The most recent large event with a magnitude $M_w = 8,8$ took place in 2010, with an epicentre for the coast of Concepcion. The earthquake shook the entire centre area of Chile and the subsequent tsunami inundated large areas of the Concepcion bay, taking approximately 160 lives and causing damage and chaos in many affected areas (USGS [8]).

FUTURE SCENARIO'S

Seismologic analysis of the Chilean coast regions shows that the accumulated energy in the subduction zone in the Iquique region is enough to generate a large event in the near future. An $M_w = 8,1$ event took place in April 2014, after this event is thought that only 20 % of the accumulated energy since 1877 is released in the entire Northern seismic gap (Schurr *et al.* [9]). Research on the impact of an earthquake and tsunami in this region is therefore very relevant.

RESEARCH SCOPE & OBJECTIVES

In this chapter the scope of the project is elaborated and the objectives for the research are given.

RESEARCH QUESTIONS

The main research question in this report can be considered the following:

How can the impact of a likely future tsunami on the city of Iquique be reduced with respect to the criteria loss of life, material and economical damage and post-event disruption of society.

Sub-research questions are formulated per part. The criteria for impact reduction, that will be considered during the research, are elaborated in the next section.

NOTE ON IMPACT VERSUS RISK

It is interesting to address the use of the word impact instead of the word risk when speaking of hazard mitigation. Risk is defined as *impact x probability*. In the case of a tsunami, probability is not such a relevant term. In a tsunami prone region, the probability is not assumed to be zero. The consequence of the worst case scenario is often considered unacceptable, no matter how small the likelihood. Therefore, in tsunami mitigation, the term impact is more feasible.

DEFINITION OF CRITERIA

These criteria are defined in order to have a constant means by which the various parts in this report can be validated. Also it grants the authors a method to demarcate the concept of impact reduction. Negative impact, due to the occurrence of a tsunami, can be quantified using the criteria.

1. *Loss of life*

The amount of lives lost during or in the aftermath the event of a tsunami is quantifiable. However, the reduction of this loss due to mitigation will often be an estimation. Nonetheless, this criterion should always be on top of mind during the design of mitigation measures. The goal should be to reach a zero loss of life situation.

2. *Damage*

Damage is defined as harm to non-human objects due to tsunami impact. In this report, a rough division is made between economical and material damage.

(a) *Material Damage*

Material damage is considered the harm to physical property, such as houses and infrastructure, that has to be rebuild after the event.

(b) *Economical Damage*

This is a more vague term referring to income lost, both during the event and in the future. Examples could be missed-out business during the event but also possible damage to the image of a tourist region, reducing future income.

3. *Post-event disruption of Society*

After a tsunami strikes, a municipality is challenged to keep order and distribute help where needed. Also a society should get back to 'normal' as soon as possible. If a municipality is not well prepared, a society can remain disrupted for quite some time. In this report, reduction of disruption of a society is considered an important criterion in mitigation design.

PART ONE: TSUNAMI SCENARIO ANALYSIS

1. What is the most relevant event scenario for the Iquique region to take into account when answering the main research question?
2. What is the impact of the event on a *global*¹ level?
3. What Iquique areas are in such a way affected that mitigation measures should be designed taking into account the defined criteria?
4. What is the impact of the event on a *local* level?

¹The term global is applied as opposed to *local* en refers to the city of Iquique as an entity

PART TWO: TSUNAMI MITIGATION

1. What available mitigation measures are suitable for the Iquique region?
2. What complex² solutions of mitigation measures can be proposed for the severely affected areas?
3. What can be said on the proposed complex solution when regarding:
 - (a) Effectiveness with respect to tsunami impact reduction
 - (b) Generation of side-effects

RESEARCH SCOPE & BOUNDARIES

This research consists of two separate research questions which are elaborated in two different parts. Therefore also the scope is formulated in two sections.

PART ONE: TSUNAMI SCENARIO ANALYSIS

1. The Event:
 - (a) The research will focus only on the Iquique region. The grid size is thus chosen to obtain accurate information on this region alone.
 - (b) A return period of 111 ± 33 years on large earthquakes in the region is determined based on historic events. Therefore a large event may be expected in the near future.
 - (c) The 1877 Iquique earthquake is used as a reference to simulate the size and impact of a future event.
 - (d) The 2014 earthquake is assumed to have dissipated about 20 % of the accumulated energy in the entire faultzone since the 1877 event. A future event is therefore considered likely to have a large impact.
 - (e) A future event is confined in length due to natural earthquake barriers.
2. The Model:
 - (a) The scenario's shall be modelled using NEOWAVE and further analysed using Matlab. A restriction to the model accuracy is the limited use of 5 nested grids in the analysis.
 - (b) The gridsize in relation to observed area is limited due to the required running time during the project.
 - (c) The model generates a tsunami on the coast of Iquique. In this model possible subsidence and displacement due to the earthquake are not taken into account.

PART TWO: TSUNAMI MITIGATION

1. Area of Interest:
 - (a) The affected areas that will be considered for tsunami mitigation will follow from the Part One recommendations.
1. Mitigation Measures:
 - (a) The measures that can be implemented are limited due to local bathymetry and topography and technical design possibilities, social discussion on desirable mitigation methods and limited means for investments.

²A complex solution indicates a combination of mitigation measures that provide an effective and safe solution

RESEARCH OBJECTIVES

The aim of this project is to contribute to the JICA project of Tsunami Risk Mitigation in Chile to reduce the impact in terms of loss of life, material and economical damage and post-disaster disruption of society.

PART ONE: TSUNAMI SCENARIO ANALYSIS

1. Determine the most likely tsunami scenario to happen in the new future in the Iquique region.
2. Quantify the impact of the modelled tsunami on the city of Iquique.
3. Single out the most severely affected and relevant area(s) for mitigation measure design.

PART TWO: TSUNAMI MITIGATION

1. Investigate possible tsunami impact mitigation measures that can be applied within the local restrictions and criteria.
2. Determine the most suitable combination of measures for a singled out affected area.
3. Validate the engineered set of multi-layered mitigation measures.
4. Use obtained results to answer the main research question in order to propose a method to reduce the tsunami impact in Iquique.

A MULTIDISCIPLINARY APPROACH

The team members of project Iquique all have different backgrounds and represent a different field of expertise to obtain a full multidisciplinary approach on this research.

Processes related to the generation of earthquakes and tsunamis are triggered deep in the earth, due to tectonic movement. Understanding these processes requires an engineering geology perspective.

The understanding of the generation and propagation of a tsunami wave requires both an offshore- and hydraulic engineering point of view, especially for the numerical modelling and the analyses of the inundation maps, run-up heights and flow velocities. This includes the understanding of the shallow water wave equations used in the numerical model and the coastal processes such as wave propagation, refraction, diffraction and reflection.

When analyzing the inundation of the urban area of Iquique, water prone areas can be designated and the effectiveness of the mitigation measures can be approached by assessing human behaviour and city-planning on the available evacuation time and possibilities. Also the state of evaluation routes and the stability of current structures are (partially) dependent on the earthquake- and flooding-affected subsurface. Both the geotechnical and the water management point of view can be of great value on this topic.

Designing a civil structure (as a mitigation measure) has impact on the subsurface and vice versa. The relevance of the geotechnical design only increases when dealing with a seismically active and tsunami prone region, for aspects like dynamic loading, scour and liquefaction risks rear their ugly heads. Also from an offshore- and hydraulic engineering point of view these retaining and mitigation measures are very interesting due to wave breaking and the hydrodynamic forces on the structures.

When evaluating mitigation measures the drainage of the city, after the tsunami event, must be assessed as well. This also relates to the hydraulic and water management fields of expertise.

OUTLINE OF THE RESEARCH

This report consists of three separate parts. Part 1 and 2 contain the chapters Introduction, Methodology, Results and Analysis, Conclusions and Discussion and Recommendations.

- In part zero, the physical phenomena of an earthquake and a tsunami will be elaborated. Also a more accurate history of seismology in Chile will be accounted.
- In part one, various event scenarios for the Iquique region will be investigated and analysed. Recommendations on strongly affected areas can be made using a numerical model to simulate flow velocity and inundation depth. These recommendations will be a starting point for part two.

- In part two, a multi-layered mitigation approach will be applied for the strongly affected areas. A combination of structural intervention measures, smart city planning and design and a accurate evaluation system will be validated using the available data.

PART 0

GENERAL CONCEPTS

I. INTRODUCTION

The objective of this chapter is to introduce the reader to various relevant processes and theories that will be addressed frequently in this research report. The scope of the research is divided in two parts; first assessing the size of the impact of a future tsunami and second the design of measures to mitigate this impact. In order to understand such an impact, it is crucial to understand the driving processes of a tsunami event. Therefore, the phenomenon of an earthquake, the source of a tsunami, is addressed. Next a tsunami itself is investigated. In order to grant some background information of the location of interest a few remarks on the geology are made. This introductory chapter will be concluded with the elaboration on relevant events in the seismic history in Chile.

II. EARTHQUAKES

In this chapter a short introduction to earthquakes to create a better understanding of this phenomena, the physics and the forecast possibilities.

II.I. PLATE TECTONICS

Due to the location of Chile with regard to the Nazca- and South American plate there is a lot of seismic activity in this area. The Nazca plate is subducting under the South American plate and the South American plate couples to the Nazca plate, see figure 2a and b. When the South American plate is released from the Nazca plate a part of the energy stored by the coupling is released and an earthquake is induced, see figure 2c. The earthquakes that occur at subduction zones on plate boundaries are referred to as megathrust earthquakes.

II.II. SEISMIC POTENTIAL

In this section the seismic gap theory will be discussed.

SEISMIC GAP THEORIE (KAGAN AND JACKSON [10])

When regarding a subduction zone with elastic³ inter-seismic slip a seismic cycle can be noticed, the process of subduction causing long periods of locking and short periods of slip. This process repeats itself over a long, but not constant, amount of time, hence the mentioned cycle. The cycle can be divided into three periods:

1. Inter-seismic slip
The process of steadily accumulating strain between earthquakes.
2. Co-seismic slip
The slip that occurs and initiates an earthquake
3. Post-seismic slip
The aftershocks, this implies the occurring slip after the event.

The inter-seismic slip occurs for long periods, until the moment that the elastic strain build-up will exceed the coupling friction (see figure 2a and b), this period also referred to as the inter-seismic gap. The moment that the inter-seismic slip changes into the co-seismic slip is the moment of the actual earthquake and this will occur in a matter of seconds (see figure 2c). In this phase the upper plate will form back to its initial deformed state. The last phase, the post-seismic slip, can occur over a period of several seconds to years. This phase consists of two main processes, the first being the plates additional slip, also referred to as aftershocks. The second is the re-stabilization of the pressure, this mainly consists of water flowing to the created low pressure areas.

SLIP DEFICIT

Slip deficit is the discrepancy between the slip that would occur without coupling and the slip that occurs when an elastic plate is regarded and thus coupling occurs. The slip deficit is increasing depending on the movement of the plates and the strength of the coupling. In the case of an earthquake it is likely that the slip deficit decreases.

³The material of the plate must be elastic in order to cause a bowed plate. If the plate has no elasticity no coupling will occur

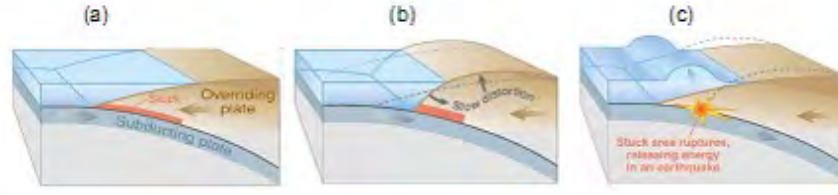


Figure 2: Subduction and energy release

II.III. BARRIERS

All the recent large ruptures appear to have stopped in areas where the inter-seismic coupling is suggested to be low. This implies that these parts of the Nazca rupture zone play the role of a barrier to seismic rupture propagation (Chlieh *et al.* [11]). Because of these barriers the location and the length of the earthquakes can be predicted more accurately.

II.IV. BASIC CALCULATION OF EARTHQUAKE MAGNITUDE (M_w)

The origin of a tsunami is an earthquake. The magnitude of the earthquake determines the size of the tsunami that follows. To calculate the magnitude M_w of an earthquake first the seismic moment (M_0) must be determined, see formula 1. Where μ ([-]) is the coefficient of friction, which is an empirical property of the contacting materials, L is the length of the fault plane ([m]), W is the width of the fault plane ([m]) and D_0 is the displacement of the fault plane ([m]) (see figure 3).

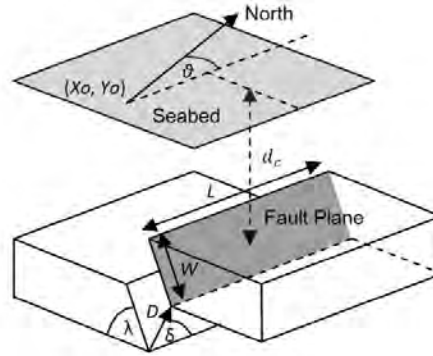


Figure 3: Fault plane

The magnitude (M_w) is a log formula that indicates the magnitude of the earthquake (see formula 2).

$$M_0 = \mu L W d_0 \quad (1)$$

$$M_w = \frac{2}{3} (\log(M_0) - 9.1) \quad (2)$$

The magnitude is dependent on the length, width and displacement (slip) of the fault plane. An earthquake is not one big displacement, it is a collection of numerous smaller displacements. This collection of smaller displacements together cause a certain magnitude of an earthquake. This implies that an earthquake with a certain magnitude can have a period varying from seconds to hours. The epicentre of an earthquake is there were the first shocks of the main event were observed.

The size, this means the length and width of the fault plane that displaces, of an earthquake is closely related to the magnitude. In figure ?? the relation between these is illustrated. These relations can be use to predict or asses the magnitude of an earthquake and its impact.

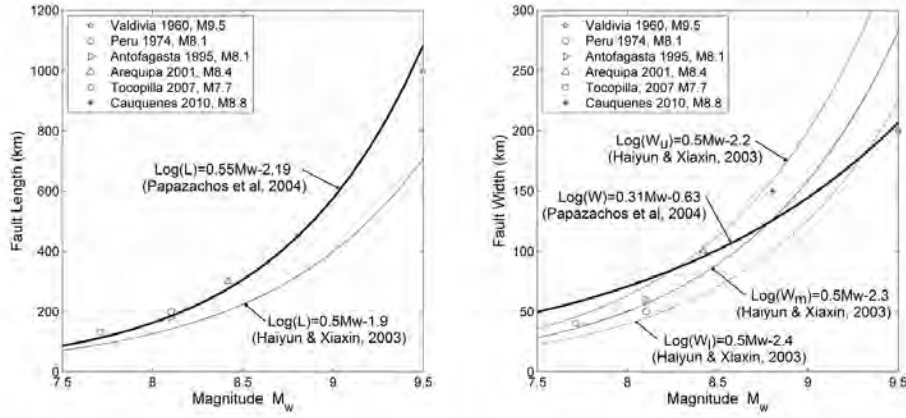


Figure 4: Width and Length to asses the magnitude of a Earthquake

II.V. THE ABILITY TO FORECAST

Due to the introduction of GPS, the displacements of the tectonic plates can be accurately measured. These displacements are related to interseismic strain build up and to the co-seismic strain release. To be able to predict future earthquakes two methods can be used. Both methods use historical records of earthquakes.

The first method is based on the movement of the plates and the return period in certain areas. The second method is based on historical data about the magnitude of large earthquake events.

For the first method the movement the GPS measurements of the plate movement are used. The Nazca plate in the Central Andes⁴ moves 63 mm/a on average (Kendrick *et al.* [12]). This movement of plates is multiplied with the return period and this is regarded as the total slip of the earthquake. With this data the magnitude (M_w) can be calculated as above mentioned.

The second method uses the history of the magnitude (M_w) of earthquakes. The historically large earthquakes are used to predict a return period and a maximum seismic potential. In this assessment also the smaller earthquakes are taken into account. These small earthquakes might not have high impacts, but they do dissipate stored energy which will decrease the seismic potential.

III. TSUNAMIS

A tsunami (Japanese for "harbour wave") is a long wave generated by an earthquake, an under water explosion (such as a volcanic eruption) or a landslide. In the case of an earthquake in the ocean crust, the sea bottom will be displaced due to the co-seismic slip which causes the entire water column above to move. This will create a displacement at the sea surface in the same order of the co-seismic slip which will generates a wave with a period in the order of 10-90 minutes. The wave generated by an earthquake has different characteristics than for example wind induced waves. Because of the long wave length (approximately 100 km) the ratio of the water depth over the wave length is very small ($d/L < 0,05$) this makes it a typical shallow-water wave. The propagation speed is then non-dispersive and equal to the square root of the gravitational acceleration times the water depth, see equation 3.

$$c = \sqrt{gd} \quad (3)$$

If an earthquake is in the order of minutes, only one wave will be generated. However, due to reflection at the coastline an interference pattern will occur and the waves will start to propagate along the coastline. This is why, during the tsunami event, more than one wave can be observed and it can have a period of several hours.

⁴This area stretches from approximately Lima in the North to Antofagasta in the South

III.I. PROPAGATION

Besides the water depth, the propagation of the tsunami wave is influenced by many other processes. In this section the propagation of a tsunami wave and the basic calculations are discussed. In this research the NEOWAVE model is used to model the tsunami, for further elaboration on this model see appendix C.

In general wave propagation (c) can be influenced by four principles, this also holds for a tsunami wave. (see figure ??):

- Shoaling
The increase of the wave amplitude due to the decrease in water depth near the coast
- Refraction
The change of the wave direction due to the bathymetry
- Diffraction
The change in wave direction and attenuation due to islands, peninsulas and structures
- Reflection
The wave reflection due to interaction with the coast or structures

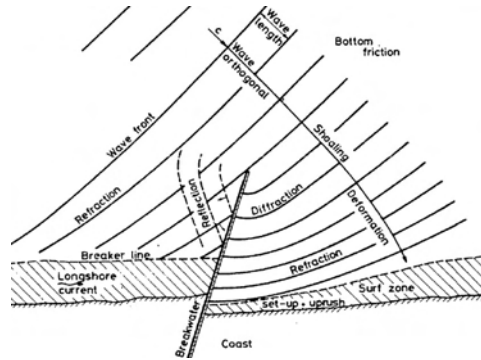


Figure 5: Wave shoaling, refraction and diffraction

Reflected waves will most of the times return to the open sea, however some waves with a designated period corresponding to the sea floor will bend towards the coast again and stay on the continental shelf. So the wave gets reflected by the land and returns to the land again, sometimes the process is repeated and the wave gets trapped on the continental shelf. Wave which get trapped at the continental shelf are called edge waves. If the period of the tsunami wave that becomes trapped is close to the average period of the tsunami wave, large tsunami energy will be trapped and the tsunami wave will be able to propagate along the coastline.

Another principle related to tsunami propagation is the resonance phenomena. The oscillation of the sea water in a bay is related to the natural period of the bay, which is depending on the size of the bay. The natural period includes many modes, from low-order (with long wave periods) to high-order (with short wave periods). When a tsunami invades a bay with a period that corresponds to the natural period of the bay it displays a large oscillation, this is called resonance. When resonance occurs it is possible that the second or third wave is larger than the first one. That is why it is recommended to evacuate always for a longer period of time.

BASIC CALCULATION OF TSUNAMI WAVE CHARACTERISTICS AND PROPAGATION

For the calculation of the propagation of the tsunami wave the NEOWAVE model is used. In this model the shallow wave equations are used to calculate the propagation, see equations 4, 5, 6 and 7. Where equations 4 and 5 represent respectively the non-linear x- and y-momentum equations, equation 6 the continuity equation and 7 the friction term.

$$\frac{\delta U}{\delta t} + U \frac{\delta U}{\delta y} + V \frac{\delta U}{\delta y} = -g \frac{\delta \xi}{\delta x} \quad (4)$$

$$\frac{\delta V}{\delta t} + U \frac{\delta V}{\delta x} + V \frac{\delta V}{\delta y} = -g \frac{\delta \xi}{\delta x} \quad (5)$$

$$\frac{\delta(\xi - \eta)}{\delta t} + \frac{\delta(UD)}{\delta x} + \frac{\delta(VD)}{\delta x} = 0 \quad (6)$$

$$-f \frac{U\sqrt{U^2+V^2}}{D} \quad (7)$$

The term that is most important for the evaluation of tsunami hazard is ξ , the surface elevation level. This is illustrated in figure ?? and equation 8 .

$$D = \xi + (h - \eta) \quad (8)$$

Where D is the total water depth [m], h the still water depth [m] and η [m] the bottom displacement.

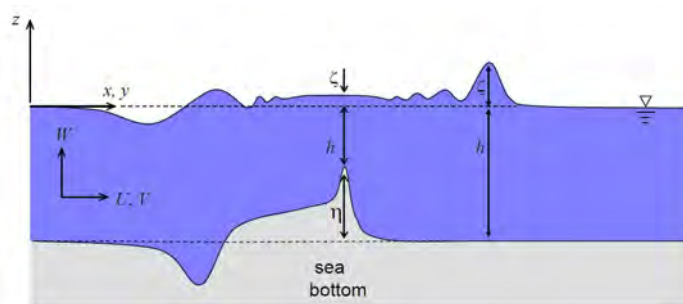


Figure 6: Surface elevation tsunami wave

RUN UP EFFECT

The quantification of the tsunami wave often refers to run up. The run up is the highest point of the tsunami wave on the shore. This principle is illustrated in figure 7 where the run up and flow depth phenomena are illustrated. The flow depth is obtained by taking the wave height and subtracting the topography. The run up is commonly used to summarize a tsunami event, the value shows the highest contour of the wave which gives a good estimation of the impact. The flow depth is more important for damage estimation especially since the flow depth can exceed the run up height close to shore.

III.II. NOTE ON THE GEOLOGY OF THE NORTHERN COASTAL ZONE

In the north of Chile to major continuous longitudinal morphological formations are recognized; the coastal range and the coastal planes. The coastal range consists of the Great coastal escarpment and the Coastal cordillera. The escarpment of 700 km long and approximately 700 m high generates the rough signature coastline of the north Chilean region (Casanova *et al.* [13]). The coastal planes, with an average of three kilometers width, contain sedimentary deposits and marine terraces, partly covered with alluvial fans. The presence of the marine terraces along the escarpment attest to the marine degradation of the actively uplifting coastal range, a process ongoing since the Pliocene (Moreno and Gibbons [14]).

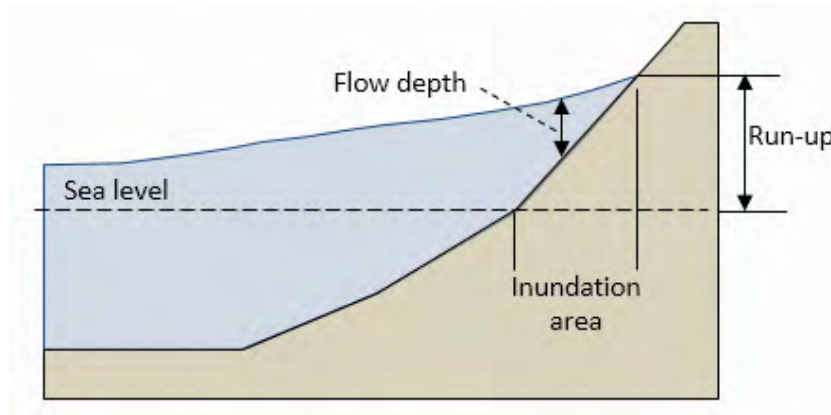


Figure 7: In the figure the different tsunami quantification terms are visible. Run up is the maximum height of the tsunami wave onshore. Flow depth is the tsunami height minus the topography.

III.III. IQUIQUE

At our location of interest, Iquique, very little of the coastal plane is preserved (Moreno and Gibbons [14]). The horizontally bedded tertiary sandstone formations, found north of Antofagasta (Casanova *et al.* [13]) are presumed to continue along this region. The soil profiles found in the region are described as skeletal sandy and sandy loam soils, stony at the surface and with frequent rock outcrops (Casanova *et al.* [13]). The present day rainfall measured in the region is only 0.5 mm/year. Due to the arid local conditions future referral to the subsoil the material is assumed to be unsaturated (dry).

III.IV. SEISMICITY IN CHILE

The first records of earthquakes and tsunamis exist of legends and stories in the Chilean, Peruvian and southern Ecuador. These legends tell us about the earth shaking, the ocean ignoring its boundary and inundate dry land. The chronicles relate on the appearance and disappearance of hills and lagoons.

Local people learned to live with the natural hazards and developed a culture around them. The Mapuche people in central Chile believed their world originated in a great battle of the serpents of sea and land. The humanfriendly Xeg-Xeg filu formed the mountains onto which the people could escape during the marine attacks of Kai-Kai filu, ruler of the ocean (Dillehay [15]).

The people still know to escape to sacred higher ground after a large earthquake to avoid the dangers of a tsunami.

The Chilean earthquakes and tsunamis have been officially logged since the 16th century, after the arrival of the Spanish conquistador Pedro Valdivia. Due to these records accurate returnperiods for earthquakes in Chile can be determined and the seismic gaps can be calculated.

RELEVANT SEISMIC ACTIVITY IN CHILE

Chile has seen many seismic events. In this section only the events that are relevant for the determination of the northern Chile & southern Peru seismic gap and the Iquique region are discussed.

1868 Southern Peru $M_w = 8.8$ A terrible earthquake shook up the south of Peru and north of Chile, evoking multiple avalanches in the Andes and destroying towns in the entire affected area. The tsunami following the earthquake is known as the Arica tsunami. The impact was noticeable down to central Chile. The city of Arica was flooded with waves described by eyewitnesses as 15 to 18 meters high. In the city of Iquique, waves up to 12 meters were seen. This event is thought to have broken the highly coupled southern Peru subduction zone section. (Soloviev and Chi [7]).

1877 Northern Chile (Iquique region) $M_w = 8.8$ Only a few years later, another large event hit the north of Chile, rupturing the subduction zone from Arica to the Mejillones peninsula. In Iquique, a tsunami flooded the city, causing death and destruction. However, the loss of live was noticeably less than when the Arica tsunami hit, suggesting that people took a lesson from the event only 9 years earlier.

Since this event, a slip deficit is thought to have accumulated of approximately 8-9 meters in the region. This is referred to as the post 1877 seismic gap. (Soloviev and Chi [7]).

1960 Valdivia, Chile $M_w = 9.5$ This event counts as the largest earthquake in written history. A sequence of events during 33 hours ruptured the coastline over 1000 kilometres. The great impact of the subsequent tsunami was felt not only in Chile but also in other Pacific countries (such as Japan and Hawaii) (Aranguiz [16]). This event indicates the impact even a far-field tsunami can exercise on a coastline.

1967 Northern Chile $M_w = 7.4$ A relatively small event occurred some 200 kilometers south of Iquique, damaging the town of Tocopilla and causing a small but noticeable water rise in the port. This event released a small amount of the accumulated energy in the southern zone of the northern Chile seismic gap. (Soloviev and Chi [7]).

1995 Antofagasta, Chile $M_w = 8.1$ The Antofagasta earthquake is thought to have broken the seismogenic zone south of the Mejillones peninsula, which is often mentioned as a seismic barrier. (Hayes *et al.* [1]).

2001 Arequipa, Peru $M_w = 8.4$ This earthquake is thought to have released a large part of the slip deficit in the zone north of Arica, which had accumulated since the event of 1868. (Hayes *et al.* [1]).

2007 Tocopilla, Chile $M_w = 7.7$ This event is thought to have ruptured a section of the seismic gap present since the large 1877 event. Due to the limited size of the event, only a small amount of energy was released. (Hayes *et al.* [1])

Above events gives a context to the increased interest in the Iquique zone. The post 1877 seismic gap was thought to have accumulated enough energy to host a large event, in the worst case scenario rupturing an area of over 530 kilometers.

2010 Middle Chile region $M_w = 8.8$ This event did not greatly affect our area of interest but is mentioned nonetheless for its great size and valuable lessons learned. The event shook up the region since too little information was accessible before and during the event. Many coastal areas were severely damaged. The lessons learned can be summarized as the following:

People were surprised by the event and insufficiently informed. Under the tsunami victims were many non locals (tourists) who had no prior experience with this type of risks. In a local fisherman town there were no casualties for the older inhabitants still has the memory of the 1960 earthquake and tsunami and urged everyone to fly from the coastal region. The value of education and clear information, both in evacuation signs and leaflets, became very visible.

It was generally assumed that a tsunami consists of one big wave. In this case, the third wave, arriving little over three hours post earthquake, was the largest and caught many people, returning to their houses, by surprise.

After this event, tsunami mitigation measures such as (small) seawalls and evacuation signs were more consequently implemented along the entire coastline.

2014 IQUIQUE EARTHQUAKE

In March - April of 2014, the north Chile seismogenic zone partially ruptured during a sequence of events, the largest of which the $M_w = 8.1$ Iquique earthquake on the first of April and the $M_w = 7.7$ aftershock two days later.

The event caused six fatalities and triggered a ~2 m high tsunami, damaging approximately 13.000 houses. The total economic damage was estimated at US\$ 100 million. (Hayes *et al.* [1])

According to seismic gap theory enough energy was accumulated in the region to expect an event with a magnitude up to $M_w = 8.9$ (Schurr *et al.* [9]). The many foreshocks are expected to have weakened the central part of the seismic gap where an intermediate seismic coupling occurred leading up to the final failure. Kinetic analysis of the rupture conducted by Schurr *et al.* shows that indeed only a partly-locked segment of the gap broke, locally releasing 50 % of the slip deficit accumulated here since 1877 (Schurr *et al.* [9]). This earthquake leaves the highly coupled southern segment unbroken, where since the 1877 event a slip deficit of 8-9 m has accumulated. Also, the northern segment to the Iquique region, stressed by the event, could rupture. It is by no means certain that the reduced slip deficit in the Iquique region shall function as a barrier when either of these event occurs. Therefore the entire northern Chile seismic gap remains a potential hazardous area (Schurr *et al.* [9]). This is illustrated in figure 8.

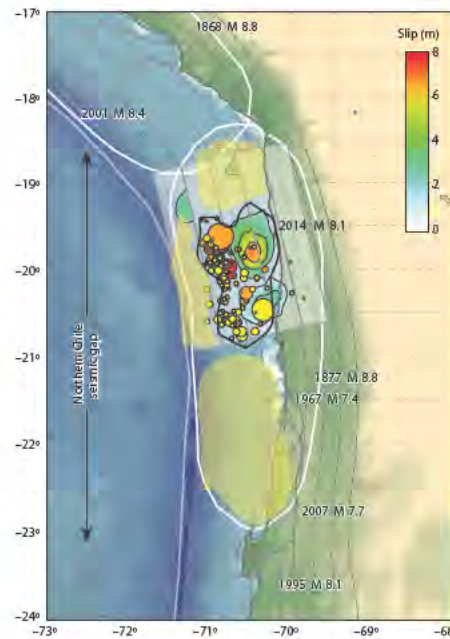


Figure 8: In the figure the northern Chile Seismic gap is displayed. The white and gray circles indicate past events. The black circle represents the Iquique 2014 event. The transparent circles indicate the unbroken northern, centre and southern zones that are considered to host a future event. A combination of these areas would give a less likely total rupture of the seismic gap generating a very large event. (Hayes *et al.* [1])

THE LESSONS LEARNED FROM THE 2004, INDIAN OCEAN AND 2011, JAPAN TSUNAMIS

These two events have had an major impact on the way the world assesses the force and impact of tsunamis. The area of impact was completely different. In 2004, various countries in South-east Asia were completely surprised by the event for knowledge and preparation on tsunamis was very low to non-exciting. In 2011 Japan, a country that has developed an expertise on tsunami mitigation and has invested in tsunami safety measures over the years, was hit, nonetheless with a destructive result.

2004 Indonesia, Sri Lanka and India $M_w = 9.1$ The impact in terms of damage en loss of life was tremendous. The countries it struck were not aware of the danger of tsunamis, there was no warning system in the Indian ocean and the inhabitants were not prepared. Things as evacuation plans or even the knowledge to run from the sea were absent.

This tsunami opened the eyes of the world to the immense losses that a tsunami can cause when there is no awareness. It shows that even in poor areas where mitigation structures might not be economical feasible it remains important to educate people.

2011 Japan $M_w = 9.0$ The tsunami in Japan had a different impact. Japan is a country with numerous mitigation measures to increase tsunami safety. However, mitigation measures are based on assumptions with regard to the properties of the tsunami, wave height for example. In Japan the estimation appeared to be to low. The authorities however were convinced that they were right and advised people to evacuate to certain heights. As people in Japan have total confidence in the authorities they did exactly as recommended. When the tsunami appeared to be larger than predicted the people couldn't be evacuated and numerous people died because of this mistake.

The lesson learned from this event is twofold. The first is that *retaining all water* with constructions is not a sufficient approach. The event was thought highly unlikely and therefore construction were not designed to withstand the force of the tsunami wave.

As a second authorities must at all time be aware of the possibility of wrong estimations. The norm for evacuating should be to go to as heigh a place as possible. This should be taken into account when evacuation plans are established.

PART 1

SCENARIO MODELLING

1

INTRODUCTION

Chile is due to its location at the edge of the Nazca and the South American plate one of the most earthquake and tsunami prone countries of the world. In the introduction of the report a brief overview of large earthquakes in the past is given. The last great earthquake (M_w 8.8) in the Iquique region happened in 1877. Based on historical data of the last 500 years the return period for such large events is estimated at 111 ± 33 years (Schurr *et al.* [17]) which makes it probable that another large earthquake will occur soon. Since the earthquake in 1877 the accumulated seismic slip in the area around Iquique is estimated in the order of 8-9 m which yields a potential for an earthquake with a magnitude of M_w 8.9.

In April of 2014 an earthquake of $M_w = 8.1$ struck the central portion of the northern gap in front of the coast of Iquique. According to Schurr *et al.* [17] the earthquake released locally 50% of the slip deficit, stressed the Northern segment and left the highly coupled Southern segment unbroken. Together with the $M_w = 7.7$ in Tocopilla in 2007 it is assumed that only 20% of the total accumulated slip is released in the entire northern seismic gap of Chile. Therefore this area, including all coastal cities like Iquique, remain potential hazardous areas, see figure 1.1 (Schurr *et al.* [17]). Part One will focus on the analyses for possible future earthquakes and tsunamis in order to get a better understanding of the size of the threat of the future event.

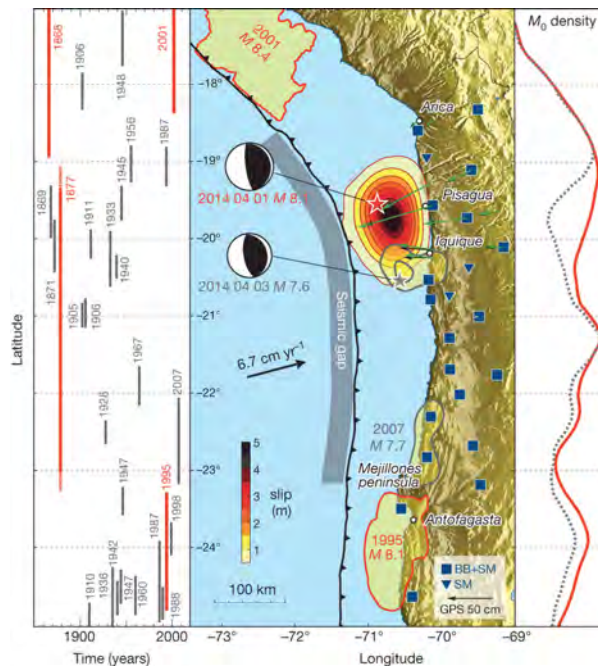


Figure 1.1: Map of Northern Chile and Southern Peru showing historical earthquake and instrumentally recorded megathrust ruptures

2

METHODOLOGY

The objective of this part is to estimate the impact of a likely future tsunami on the city of Iquique. In the introduction, this objective is formulated with the aid of sub-research questions. To do so, the authors of this report use the proposed earthquake scenarios to give an answer to the four sub-research questions formulated in the introduction.

- What is the most relevant scenario for the Iquique region in terms of tsunami hazard?
- What is the impact of the event on a global level?
- What Iquique areas are in such a way affected that mitigation measures should be designed?
- What is the impact of the event on a local level?

How the authors go about answering the sub-research questions is elaborated in the following sections. The first two questions are strongly correlated, both will be answered during the general analyses. The results of the general analysis are used as input for the subsequent sections, in which a detailed local analysis of affected areas is performed.

2.1. SCENARIOS

In order to approximate the size of the threat, several possible earthquake scenarios are proposed for the Northern seismic gap of Chile. These scenarios are based on seismic data, earthquakes from the past and proposed seismic gap models. The event of each scenario generates a tsunami of which the impact can be studied.

The location of the possible rupture zones is based on historic and seismic data. Next the scenarios are generated with a seismic model. The possible rupture zone is divided in smaller sub-faults like a grid. By estimating the co-seismic slip based on seismic data for each sub-fault the seismic moment for each grid cell can be calculated using equation 1 from Part Zero. By integrating the seismic moment of each grid cell over the rupture zone the total seismic moment can be obtained. The magnitude of the earthquake can be calculated using equation 2 from Part Zero. The mean slip of the rupture zone is an indication for the size of the possible tsunami, however this is still depending on the distribution of the co-seismic slip in the rupture zone.

2.2. NEOWAVE MODELLING

To calculate the generated tsunamis the proposed scenarios are modelled with NEOWAVE. This numerical model calculates the propagation and run-up of the tsunami wave based on the co-seismic slip of a certain scenario and the bathymetry of the continental shelf and the coastline. The model uses a five nested grid with the highest resolution of 10 meters. This is accurate enough to estimate inundation areas and flow velocities. The results of the NEOWAVE model are further analysed with Matlab and Google-earth for a better understanding of the impact on Iquique. For a detailed description on the NEOWAVE model see appendix C.

The default settings of NEOWAVE do not take the tidal elevation into account, this makes a difference for the impact of the tsunami. In case of a high tide not only higher inundation depth should be taken into account but also a larger inundation area and higher flow velocities could occur. The tidal range in Iquique is 1,3 m based on IOC [18] with the highest astronomical tide of +0,8 m. In order to obtain the most relevant scenario for Iquique when designing mitigation measures the tidal elevation of +0,8 m is taken into account in the modelling of the scenarios with NEOWAVE.

2.3. GENERAL ANALYSES

The impact of the proposed scenarios on a global are analysed by the inundation maps of Iquique. In combination with a general analyses of the coastal zone of Iquique the most relevant scenario in terms of tsunami hazard can be chosen for further analyses. This answers the first sub-research question. For a global impact the arrival times of the wave are plotted for each scenario. In combination with the inundation maps, the arrival times of the waves will give a better understanding of the possible evacuation times for each area. This will give a good overview of the impact on a global level of the most relevant scenario and answers the second sub-research question. Based on the answers to the first and second question the most severely effected areas in Iquique can be indicated. These will be the areas for which mitigation measures should be designed what gives an answer to the third sub-research question.

2.4. DETAILED ANALYSES

With the answers to the first three sub-research questions a detailed analyses can be performed to answer the fourth question. The indicated hazardous areas will be analysed according to the criteria loss of life, material damage, economical damage and post-event disruption of society as formulated in the introduction . This involves looking closer into to the inundation depths at several points in the area, the different waves approaching in different areas and an estimation of the flow velocities. Also, several cross-sections during the tsunami event are evaluated to get a good understanding of the topography in order to indicate natural barriers and safe zones.

2.5. RECOMMENDATIONS & DISCUSSION

To conclude this part the modelled results will be discussed and knowledge gaps will be indicated. Also recommendations based on the discussion will be given for further research. These results will be used in part two where several mitigation measures are proposed for the city of Iquique.

3

PROPOSED SCENARIOS

After the earthquake in April 2014 in Iquique only 20% of the accumulated co-seismic slip is released, this gives reason to believe that another earthquake could happen in the near future. All the substantiations and assumptions for possible future earthquakes scenarios in the Northern seismic gap of Chile are briefly discussed in this chapter, an overview of the scenarios is presented in table 3.1.

Table 3.1: Proposed earthquake scenarios for the Northern seismic gap of Chile

Scenario	Description	Magnitude M_w [-]	Max. co-seismic slip [m]	Mean co-seismic slip [m]	Initial wave height [m]
Scenario 1	8.8 based on Chlieh et al	8,81	7,25	3,20	2,55
Scenario 2	Northern part	8,29	6,59	1,21	1,60
Scenario 3	Southern part	8,51	7,34	3,06	2,14
Scenario 4	Northern + Southern part	8,62	7,34	2,06	2,14
Scenario 5	Centre part (without April '14)	8,45	7,05	2,64	2,07
Scenario 6	Northern + Centre part	8,58	7,05	1,90	2,56
Scenario 7	Southern + Centre part	8,68	7,34	2,96	2,12
Scenario 8	Northern + Centre + Southern	8,75	7,34	2,28	2,53

3.1. SCENARIOS BEFORE APRIL 2014

In 2011 Chlieh *et al.* [11] proposed a back-slip model for the northern seismic gap of Chile. This model describes the expected co-seismic slip in the case of an event based on the accumulated slip since 1877. Based on this back-slip model Yagi *et al.* [19] proposed a possible scenario for the northern seismic gap. The proposed scenario is assumed to be in the same area of the 1877 earthquake and has a maximum co-seismic slip of 7,25 m. Furthermore it is assumed that all slip deficit is released during the event. Both rake and dip angle used for the simulation of the rupture zone are respectively 90° and 20° . Both are constant and do not change with the position of the sub-faults.

To evaluate a possible worst-case scenario, as happened in Tohoku in 2011, a $M_w = 9,0$ earthquake is proposed. This scenario is based on the $M_w = 8,81$ earthquake but it is assumed to have a higher slip. This scenario is calculated by assuming the same area as the $M_w = 8,81$ with the same amount of sub-faults and multiplying the slip of each sub-fault by a factor to increase the M_w to 9,0, the associated co-seismic slip is 13,5 m which corresponds to a factor 1,9. Based on the back-slip models it would take another 122 years (260 years from the last large event in 1877) before such a scenario could occur. Based on the historical return period of 111 ± 33 years this scenario is not likely to happen. Because the $M_w = 9.0$ scenario has no real scientific proof and is just to evaluate a worst-case scenario compared to the size of the earthquake in Tohoku in 2011 it is not further elaborated in this analyses.

3.2. SCENARIOS INCLUDING THE EARTHQUAKE IN APRIL 2014

Because the back-slip model of Chlieh *et al.* [11] was proposed before the $M_w = 8,1$ earthquake in April 2014 the new situation should be taken into account. However the earthquake in April 2014 released locally only 50% of the energy, stressed the northern segment and left the highly coupled southern segment unbroken the $M_w = 8,81$ scenario will be an over estimation in the case of an actual event.

That is why Cienfuegos *et al.* [2] proposed several new scenarios for the Northern, Centre and Southern part of the Northern seismic gap in Chile. These scenarios are based on the back-slip model of Chlieh *et al.* [11] but include the released energy after the earthquake in April 2014. Also the rake angle used for each sub fault varies along the rupture zone and follows the Arica bend. Besides the dip angle is adjusted to 18° which is more in agreement with seismic data of the area. Although these scenarios are still preliminary results, they are already used in this analyses assuming they are more likely then the $M_w = 8,81$ scenario proposed by Yagi *et al.* [19].

Cienfuegos *et al.* [2] proposed three different scenarios. The first one is in the Northern part of the Northern seismic gap of Chile from Ilo to Arica. The location is in agreement with (Schurr *et al.* [17]) who stated that the Northern part of the Northern seismic gap is stressed due to the $M_w = 8,1$ earthquake in April 2014 which makes it more likely rupture. The second scenario is more to the South than the earthquake in April. The area covered by the fault plan reaches from Patache till Mejilones, and stops before the Mejilones peninsula. The third scenario covers a smaller part located next to the rupture zone of the April 2014 event. This is the part in the seismic gap that did not rupture but got stressed during the earthquake in April 2014.

3.3. COMBINATION OF PROPOSED SCENARIOS

It is possible that the proposed scenarios occur at the same time. For example when the Northern part with a higher probability of occurrence triggers the Southern part. Because the earthquake in April 2014 reduced the potential slip locally by about 50%, the probability that a future earthquake would release the whole seismic gap decreased. However the slip reduction due to the April 2014 earthquake is only partial so this region will not necessarily act as a barrier (Schurr *et al.* [17]). This gives reason to belief that a combined scenarios are also possible.

For simplification the initiation of the combined scenarios are all set on $t=0$. However it could be possible that first the Northern part ruptures and the Southern part follows a few seconds later. This will generate a different type of tsunami wave. This should be taken into account when analysing the inundation maps.

4

GENERAL ANALYSES

In this section the scenarios are modelled with NEOWAVE and analysed on a global level in order to answer the first three sub-research questions. The modelling results are compiled for each scenario to establish the worst-case scenario and to indicate the area where mitigation measures should be designed for. In this chapter only the relevant results are presented, in the appendix A the results of all scenarios are compared.

4.1. MOST RELEVANT SCENARIO

To determine the most relevant scenario in terms of tsunami hazard, the inundation plots of all proposed scenarios are carefully analysed. The criteria for most relevant scenario is usually a consideration between largest impact and highest probability of occurrence of a certain scenario. However, the probability of occurrence is not relevant in the case of mitigation measures because the consequence of a worst case scenario is not acceptable. Besides, the actual probability of occurrence of a certain scenario has a large range of variation depending on unpredictable seismic processes. In this research the scenario with the largest impact, as defined using the impact criteria, is therefore considered the most relevant.

According to the inundation plots presented in the appendix A all proposed scenarios create inundation in the same coastal areas, only the total inundated area per scenario differs depending on the magnitude of the earthquake and the size of the generated tsunami wave. Especially for the smaller rupture zones where the co-seismic slip is concentrated in a smaller area, large tsunami waves will be generated. The scenario with the most severe inundation is the 8th scenario that combines the Northern part, Centre part and the Southern part as proposed by Cienfuegos *et al.* [2], see figure 4.2. Even though the probability of this scenario is debatable because all scenarios are assumed to occur at the same time, it shows that a combination of all proposed rupture zones can have a severe impact on Iquique. Figure 4.1 shows the surface displacement due to this scenario with an earthquake of $M_w=8,75$.

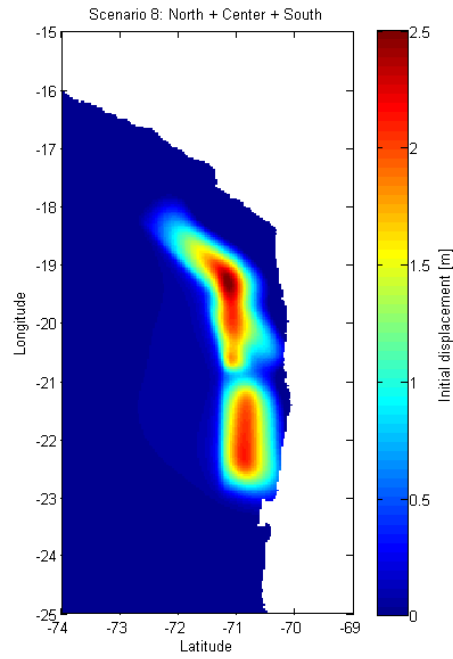


Figure 4.1: Surface displacement due to the $M_w=8.75$ earthquake based on Cienfuegos *et al.* [2]

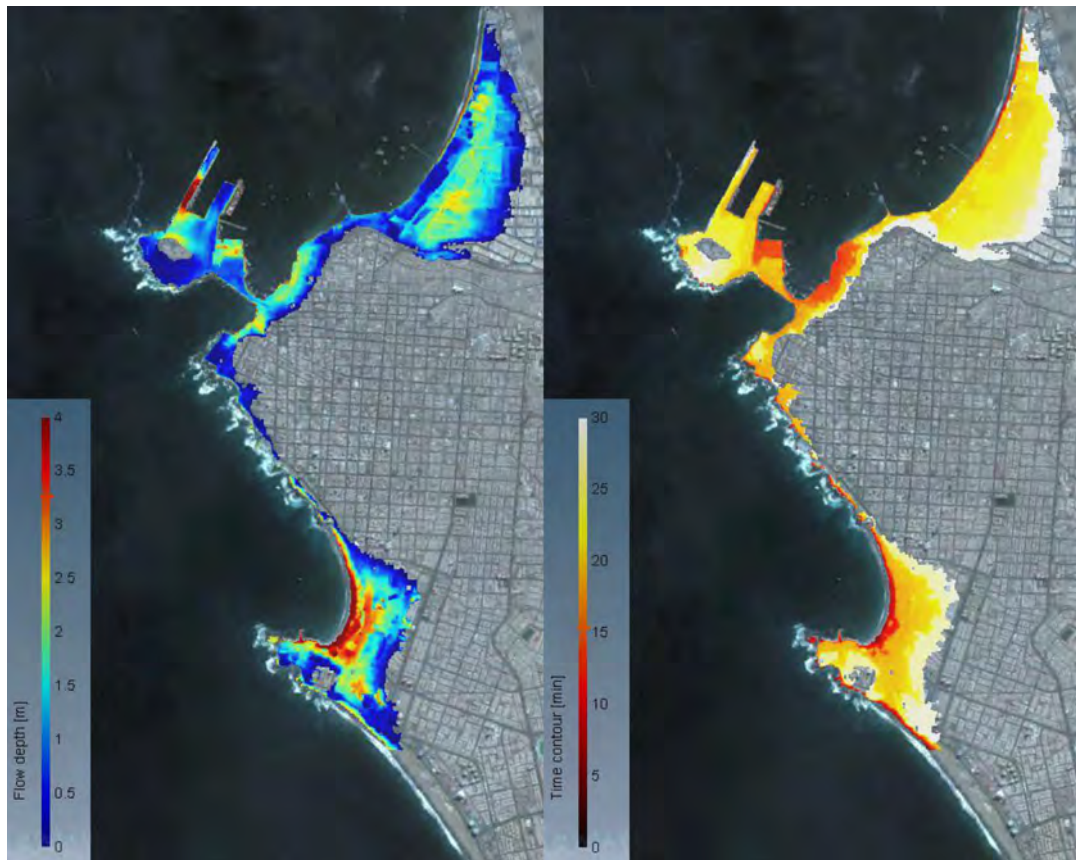


Figure 4.2: Tsunami impact on Iquique for scenario 8 ($M_w=8.75$), left the flow depth and right arrival time.

Down to the South there is severe inundation in the coastal area between Zofri and the Port. This area contains the navy base in the North, the replica of a battleship (the Esmeralda) and the new building of the municipality. Also the fish auction is severely inundated with almost 2,5 meter of maximum flow depth during the event. The water enters this coastal area within 10 minutes after the earthquake. Also the entire Port is inundated due to the tsunami, only the storage area in the center stays dry. The storage area to the right of the centre is a lower lying part with, according to the model, maximum flow depths of 1,5 till 2 meters. This is also the first part of the port which is subject to inundation. Also the berths are inundated but with largely varying flow depths, these are assumed to be numerical errors due the rapid changes of the bathymetry. Furthermore the connection of the Port to the mainland is inundated which cuts off any evacuation possibilities for the port. Directly South of the connection with the port inundation heights of 0,5 till 2,5 meters can be found.

Until the 'Playa Cavancha' hardly any severe inundation is found in the coastal areas, only till 0,5 meters in the shallower coastal areas along the Av. Arturo Prat Chacón. However, the Canvanca beach and peninsula itself are subject of severe inundation due to the tsunami. At the Northern part of the beach maximum flow depths of 4 to 5 meters are found at the waterline whereas behind the beach and at the street the maximum flow depths are slightly reduced to 3 meters at the Av. Arturo Prat Chacón. Here also the first lines of buildings get inundated. At the South side of the Cavancha beach the water is not stopped by natural barriers and extends further onshore till the roundabout, here the water closes all the evacuation possibilities of the peninsula. Also the the peninsula itself gets inundated with average flow depths varying between 3 meters in the North and 0,5 meter in the South.

At the 'Playa Brava', to the South of the peninsula, the beach is inundated with flow depths of around 2,5 meter at the waterline. However, here the wave does not extend further onshore and only the beach is subject to inundation. The Av. Arturo Prat Chacón is subject to 0,5 to 1 meter inundation.

4.2. HAZARDOUS AREAS

The areas that are most affected according to the model results are **Zofri**, the **Port** and the **Cavancha** beach and peninsula. In the analyses of the coastal areas of Iquique in appendix B shows that in Zofri and Cavancha most human lives area at stake on a daily bases. Also both areas have a high economical value for Iquique. For Zofri this is due to the industrial activities and the mall, for the Cavancha peninsula this is due to the tourist activities at the beach and the hotels at the peninsula. The port is also of economical importance for Iquique, see B, however the amount of human lives at stake is less. Besides the port is already subject of another sub group within the JICA-SATREPS research. That is why the focus of this research will be on the Zofri area and the Cavancha peninsula.

5

DETAILED ANALYSES

In this section a detailed analyses will be performed on the Zofri area and the Cavancha peninsula for the impact according to the eight scenario proposed by Cienfuegos *et al.* [2].

5.1. ZOFRI AREA

The inundated area is approximately 760.000 m^2 and covers almost 50% of the total Zofri area. The water reaches from the coastline till the Circunvalación road in the North and the Las Carbas road in the South, this is also the area where the Zofri Mall is situated. The mall is visited daily by approximately 10.000 people and is assumed to have the highest density of people in the Zofri area. The highest maximum flow depth of 3 meters in the Zofri area is recorded around the intersection between the Oficina Salitrera Victoria and the Centenario, see figure 5.1, this is close to the parking area in front of the Zofri Mall. Also north of the COPEC oil storage along the coastline, the flow depth reaches 3 meters. In terms of runup the modelled results of the worst case scenario gives a maximum runup of 4,7 meters in the Zofri area, see figure 5.2. These values are based on bathymetry corresponding with the most right grid points that contain a flow depth.

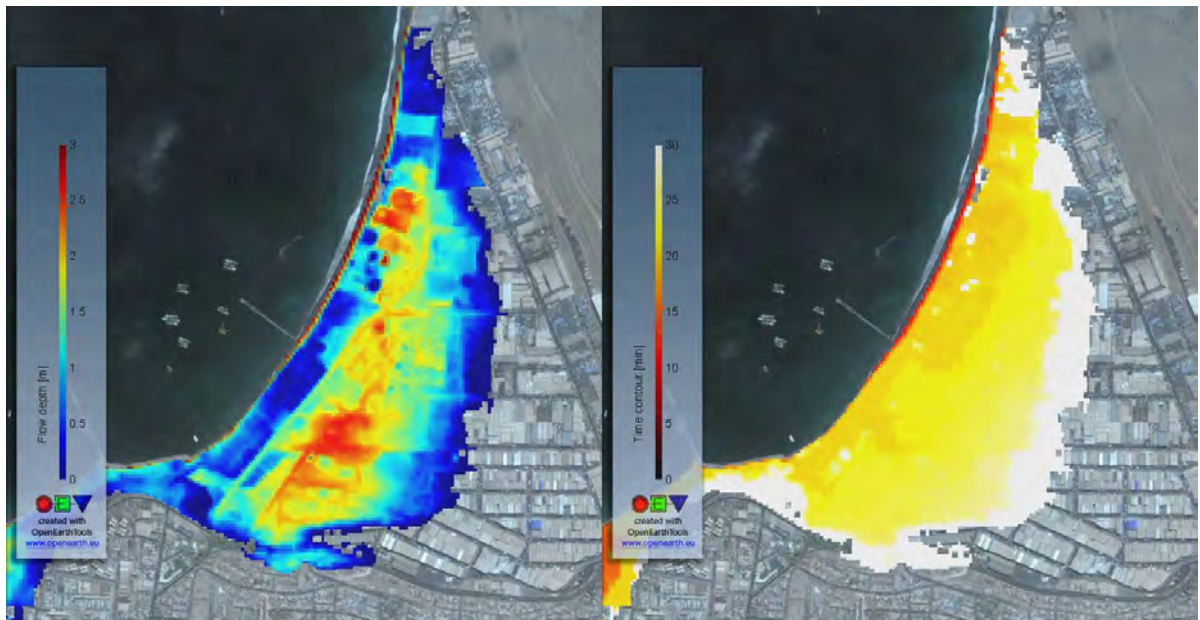


Figure 5.1: Tsunami impact on Zofri for 8th scenario ($M_w=8.75$), left the flow depth and right arrival time of the water. Scales for the flow depth are different and adjusted compared to figure 4.2 for a better understanding of the inundation in Zofri.

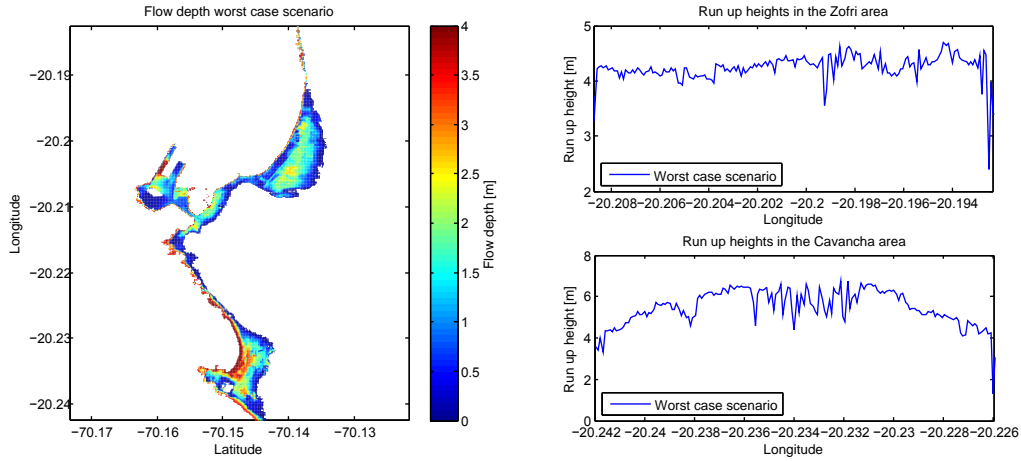


Figure 5.2: Runup height in zofri and cavancha area for 8th scenario ($M_w=8.75$)

5.1.1.1. BATHTUB EFFECT

As described in the general analyses (4) the Zofri area has a natural embankment along the coastline that protects the lower lying hinterland from flooding till a certain threshold, this creates a 'bathtub' effect. The height of the embankment varies along the coastline between 3,4 meters around the COPEC oil storage and 4,4 meters in the centre. The arrival times, plotted in figure 5.1, show darker colors around the COPEC oil storage which is in agreement with the lower embankment at that point, the water breaches the embankment here first. At this breaching point the embankment is over topped with 1 meter of water, see figure 5.3. Cross-section A in figure 5.3 is along the COPEC oil storage and clearly shows how the water flows over the embankment. Cross-section B is more to the South and shows how the waves pill up against the embankment and only a small part will over top. This is due to the process that when the wave starts to over top the embankment it is already retreating, so the height of the flowing water over the embankment will be lower than the actual maximum wave height just in front of the embankment. In the case of a tsunami with a smaller wave height it could be possible that the embankment is able to retain the water, however in that case the runup against the embankment should be taken into account. In the case of the $M_w=8.75$ earthquake proposed by Cienfuegos *et al.* [2] the threshold is slightly exceeded to inundate the entire Zofri area.

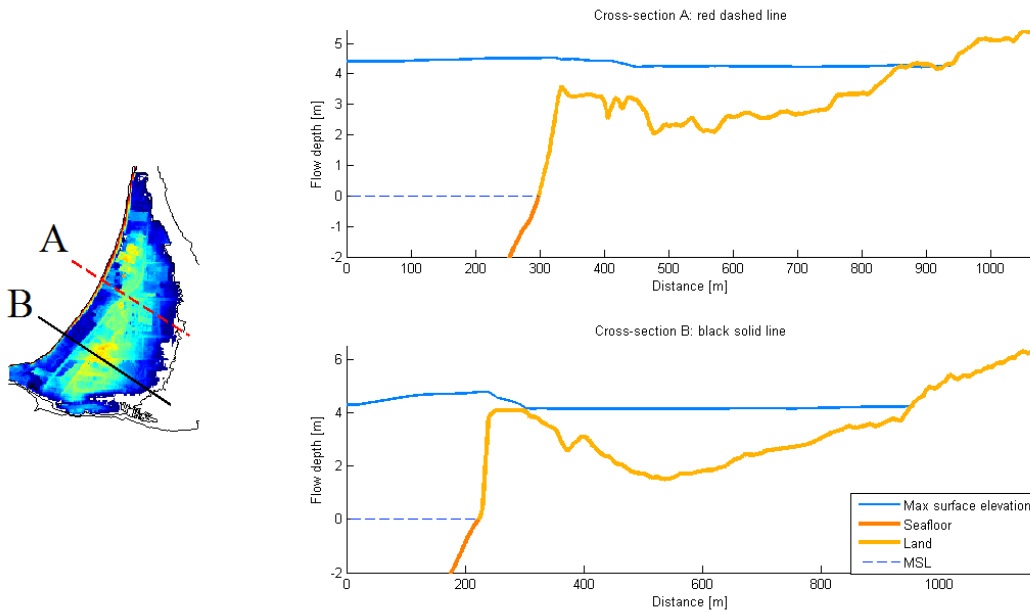


Figure 5.3: Tsunami impact on Zofri for 8th scenario ($M_w=8.75$), cross-section of the bathymetry and maximum inundation.

5.1.2. DEVELOPMENT OF INUNDATION

The development of the inundation in the area is clearly visible in the time-laps plot of the Zofri area in figure 5.4. Here the inundation is plotted for different moments in time, respectively from 20, 21, 22, 23, 30 and 60 minutes. The first wave reaches the embankment after 19 minutes, after that it takes approximately four minutes to inundate the area. This is also in agreement with the wave records in front of the Zofri coast, see figure 5.5. The time record of the tsunami wave shows that the first wave is not the highest. After 115 minutes a even bigger wave will approach the Zofri bay which will breach the embankment for the second time. This bigger wave occurs due to resonance phenomena along the coastline and in the bay, here the natural frequency of the bay gets excited by the incoming wave. The smaller waves in between only breach the lower points along the embankment and add small volumes of water to the 'bathtub'.

According to the model the water reaches the parking area of the Zofri Mall within 22 minutes after the earthquake, after 23 minutes the water level starts to increases to 2 meter around the Zofri Mall in a period of approximately 7 minutes. In total it will take approximately 60 minutes before the Zofri Mall is completely inundated till the highest level.

The rapid development of the inundation area is also in agreement with the high flow velocities as can be seen in figure 5.6, here the maximum flow velocities during the event are plotted in the area. Locally and close to the embankment flow velocities in the order of 3 m/s can be found, further away from the embankment the flow velocities decrease to 0,5 m/s. Due to the high flow velocities and flow depths lose objects like cars can be picked up and accelerated by the streaming water, this cloud lead to high debris forces. Also the hydrodynamic forces on obstructions like buildings can be severe. This will vary for each obstruction since the forces are depending on the size and the shape of the obstructions and the local flow depths and flow velocities. In terms of material damage the impact is severe in this area.

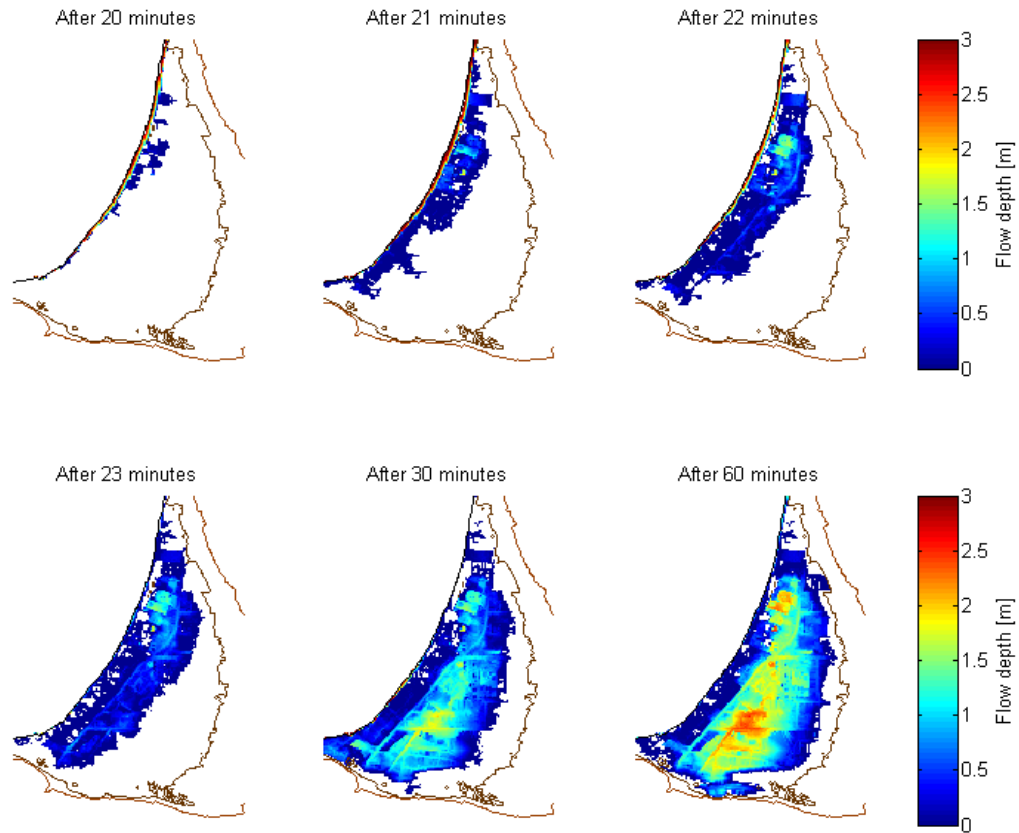


Figure 5.4: Tsunami impact on Zofri for the 8th scenario ($M_w=8.75$), for different moments in time.

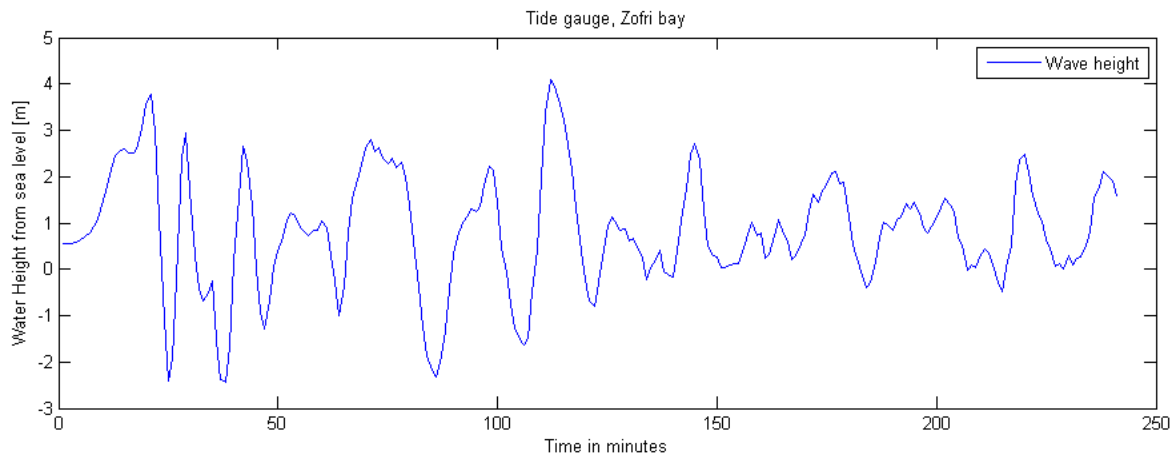


Figure 5.5: Time record of the tsunami wave in front of the Zofri area for the 8th scenario ($M_w=8.75$), tidal level is +0.8m.

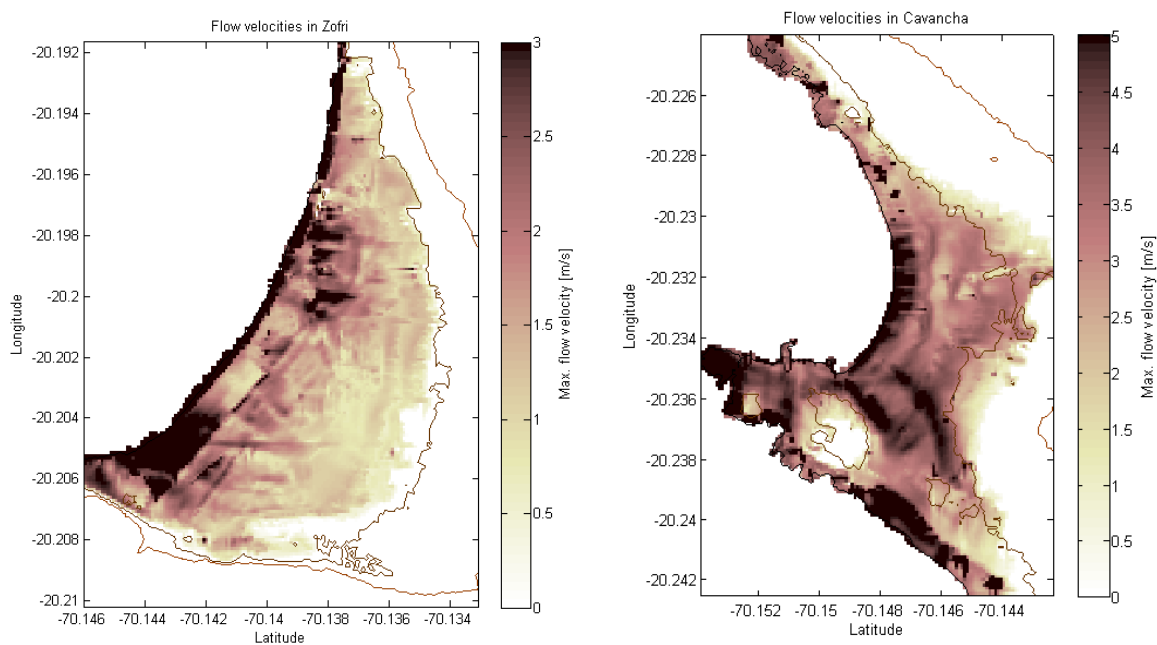


Figure 5.6: Flow velocities in Zofri (left) and Cavancha (right) for the 8th scenario ($M_w=8.75$)

5.1.3. POST-EVENT DISRUPTION

In terms of post-event disruption of society the Zofri area faces two main problems. In the first place it is possible that the inflowing water will pollute the area due to the oil refineries and other heavy industrial activities in the Northern coastal area, especially when they are damaged due to the earthquake. The pollution will spread through the Zofri area which has to be cleaned afterwards. Another issue is based on the bathtub principle earlier discussed. When the natural embankment is over topped the area will be flooded, however it is not possible to drain the area by a natural gradient because it is trapped in the 'bathtub'. The slight benefit of this natural embankment is that the polluted water is contained inside the Zofri 'bathtub' and will not spread into the ocean. To restore the Zofri area to its initial function the polluted water inside the 'bathtub' has to be removed and needs treatment before pumping back into the ocean.

5.2. CAVANCHA PENINSULA

As described in the general analysis the peninsula is subjected to large inundation. Here the main problem is related to the cut-off of evacuation routes from the peninsula to the high ground. The cut-off is critical since the Cavancha peninsula and the Cavancha beach are the tourist epicentre of Iquique. The inundated area extends almost 500 meter onshore from the Cavancha beach in the East to the Jumbo supermarket at the Heroes De La Concepción in the West and from the Playa Brava in the South to the Diego Portales in the North. The total inundated area is approximately 700.000 m^2 . The inundation maps based on maximum flow depth and arrival times for the Cavancha peninsula are presented in figure 5.7.

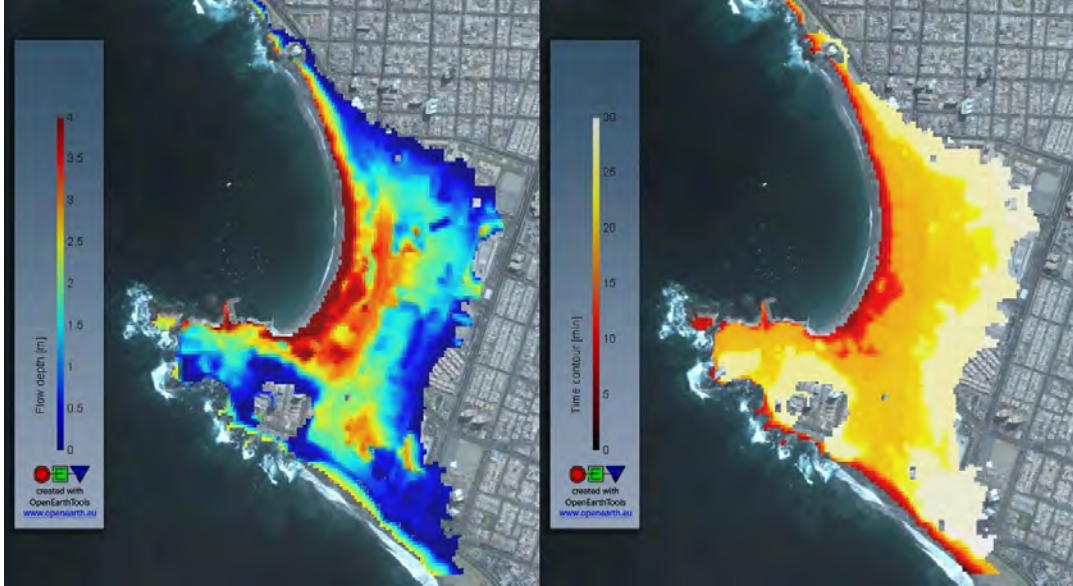


Figure 5.7: Tsunami impact on Cavancha for 8th scenario ($M_w=8.75$), left the flow depth and right arrival time of the water.

5.2.1. INUNDATED AREAS IN CAVANCHA

According to the model the maximum flow depth is 5 meters and will occur at the waterline on the Cavancha beach. Around the North side of the beach also the first few rows of residential building will be touched by the water with maximum flow depths in the order of 1,5 meters. At the main road along the coast (Av. Arturo Prat Chacón) maximum flow depths of 3,5 meters will be found between the roundabout and the Archipelago las Anfillas Hotel. Also the Casino, in the area between the Playa Cavancha and the roundabout will be inundated with 2,5 meters of water. According to the inundation maps and the topography the pedestrian road along the Playa Cavancha seems to be the highest tracing in the area because it has a lower flow depth then the neighbouring road and beach. Since the beach is mostly crowded with people the impact will be high here in terms of the criterion loss-of-life.

At the Northern edge of the peninsula the water pills up against the steep rocks and flows over the embankment to inundate the hotels and the Av. Captain Roberto Pérez, here flow depths vary between 2 and 2,5 meters. The Southern side of the peninsula is less inundated compared to the Northern side, here flow depths of 0,5 meter are found. More to the South, at the Playa Brava, flow depths of 2,5 meters are the maximum. Due to the increased height of the road the water does not reach the hinterland and inundates only the beach.

5.2.2. FUNNEL EFFECT

In figure 5.8 a time series of the tsunami wave in the Cavancha bay is plotted, this shows that in the first 30 minutes two high waves are approaching of which the second wave is even higher than the first. This second wave is probably generated due to resonance effects of the bay. In figure 5.9 the inundated areas for different moments in time are plotted to show the impact of the first and the second wave. The first wave enters the Playa Cavancha around the 17th minute after the earthquake and closes the peninsula for evacuation after the 21th minute, so within 5 minutes the entire peninsula is cut off. The second wave arrives approximately 7 minutes later and inundates an even larger area. Within 30 minutes after the earthquake the maximum flood map is reached. In total it takes approximately 10 minutes to inundates the 700.000 m^2 .

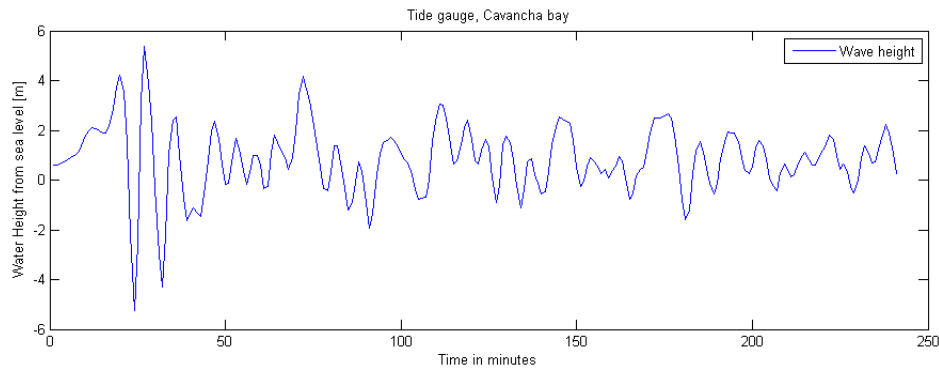


Figure 5.8: Time record of the tsunami wave in front of the Cavancha beach for the 8th scenario ($M_W=8.75$), tidal level is +0,8m.

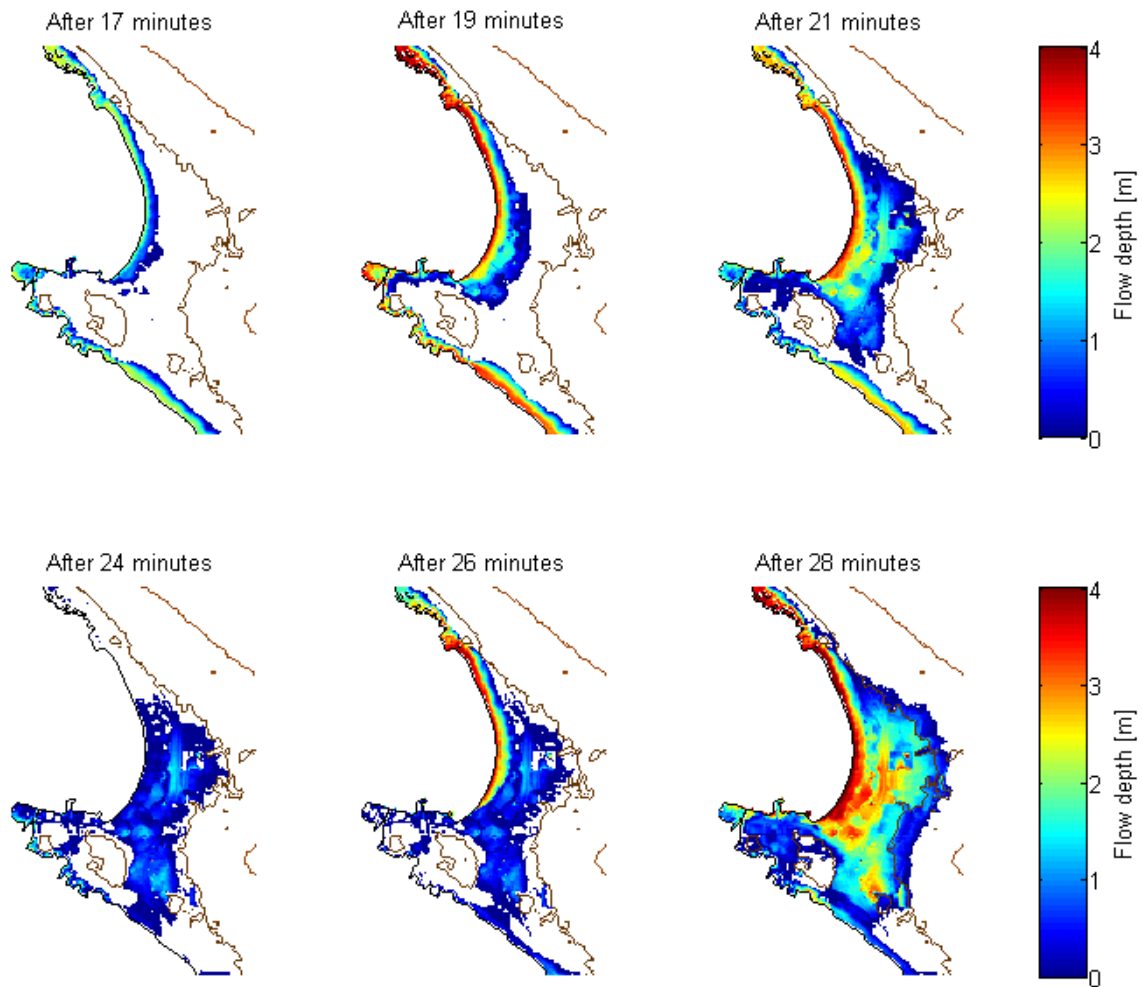


Figure 5.9: Tsunami impact on Cavancha for the 8th scenario ($M_w=8.75$), for different moments in time.

Analysing figure 5.9 it can be concluded that the largest waves approaches the peninsula from the Playa Cavancha in the North. From a physical point of view this can be understood by the shoaling effect due to decreasing water depths in the Cavancha bay, this effect increases the wave height. In combination with the concave shape of the bay and the lower lying Southern part of the beach, the water is forced and concentrated towards the most Southern part of the Cavancha beach.

Here it will flow onshore towards the casino and the roundabout after which it flows over the peninsula to the Southern side. The bay acts like a funnel which forces the water through one point. At the Playa Brava on the South side of the peninsula, the beach is steeper and higher due to which it will not be as easily inundated as the Playa Cavancha. To get a good understanding of the topography and inundated area at the Cavancha peninsula two cross-sections are plotted in figure 5.10. Cross-section A in 5.10 gives a overview from North to South, here it is clearly visible how the water flows in from the North (left) and flows over the roundabout to the Southern side (right). Cross-section B, form West to East, gives a good understanding of the island that is formed at the peninsula and the flow depth that it is surrounded by. In terms of runup the modelled results of the worst case scenario gives a maximum runup of 6,8 meters in the Cavacha bay, see figure 5.2. These values are based on bathymetry corresponding with the most right grid points that contain a flow depth.

5.2.3. MATERIAL DAMAGE

According to the modelled results as presented in 5.6, high flow velocities can be found at the peninsula. During the incoming and retreating wave high flow velocities can be found on both beaches because there are no obstructions and they have a relative smooth floodplains, both are in the order of 5 m/s. In the North the high flow velocities could also be explained with the funnel effect of the bay where a large amount of water is flowing onshore in small amount of time. Also onshore there are a few areas where high flow velocities can be identified. For example just South, behind of the casino and at the roundabout it seems that flow velocities locally reach 5 m/s, this could be associated with the lower flow depths at these point. Behind the Northern part of the Cavanca beach and on the peninsula flow velocities reach approximately 3 m/s which is still quite fast especially when you relate them to the flow depths that are found in these areas. The large flow velocities in combination with the fact the largest wave is entering from the beach could lead to a large amount of sediment that is transported into the city, especially since there are certain areas where flow velocities decrease rapidly or where the topography is lower and there is the ability to trap the sediment. The high flow velocities make it likely to bring severe damage to the buildings and infrastructure in the inundated area. Cars and other loose objects can be picked up by these currents and can be flushed away generating large impact forces on buildings and other obstructions. Another consequence of the high flow velocities are scour problems which could lead to other types of failure mechanisms of structures and buildings.

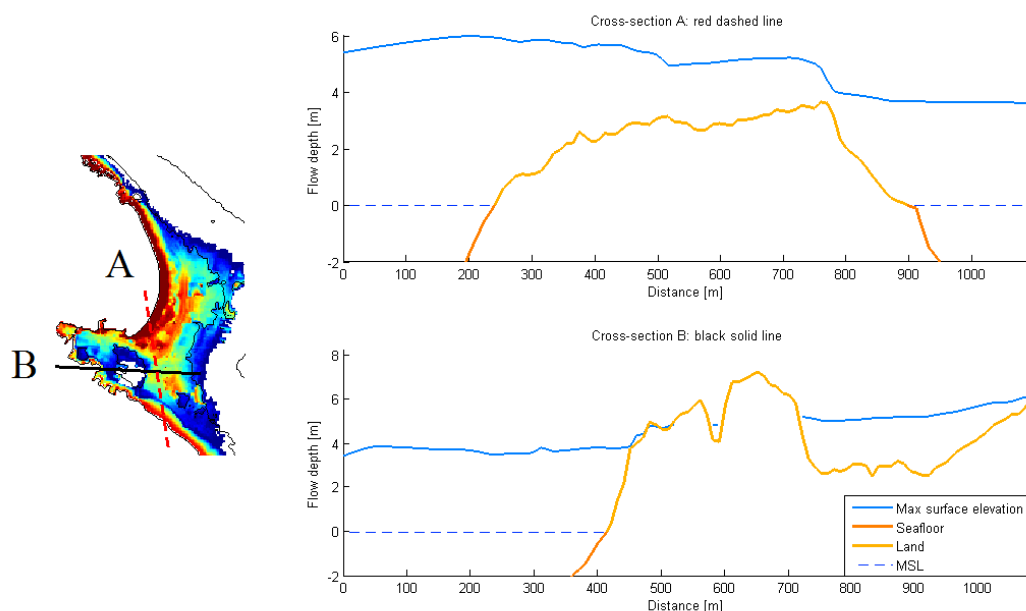


Figure 5.10: Tsunami impact on Cavanca for the 8th scenario ($M_w=8.75$), cross-section of the bathymetry and maximum inundation.

5.2.4. POST-EVENT DISRUPTION

During the tsunami event the peninsula is closed off within 21 minutes after the earthquake. The roads which connect the peninsula with the main land will be severely damaged or flushed away due to high flow velocities and flow depth in this area. In relation to post-event disruption of society this could be a problem for emergency services to reach people who are trapped on the peninsula or around the higher buildings. Another possible hazard in terms of post-event disruption in Cavanca is the possible environmental damage due to the COPEC gas station that is situated at the Southern side of the Arturo Prat Chacón. Again, the impact due to environmental damage will be less than in Zofri however it still needs to be taken into account. Especially since here the gas station is situated such that the water will flow back into the ocean by a natural gradient. Furthermore it should be mentioned that when the tsunami wave is retreated some areas stay inundated because of the lower topography, this can be compared to the 'bathtub' effect in Zofri however the effect is not that strong at the peninsula. Lower parts that will not entirely drain on a natural gradient are for example the coastal road (Arturo Prat Chacón) behind the casino and the roundabout.

6

CONCLUSIONS

In this chapter the sub-research questions as described in chapter 2 will be answered, each question is evaluated based on the modelled results in chapter 4 and 5.

6.1. MOST RELEVANT SCENARIO

The worst case scenario in terms of tsunami impact on Iquique is the 8th scenario, this scenario contains fault plains along the entire Northern seismic gap in Chile. The scenario is a combination of the Northern, Centre and Southern sub-scenarios as proposed by Cienfuegos *et al.* [2]. The combination of these scenarios contains an earthquake with a magnitude of $M_w = 8,75$ and generates a tsunami with an initial wave height of 2,53 meter. However the source of this scenario and the assumption that all fault plains rupture at the same time is debatable, this scenario gives a good understanding of the available seismic energy in the entire Northern seismic gap of Chile and the related tsunami impact on Iquique. In the terms of tsunami hazard, the criteria for most relevant scenario is established to be the scenario with the largest impact on Iquique. That is why the combined scenario of the Northern, Centre and Southern part is found to be the most relevant scenario for Iquique.

6.2. GLOBAL IMPACT

The impact of the 8th scenario on Iquique is described in chapter 4 from North till South. In general inundation is found along in three main areas along the coast which are the Zofri area, the Port and Cavancha peninsula. The total inundated area is approximately 2 km^2 and almost equally divided over the three area. The maximum flow depth of 5 meters is found in the south at the Cavancha beach and the tsunami wave reaches the coastline within 15 minutes after the earthquake.

6.3. HAZARDOUS AREAS IN IQUIQUE

Based on the global impact study the Zofri area and the Cavancha peninsula are indicted as hazardous areas to focus this research on. Both areas are severely inundated due to the worst case scenario, contain a large amount of people on a daily bases and have a high economical value for the city of Iquique. Also the port has a high economic value for Iquique however it contains fewer people on a daily bases, that is why the scope of the research is focussed on the Zofri area and the Cavancha peninsula. Besides the Port is already subject of another sub group within the JICA-SATREPS research.

6.4. LOCAL IMPACT

Based on the the detailed analyses for Zofri and Cavancha several conclusions can be drawn. For both areas holds that they are not safe during a tsunami event and should be evacuated or protected against the inflowing water.

6.4.1. ZOFRI AREA

In general the Zofri area is severely inundated due to the worst case scenario, the total inundation area in Zofri is approximately 760.000 m^2 which is almost equal to 50% of total Zofri area. The highest flow depth of 3 meters is found at the intersection between the Av. Oficina Salitrera Victoria and the Av. Centenario and the first inundation starts within 19 minutes after the earthquake. However another, even larger, wave follows 115 minutes after the event. This can be explained with the resonance phenomena along the coastline and in the bay. Due to the natural embankment at the coastline, Zofri is turned into a 'bathtub' with a depth of 2,5 meters. At the lowest point of the embankment 1 meter of water flows over the embankment to flood the area. It can be concluded that the height of the natural embankment is critical for inundation of the Zofri area.

The Zofri Mall is concerned as most important location within the Zofri area in terms of loss-of-life due to the high density of people in the mall. The maximum inundation at the Zofri mall is 2 meters and it takes almost 22 minutes before water reaches Zofri Mall. This can be important to take into account during an evacuation exercise. Flow velocities in the area will be around 0,5 m/s with locally higher values of 3 m/s. In terms of post-event disruption of society the embankment plays an important role because the water can not drain on a natural gradient. This also has a small benefit because the water will be polluted due to the industrial activities in the Zofri area and will be contained within the 'bathtub'.

6.4.2. CAVANCHA PENINSULA

The Cavancha peninsula is the tourist epicentre of Iquique and therefore important when proposing mitigation measures. The peninsula and the surrounded area is subject to severe inundation in the worst case scenario. The inundated area is approximately 700.000 m^2 with the maximum flow depth of 5 meters at the beach. Average flow depth in the rest of the inundated area is 1,5 meters with locally small areas of 3 meters flow depths. Due to the shoaling and resonance effects in the Cavancha bay the largest waves enter the peninsula from the North and flow over the peninsula to the South. It can be concluded that the peninsula and its evacuation roads is vulnerable due this shape of the bay and the lower lying part at the Cavancha beach.

The first wave arrives within 17 minutes after the earthquake and 5 minutes later the peninsula is cut-off for evacuation. The second and larger wave arrives approximately 7 minutes later and inundates an even larger area. Flow velocities are in the order of 3 m/s with locally spots with 5 m/s, this could lead to scour problems around structures, sediment transport into the city and severe damage on buildings and other obstructions. In relation to post-event disruption the cut-off of the evacuation possibilities of the peninsula in combination with possible damaged roads could be a problem for emergency services to reach the people who are trapped on the peninsula.

7

DISCUSSION

The NEOWAVE model gives a representation of the reality by calculation of the shallow water equations with a numerical scheme. Also assumptions are made in order to simplify certain processes. These simplifications can cause numerical errors, which could eventually lead to a wrong interpretation of the results. That is why in this chapter the input and the results of the NEOWAVE model will be discussed.

7.1. GENERATION OF WORST CASE SCENARIO

For simplification the initiation of each sub-scenario within the combined scenarios are all set on $t = 0$. In other words the Northern, Centre and Southern part rupture at the same time. However, in reality this is unlikely to be the case. It is much more likely that the each sub-fault ruptures at a different initiation time. This is of great importance for the generation of the tsunami because each displacement of the sub surface will create its own wave component.

When there is a phase difference between the wave components other maxima can be generated due to superposition of the waves. For this principle also the distance between the different sub faults and the area of interest is of great importance. When one rupture zone has a larger distance to the point of interest than an other sub fault, the phases of the different waves component will differ. Also the decreasing propagation speed towards the coast due to decreasing water depth plays an important role in the phases difference at each location. This process of phase differences and superposition of the wave influences the maxima of the wave height and therefore the impact due to the tsunami on the city.

In the case of a combination of the proposed scenarios by Cienfuegos *et al.* [2] the importance of this phenomena can be estimated. Based on the general analyses in the appendix A the Centre part (scenario 5) has the largest contribution to the combined scenario of the Northern, Centre and Southern part. The Northern and Southern scenario by itself have on the other hand very small contributions to the worst case scenario. So when superposing the three scenarios in such a way that all the maxima coincide it will not make a significant difference compared to the modelled scenario. However it could still lead to more inundation than in the case of all sub faults at $t = 0$.

7.2. TIDAL INFLUENCE

The default settings of NEOWAVE do not include the tidal range in the model. That is why in these results the highest astronomical tide of +0,8 meter is included to obtain the worst case scenario. This is done by changing the bathymetry to -0,8 meter and running the model with default settings.

7.3. BATHYMETRY CHANGES

Due to an earthquake the ground elevation changes not only locally (cracks in the subsoil) but also on a larger scale due to the movement of the tectonic plate. Based on the location of the earthquake in relation to the location of interest it could differ if there is subsidence or uplift. In the case of Zofri this could be of great importance since this area is vulnerable to the height of the embankment.

7.4. FLOW VELOCITIES

NEOWAVE uses the topography based on the LIDAR maps with a grid size of 2 meter, however this data does not contain any buildings or other man-made obstructions which influences the model results. When including obstructions there is less available space for the water to flow. Less available space for the water due to obstructions will lead in the first place to larger inundation maps because the amount of water stays the same. Besides the less available space could lead to smaller cross-sections and higher flow velocities. However due to the obstructions the roughness of the flood plain increases which will dissipate energy. The balance between increasing flow velocities due to less available space and decreasing flow velocities due to dissipated energy depends on the location and the size of the obstructions. This should be taken into account when calculating the exact flow velocities. In general higher flow velocities will most likely occur at the roads where the roughness is relatively low which is inconvenient for evacuation purposes.

8

RECOMMENDATIONS

The recommendations in this chapter are based on the conclusions and discussion of the modelled results. In order to propose and design mitigation measures recommendations are formulated specifically for the Zofri area and the Cavanca peninsula. Also a few general recommendations related to the research methodology and proposed scenarios are formulated.

8.1. GENERAL

- **Perform detailed field analyses**

Perform a detailed field analyses in order to get a better understanding on the functions of each area, the amount of people and buildings that are located. Not all areas has to be protected from inundation. In certain areas it is sufficient to delay the water and increase arrival times.

- **Take superposition into account**

As described in the discussion the phase difference of the scenarios could lead to a higher inundation in the case that the maxima of the waves coincide. The extra effect should be taken into account when making the inundation plots.

- **Modify shape and depth of the bay**

The resonance phenomena are influenced by the periods of the incoming wave and the natural period of the bay. The latter is based on the shape and the depth of the bay. When the incoming wave has the same period as the bay, the waves inside the bay get excited which could lead to higher waves. By changing the shape or depth of the bay the natural period can be modified and resonance phenomena can be mitigated. This could be researched with a numerical model like NEOWAVE.

- **Evacuate for at least three hours**

Due to reflection and resonance phenomena more than one wave will approach the coast in a period of three hours (or more). That is why it is recommended to evacuate for at least 3 hours before returning back to the inundated area. In the case of the modelled results for the Zofri area the second wave arrives after 115 minutes and is larger than the first wave.

8.2. ZOFRI

- **Increase height of embankment**

To increase redundancy of the Zofri area the natural embankment should be elevated. In the case of the modelled scenario the flow depth over the embankment is one meter. It is recommended to increase the embankment with at least 1,5 meter to retain water also in the case of a tsunami that has higher waves than the modelled worst case.

- **Protect heavy industry**

Investigate the possibilities to protect the oil refineries and industrial activities in the coastal area in order to be more resilient to an earthquake and a tsunami. This could prevent a major pollution problem in the case of inundation.

- **Drainage of the Zofri area**

Due to the 'bathtub' effect the Zofri area contains the water with a flow depth of 2,5 meter and has to be emptied. It is possible that the water needs treatment before pumped back into the ocean due to pollution from the area.

- **Use arrival times for evacuation exercises**

Take the arrival time of the first significant wave in the Zofri area into account during evacuation exercises. Especially for the Zofri mall where the density of people is high. However the results of the arrival times should be interpreted with caution.

8.3. CAVANCHA

- **Retain the water from the North**

Because the largest amount of water is approaching the peninsula from the North and no water is flowing in from the South it should be sufficient to retain the water at the Cavanca beach in order to protect the area. The highest flow depth to retain in this area is 5 meters, when designing mitigation measures also the piling up of the waves should be taken into account. Also by delaying the water from the Cavanca beach the impact could be reduced, in that case lower retaining heights could be used depending on the level of safety and the amount of delaying that is desired.

- **Determine a tracing to retain the water**

The cycle path at the edge of the beach and the road is the highest point at the Cavanca beach, this could be a good place to retain the water because here the additional height to retain or delay is minimal.

- **Protect COPEC gasstation**

Try to protect the COPEC gas station from inundation so environmental impact in the case of a tsunami can be reduced. especially since it could be already damaged by the earthquake and the water will spread the pollution.

- **Take the drainage of Cavanca into account**

When designing mitigation measures the possibility to drain the area by a natural gradient should be taken into account. Except for the COPEC gas station there are no environmental hazards in the area.

- **Investigate evacuation possibilities of peninsula**

Investigate the possibilities to evacuate the Cavanca peninsula. If no sufficient routes are available it could be better to stay at the peninsula. Horizontal evacuating is not always the best solution in this case.

- **Evacuation information for tourists**

A main concern in this region are the tourists and the fact that they are not familiar with big earthquakes or tsunamis. That is why special attention should be paid to evacuation possibilities and information for tourists. Since the beaches inundate severely there the evacuation information for all locals and non-locals should be available.

PART 2

PROPOSING MITIGATION MEASURES

1

INTRODUCTION

1.1. REFLECTION ON PART ONE

In the introduction of this research, the main research question is formulated as the following: *How can the impact of a likely future tsunami on the city of Iquique be reduced with respect to the impact criteria loss of life, material and economical damage and post-event disruption of society.*

The objective is therefore to mitigate the impact with any means that are available and suitable. In order to determine what measure would be suitable, one needs a quantification of the impact one seeks to reduce. In Part One the size of the impact is quantified with the aid of four sub-research questions. The first of these refers to the matter how to best assess the impact. Various event scenario's are possible. An important consideration is to choose between taking the most likely scenario or the one with the most impact. It is decided that mitigation measures should be designed for the scenario with the unacceptable impact; the worst case scenario.

For this scenario, the impact is computed. The remaining three questions are used as guidelines in the analysis, assessing the impact on a global and local scale. Three areas were determined as affected most severely. Of these three areas, only two, Zofri and Cavanca, remain in the scope of this research. For these areas the impact was quantified using the impact criteria. From this analysis, the impact that needs to be mitigated is derived. This knowledge is the starting point of the second part of the research, finding an answer to the main research question by designing a suitable and effective complex solution to mitigate tsunami impact.

1.2. INTRODUCTION TO TSUNAMI MITIGATION

In this part of the research the authors will focus their attention on the mitigation of the estimated tsunami impact. In order to do this, one has to investigate what is meant by impact mitigation measures related to tsunami's and how one can come to decide on the appropriate choice of measures.

In the past large events have affected coastal areas around the world. In Part Zero of this report lessons learned from previous events both in Chile and elsewhere are discussed. These lessons often address knowledge gaps and faulty protection of people and property. It is necessary to take note of these lessons before continuing the design of future mitigation measures as to not repeat mistakes.

Mitigation measures are defined in this report as any preparations made by people to reduce the impact of a tsunami, whether these are structural, related to city planning or organisational. Impact is defined in the introduction () in terms of three criteria, *loss of life*, *damage* and the *post-event disruption of society*.

Which measures to apply to a specific situation is a complex question. Mitigation measures and their exact contribution can be structured using various methods. In part two of this report three different methods of approaching mitigation design are used to develop a framework. Also, an estimation of the fit of a measure in a specific situation must be estimated. In the next chapter, the approach employed in this research is set forth.

1.3. CURRENT STATE OF MITIGATION MEASURES IN CHILE

Most of the coastal areas of Chile are in a tsunami hazard zones. Yet mitigation measures along the coast are scarce. Many improvements have only been made after major events in the past.

Along the coast of Chile warning signs are present in tsunami danger zones. The signs indicate danger zones, evacuation routes and safe zones. The routes are, in general, routes that are also used for non evacuation purposes and lead to higher grounds. In some coastal areas an additional tsunami alarm is present.

The alarm is triggered by the Pacific Tsunami Warning and Mitigation System (ICG/PTWS), this system was established in 1965, after the 1960 tsunami, by UNESCO's Intergovernmental Oceanographic Commission (UNESCO [20]).

Also education has been improved, tsunami awareness programs are implemented in primary schools and in several cities tsunami workshops are given to governments and officials in control of evacuation plans.

Chile has been acting reactive when regarding tsunami mitigation. As an example, only after the 2010 tsunami in the bay of Concepcion, implementation of mitigation measures has started. Coastal protection is now installed (see figure 1.1), houses are relocated and the concept of Pallafita housing is more widely implemented. These measures have made these areas more tsunami prove. These measures are, unfortunately, not consequently implemented along the whole coast of Chile.



Figure 1.1: Tsunami protection for the coast of the Concepcion Bay

1.3.1. IQUIQUE

When examining more closely our area of interest, Iquique, an assessment can be made on what measures are already in place. Also lessons learned during previous events and knowledge gaps in the current system are addressed. The focus will be on the areas Cavancha and Zofri, as recommended in Part One.

MITIGATION MEASURES IN IQUIQUE

At the time of writing, no structural measures with the sole purpose of reducing future tsunami impact are present in Iquique. The focus for now is on warning and educating inhabitants on the risks of such an event and guiding the evacuation process. However, some opportunities for structural measures can be found. In the following sections, both will be elaborated.

Opportunities

In Zofri there is a wall dividing the sea from the industries (as can be seen in figure 1.2a). This wall could be structural adjusted as a seawall.

On the south of Cavancha beach, small islands are created. These are small elevations at the end of the beach, consisting of grass and palm trees. In the North of Cavancha beach, as a division between beach and the higher located road, a concrete stairs is used (figure 1.2b). With minor adjustments, these could function as impact decreasing measures.

Another possibility is the increased use of vertical evacuation buildings along the shore. In most areas, except for Zofri, have high-rise buildings that could be considered when evaluating the possibilities of vertical evacuation.



(a) Wall in Zofri area, deviding sea from industry



(b) Concreet stairs to connect the beach to the road

Current evacuation system

The following information is obtained by a meeting with ONEMI Iquique on 29 December 2014, together with interviews with lifeguards and tourist on Cavancha beach see appendix D.

Evacuation plans, implementing information and aftermath aid systems are implemented in Iquique and the responsibility of ONEMI, the ministry of internal affairs and public safety (www.onemi.cl). ONEMI operates on different fields: Evacuation routes, police/fire department/lifeguards coordination and creating awareness.

For evacuation plans and routes there is a map available that indicates evacuation routes and safe zones (see figure 1.4), also in the city there are signs placed with warnings for tsunamis and evacuation routes.

The police, fire departments and life guards are responsible to properly guide the evacuation, for this there is a division of tasks. Firemen are in charge of traffic control, the police guides the evacuation in the city, they force people out of their cars, evacuation by car is not allowed since this will cause accidents and congestions. Lifeguards are in charge of beach evacuation.

In Iquique education concerning hazardous situations is given in primary and secondary school. Children learn what hazardous events are and which precaution they can take, also evacuation plans are discussed. This education system prepares local people for tsunamis an earthquakes.

The last and biggest responsibility of ONEMI is the coordination of the evacuation and aftermath of the event.

1.3.2. KNOWLEDGE GAPS IDENTIFIED AFTER THE 2010 TSUNAMI

After the tsunami of 2010 that affected Iquique ONEMI specified problems within their organisation. These are divided in groups to be able to conceptualize a solution per identified problem. For more information see appendix D. In this chapter the main problems addressed in the meeting and the main problems identified by conducting fieldwork in Iquique in December 2014 are discussed.

FINDINGS FIELDWORK DECEMBER 2014

Signs to indicate evacuation routes are present however the evacuation signs are not always visible and the routes are not consistently indicating the same direction, see figure 1.3. Furthermore the signs are not clear, colours differ per sign and it is not always obvious which emergency it addresses (earthquake, fire or tsunami). As a second the educational system in Iquique prepares locals to tsunamis and earthquakes. Since Iquique is a touristic place there should also be attention for this group, at the moment no information is available. Awareness stops by the realization that Iquique is a tsunami hazard zone, evacuation routes and plans are unknown.



Figure 1.3: ONEMI evacuation route, conflicting directions

MAIN FINDINGS MEETING ONEMI DECEMBER 2014

In the event of 2010 several sections in the emergency plan have failed or worked inadequately. The following are the most important issues that can be taken into account when designing level 3 mitigation measures.

The means of communication during and short after the emergency where inadequate to properly communicate with the different entities that where in charge of different sections of the emergency plans, this caused disorganised evacuation and rescue operations. Communication problems where caused by, on the one hand, the hardware was not prepared and on the other hand because there was no communication plan. There were no plans or agreements with the nearby communities. Especially regarding water, potable and non-potable, this was problematic since water is scarce in the area of Iquique and it is a first need of the affected population.

A good example is the following incident: in the period after the event volunteers, individual and organizations such as the red cross, did not work together according to one plan,. This caused an unequal distribution of aid. Although there was sufficient available, large parts of the population did not receive appropriate means in the first days.

Table 1.1: Summary of the knowledge gaps for level 3 measures

ONEMI	Field survey
Means for communication were inadequate	Unclear signs
Mutual aid and resource at community level was inadequate	No information available for tourist
Unorganized humanitarian aid	

1.4. COMPLEMENTING THE MEASURES

In the previous section, the current situation in Iquique is assessed. In the next chapters, the authors will strive to improve and complement these measures where necessary. It can be stressed that elements of the procedures described above function well and shall be maintained in the various designs. The objective is to obtain a safer situation by designing a complex solution.

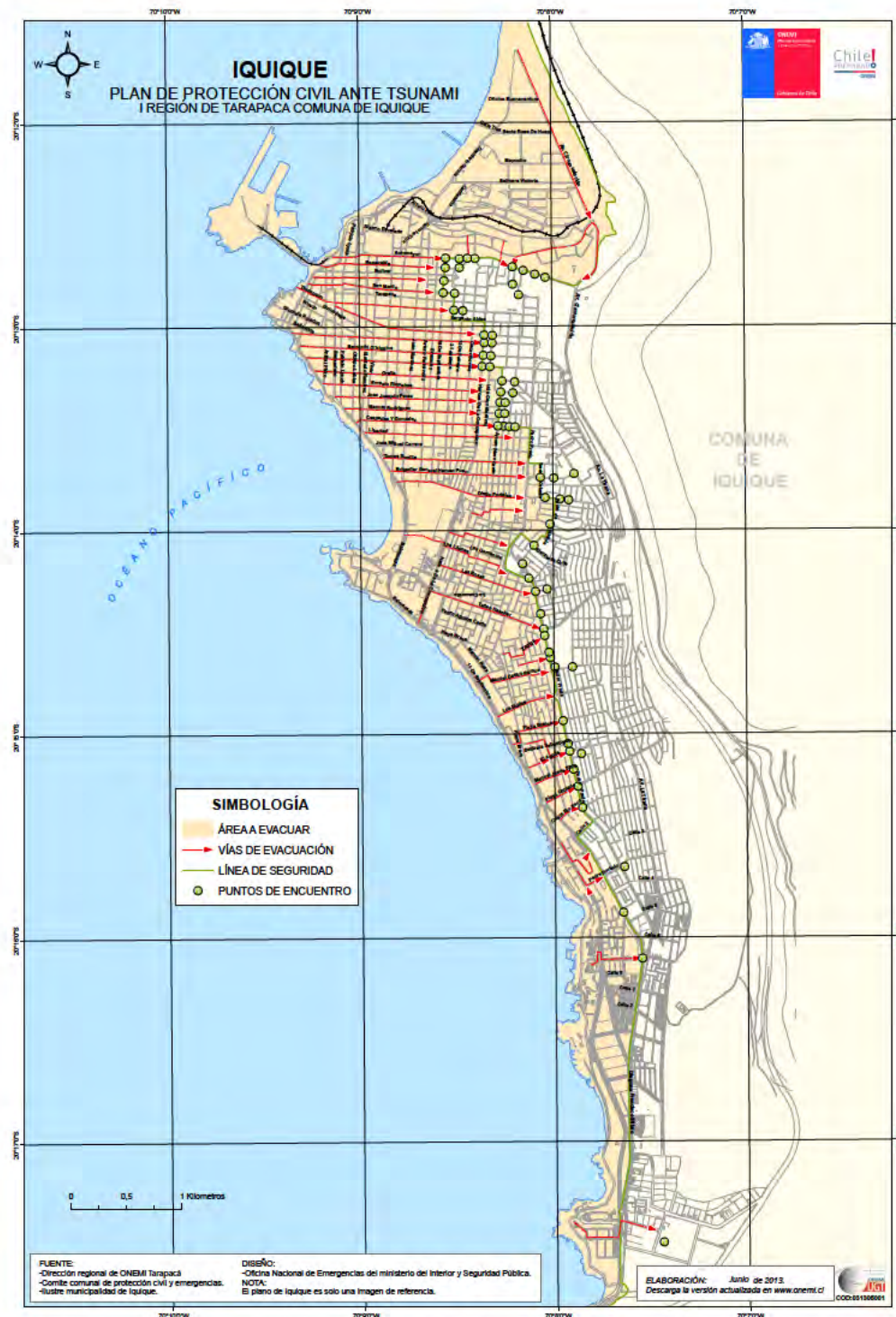


Figure 1.4: ONEMI evacuation map

2

METHODOLOGY

2.1. SUB-RESEARCH QUESTIONS

In the previous chapter, an introduction to the concept of mitigation measures in the case of tsunami impact is given. In the rest of the chapters, the authors strive to find an answer to the main research question: how should the impact be mitigated. The methodology applied for this process is described in the following sections.

With the aid of the earlier defined sub research questions an answer should be found on how to reduce the tsunami impact. To increase legibility the sub research questions for part two are repeated here.

1. What available mitigation measures are suitable for the Iquique region?
2. What complex solutions can be proposed for the severely affected areas?
3. What can be said on the proposed complex solution when regarding:
 - (a) Effectiveness with respect to tsunami impact reduction
 - (b) Generation of side-effects

In order to deal with mitigation measures, a framework has been designed. In the next section, this framework will be further elaborated. Furthermore, the issue of determining local restrictions in Iquique will be addressed. The additional chapter shall relate on the steps taken in the research to generate answers to the above questions.

2.2. FRAMEWORK FOR TSUNAMI MITIGATION MEASURES

Three frameworks for dealing with hazards are addressed. Afterwards, the framework developed by the authors is presented.

Calamity Countermeasure Strategies

The first framework is developed by Haddon for calamities within a medical context. He defines ten strategies for disaster mitigation which correspond to a stadium that a calamity passes through before it reaches its full consequences (Haddon [21]). These strategies can roughly be summarized as the following three main strategies:

- Reduce hazard source
- Reduce exposure to the hazard
- Reduce vulnerability

The first strategy is self-explanatory, the other two might require some elaboration. The second strategy relates to limiting the actual interface between the hazard source and the impacted people and property. The third strategy aims to increase the resilience of the impacted people and property, enabling them to with greater success withstand the hazard.

Various mitigation measures can be categorized by the above strategies. This framework only relates to the phase of the disaster for which a measure is applicable and provides no further guidance in judging the effectiveness and desirability (Hoss *et al.* [22]).

Multi Level Safety

A method that is more suitable to design a location and disaster specific solution is the internationally renowned multi level safety approach. The Multi Level Safety (MLS) approach is initially formulated to deal with water management issues, such as river floods. In recent publications the method proved also applicable in the case of a tsunami (Tsimopoulou *et al.* [23]). Three different strategy levels related to flood risk mitigation are defined.

- Prevention
- Spatial solutions
- Crisis management

Within each level it is possible to relate measures to predefined risk parameters. The first strategy level contains measures to prevent impact. Prevention is in this case understood as preventing the sea from inundating areas that in normal conditions are not. The second level relates to spatial solutions, for instance tactical city planning to decrease tsunami flow velocity, limiting loss or severe damage. Level three, disaster management consists of organizational preparation such as disaster plans, risk maps, early-warning systems, evacuation, temporary physical measures such as sandbags, and medical help. The basic idea of this approach is that when a design solution covers these three layers, the safety for people and property is best preserved. (Tsimopoulou *et al.* [23]) In figure 2.1 the basic concept of multi-layered safety is represented.

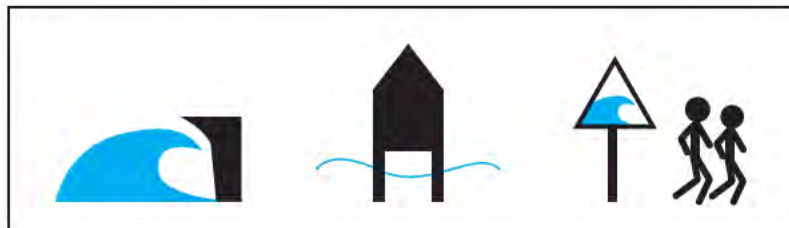


Figure 2.1: The concept of Multi-Layered Safety when applied to a tsunami hazard.

Specific Site Planning Strategies to Reduce Tsunami Risk

The third method that will be discussed is derived from *The multi-state mitigation project of the National Tsunami Hazard Mitigation Program* for the Pacific coast of the USA. In this program seven principles of designing for tsunamis are brought forward. In order to reduce tsunami risk by implementing mitigation measures, four site planning techniques are formulated (Oceanic *et al.* [24]).

- Avoid inundated areas
- Slow the water currents
- Steer the water forces
- Block the water forces

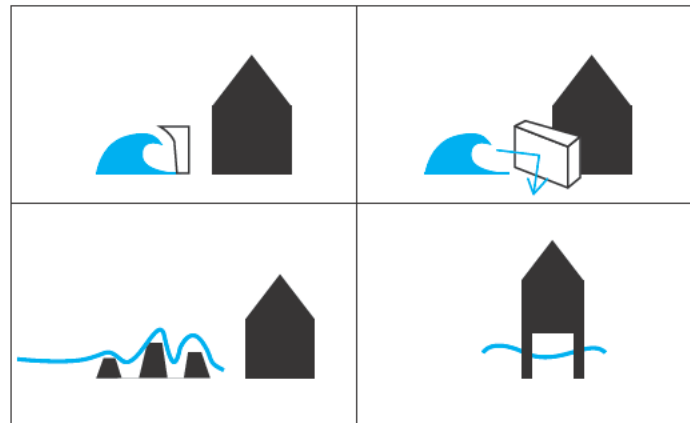


Figure 2.2: Four site planning techniques to deal with a tsunami, f.l.t.r. blocking, steering, slowing, avoiding.

Many available mitigation measures can be categorized within one of these techniques. Yet this technical framework does not give an engineer complete insight in how to develop a coherent solution to mitigate tsunami impact since soft measures aiming to reduce vulnerability (such as the design of aid- and logistics centres and information systems) are not necessarily taken into account.

Framework for Tsunami Mitigation Measures

All of the above frameworks contain very valuable notions on how one can structure a hazard such as a tsunami and formulate appropriate mitigation measures. The first takes into account the phase of the hazard and related mitigation, the second insures a safe combination of measures and the third addresses techniques of mitigation. The authors of this report share the opinion that in order to structure the available mitigation measures and present a broad ranged, hazard-phase applicable, coherent and safe solution a combination of these frameworks is desirable. Such a combination of measures is referred to as *a complex solution*. The proposed framework for tsunami impact reduction is represented in the figure below.

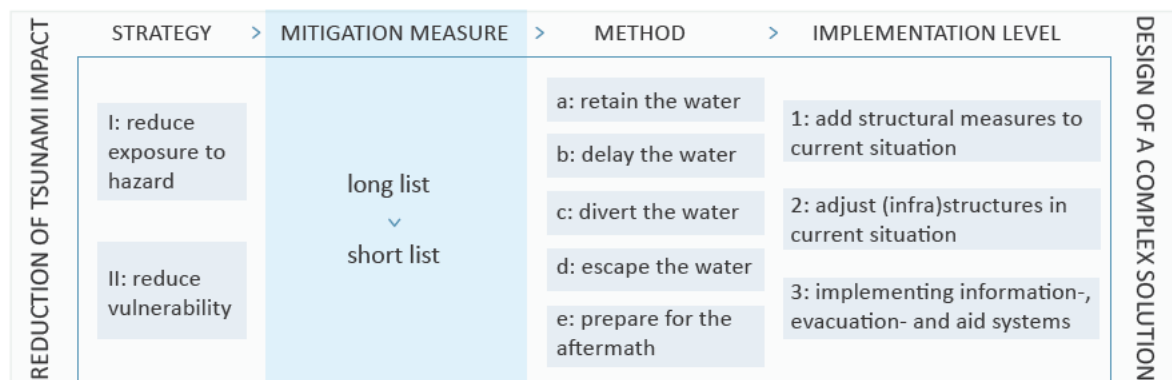


Figure 2.3: Framework for Tsunami Mitigation Measures

The main objective for mitigation measure design is to reduce the expected impact. Since one cannot (yet) reduce the tsunami source, this strategy is not taken into account. The remaining two strategies are relevant and apply to two phases in the development of the hazard.

The next step in designing a impact mitigation measure is to choose a technique or method. In order to cover all the formulated impact criteria a method is added, the preparation for the aftermath of the hazard. At this point, one should be able to make a clear review of the available measures.

In this report, MLS levels are slightly different interpreted to obtain a framework more focussed on the implementation of a complex solution. After determining the method of mitigation, the levels help to implement something into the desired location. Also the levels aim to help the designer in identifying local opportunities and to prevent a unilateral solution. Keywords in the difference between level 1 and 2 become the addition of new - protective and preventative- structures and the optimization of existing (infra)structures. In the next sections, the use of the framework is further elaborated.

2.3. SUITABLE MITIGATION MEASURES FOR THE IQUIQUE REGION

Mitigation measures are defined as any preparations made by people to reduce the expected impact of a tsunami. The objective of this section is to generate a short list of suitable area- and problem-specific mitigation measures. In the following section and figure 2.4 the actions required to obtain this list are elaborated.

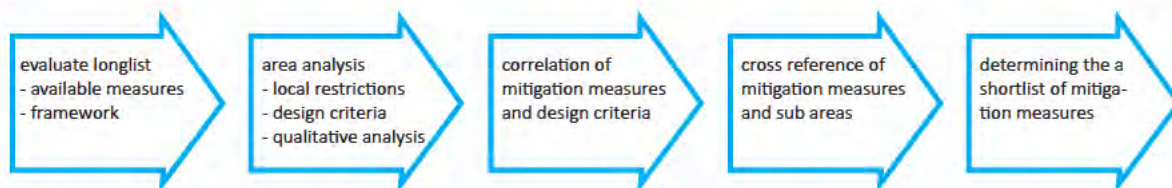


Figure 2.4: The first sub-research question can be answered using this flowchart, guiding the user from a long list of mitigation measures to a short list.

2.3.1. AVAILABLE MITIGATION MEASURES

The first step in obtaining suitable options for tsunami impact mitigation is looking into precedents in literature and tsunami prone areas in the world. With aid of these sources a list of available measures is generated. This list can be structured using the framework presented in the previous section.

2.3.2. DETERMINING THE LOCAL RESTRICTIONS

Determining the local restrictions in relevant Iquique regions will be done using a two analyses. The areas that are singled out in part one are the Cavancha area and the Zofri area. The first analysis phase is more quantitative, fact based and looks into population numbers, local functionalities and constraints due to local topography and urban planning for mitigation measures in the areas. This information is used to make a more accurate estimation in the second part. The second analysis phase takes into account less defined aspects such as desired aesthetics and accessibility of a region.

QUANTITATIVE AREA ANALYSIS

When analysing the areas of Cavancha and Zofri in more detail the areas are sub-divided in more homogeneous areas, based on; user function, inundation, hinterland properties, amount of people present and environmental threats present, sub-areas for Cavancha and Zofri will be defined.

After division into sub-areas, google earth, google streetview, field survey and consultation with ONEMI will lead to an estimation of the amount of people present and user functions per sub-area.

QUALITATIVE AREA ANALYSIS

The objective of this chapter is to obtain a shortlist of suitable mitigation measures for the Iquique region. Design criteria are needed in order to specify the constraints and opportunities in the Iquique areas and to evaluate possible mitigation measures. For the Zofri and Cavancha areas these criteria are formulated using input from the quantitative analysis and conversations with local authorities. The criteria are elaborated and substantiated in appendix G. In the table shown in figure 2.5 the criteria are represented in such a way that their specific importance per sub-area can be determined.

These criteria can be evaluated per relevant sub-area. Hereby one can make use of the classifications *high* (+), *medium* (I) and *low* (-).

Qualitative Area Analysis							
Design Criteria		Sub area in the Cavancha Area					Zofri Area
		Cavancha North Peninsula	Cavancha South Peninsula	Playa Brava	Playa Casino	Playa Cavancha	Coastal zone & industry
Necessity							
Inundation							
Protection Hinterland Necessary due to:							
Dense Population							
Economic Value							
Historic Value							
Limit Enviromental Damage							
Possibility							
Constraints topography & urban planning							
Private Functionality							
Unobstructed Evacuation							
Desirability							
On- and offshore (tourist) activities							
Required Accessibility							
Required Aesthetics							
Required Unobstructed Viewlines							

Figure 2.5: Area analysis method

2.3.3. CORRELATION OF MITIGATION MEASURES AND DESIGN CRITERIA

For each mitigation measure on the list it is possible to make an assessment of the aptitude per design criterion. If a measure is highly qualified for a certain criterion, it is rated with *high aptitude*. If the fit is acceptable, the rating *medium aptitude* applies. In the case a measure does not meet the needs for a certain criterion or is even undesirable as a solution, it is rated with *low aptitude*. If a measure has no relevance to a criterion the qualification *no relevance* is used.

2.3.4. DETERMINING A SHORT LIST OF MITIGATION MEASURES FOR IQUIQUE

After determining what criteria are important for what area and what measures are apt to deal with these criteria, one can now link together the rated mitigation measures and the analysed sub-areas. As a result, one obtains a survey of what measures are suitable for each analysed region. The highly apt solutions per sub-area can be used to make a shortlist for the relevant Iquique regions.

2.4. A COMPLEX SOLUTION TO REDUCE TSUNAMI IMPACT

In the previous section the process of obtaining a shortlist of mitigation measures is elaborated. This list can be seen as a toolbox with which the authors can assemble a complex solution per area. In the following section, the steps taken are discussed.

2.4.1. SYSTEMS OF MITIGATION

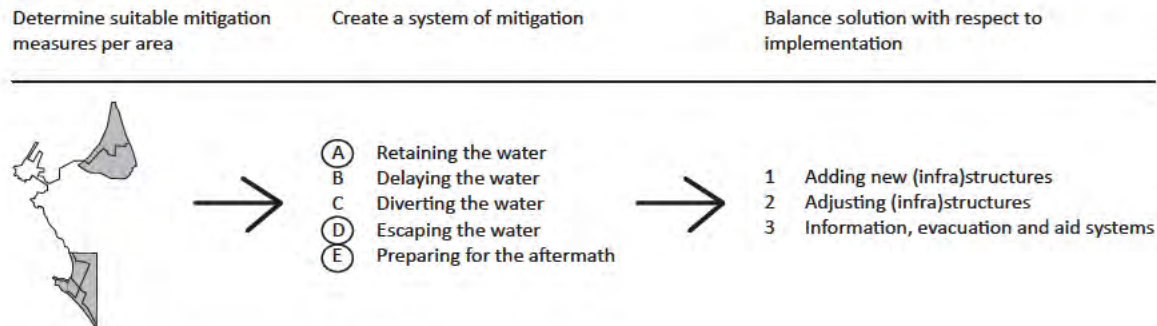


Figure 2.6: Create systems of mitigation from which a complex solution can be derived.

When the shortlist is obtained the systems of mitigation are determined using the steps illustrated in figure 2.6. First a system of mitigation is chosen. Next, for each method, suitable mitigation measures from the shortlist can be inserted. Finally, a balanced combination of mitigation measures can be made using the implementation levels. Various combinations can be made, depending of the area of interest and the preference of the engineer and client. In this report, multiple solutions will be proposed for both the Zofri and the Cavanca area.

2.5. EFFECTIVENESS & SIDE-EFFECTS OF THE COMPLEX SOLUTION

In order to assess the effectiveness of the results, the three developed systems must be approached with different validation methods. In a similar manner possible generated side-effects can be considered. For this purpose several validation methods shall be discussed. When outside the scope of the report, these should be considered a recommendation for future validation.

2.5.1. VALIDATION OF THE RESULTS

To answer the third sub research question the systems have to be validated. For each system different validation methods are applicable. The general principles which can be applied for validation of the different methods are given in this section.

VALIDATION WITH THE USE OF (NUMERICAL) MODELS

Numerical models can be used to validate structural measures implemented in the systems. Structural measures relate to the *retaining the water*, *delaying the water* and *diverting the water* methods. The possibilities with these models are elaborated.

Numerical models

Modelling elucidates the effect of added structures. The impact estimation for which the systems are designed are based on NEOWAVE simulations. In this model structures can be implemented by modifying the bathymetry of the model. The results can be used to assess the effectiveness of the added structure, to what extend is the water retained and to what level is the water delayed. Also the side effects that occur are analysed by modelling.

Additionally other models can be used depending on the desired validation. If a more detailed answer on the working of wave-climate, the effectiveness of de-watering canals or changes in bathymetry is desired, Delft3D could be a good addition to the NEOWAVE model. When a more detailed projection of the city centre is necessary, a finer grid in combination with a more detailed LIDAR image of the city can be implemented in NEOWAVE to create more reliable results of flow patterns onshore.

Other models

For a technical assessment of ground-behaviour after implementing structures the use of a finite element method program (e.g. PLAXIS) is an option.

A last option to validate a solution is to create a model, that may be used to check specific elements. A risk for newly developed models is that the validation method itself is not reviewed. Some assumptions in this model may not be objective, this has to be taken into account when reflecting the results of this model.

VALIDATION BASED ON EXPERT OPINIONS

Expert opinions are used for the validation of the system elements regarding *escaping the water* and *preparation for the aftermath*. The mitigation measures will be presented accompanied by a short questionnaire, in this way experts will be asked for their opinion on feasibility of the proposed measures.

These questionnaires will be used to check the theoretical feasibility of the proposed measures.

PEER REVIEWS

A validation method that may be applied is the peer review. The research results can be checked by a colleague in a similar field.

EVACUATION DRILLS

For *escaping the water* and *preparation for the aftermath* real time testing of evacuation- and coordination plans by means of evacuation- and coordination drills are valuable means of validating these kinds of mitigation measures. Therefore the authors suggest the following drills:

Large scale evacuation drill	Drill where everyone is participating and the coordinating tasks are included.
Small scale evacuation drill	Entities participate to practice their responsibilities and communication procedures.
School drills	Solely schools participate to prepare children for the event.
Coordination drill	Coordination drill to evaluate logistics in coordination plan.

With organizing these drills real time evaluation and validation can be performed on the measures proposed.

2.5.2. OCCURRING SIDE-EFFECTS

Side-effects of the mitigation measures are based on interpretation of the results of the validation. The knowledge of the authors is used to appoint side-effects within the validation methods. No extra methods are implemented to search for side effects.

2.6. ANSWERING THE MAIN RESEARCH QUESTION

With the validated results obtained using the methodology, the proper conclusions can be drawn to answer the main research question.

3

RESULTS

3.1. INTRODUCTION

In the previous chapter the methodology is put forward. In this chapter an answer should be found on the first two sub research questions, that have been formulated in the general introduction. This is an important step in the process of answering the main research question.

3.2. AVAILABLE MITIGATION MEASURES

The first sub research question is formulated as: *What mitigation measures are available for the Iquique region taking into account local restrictions?*

The aim of this section is to obtain a shortlist of qualified mitigation measures for the specifically affected areas Cavancha and Zofri, Iquique.

3.2.1. THE FRAMEWORK APPLIED

In the chapter Methodology, the chosen framework of this report is explained. In this section, this framework is used to structure the list of mitigation measures deemed feasible. This list is based on review of literature, new research on tsunami mitigation and past solutions. In appendix G the selection is further elaborated. In figure 3.3 the result is presented.

3.2.2. LOCAL RESTRICTIONS ANALYSIS

In this section, the analysis of the affected Iquique sub-areas is performed. This analysis gives information on what mitigation measures are preferable for specific locations and corresponding inundation.

QUANTITATIVE ANALYSIS

Sub-areas

In Part One a recommendation has been made to look into the areas of Zofri and Cavancha for the design of mitigation measures. In this section, an additional analysis of the areas is performed. First, the area is divided into sub-areas. This division based on local similarities, functionality, geography and difference in hazard impact. In figure 3.1 the sub-areas are represented. The analysis of these sub-areas can be found in appendix E.

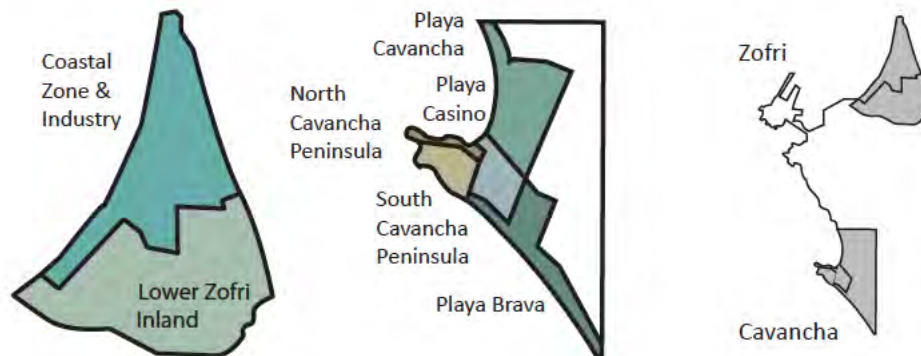


Figure 3.1: Sub-areas in Iquique

Affected areas due to inundation

In Part One an analysis of the areas of Zofri and Cavancha is performed. In this part, the maximum flowdepth, abstracted to the levels of low, medium and high inundation, is illustrated per sub-area since this criterion is considered the most direct motivation to develop any form of mitigation.

Zofri The Zofri area has a natural barrier along the shoreline. When this slightly higher area is overtopped by the tsunami, the lower hinterland is inundated and serves as a 'bathtub'. Therefore protecting the shoreline from inundation prevents both sub-areas from inundating.

Cavancha In part 1 is found that the tsunami wave does not reach the hinterland of Playa Brava and the Southern side of the Cavancha peninsula. Therefore it is not necessary to retain or delay the water in these sub-areas. The inundation of the peninsula and the hinterland is mainly due to the water that enters from the North in the Cavancha bay, as concluded in part 1, chapter 6. This implies that it is desirable for the Playa Cavancha, Playa casino and the North side of the peninsula to be protected against the tsunami wave.

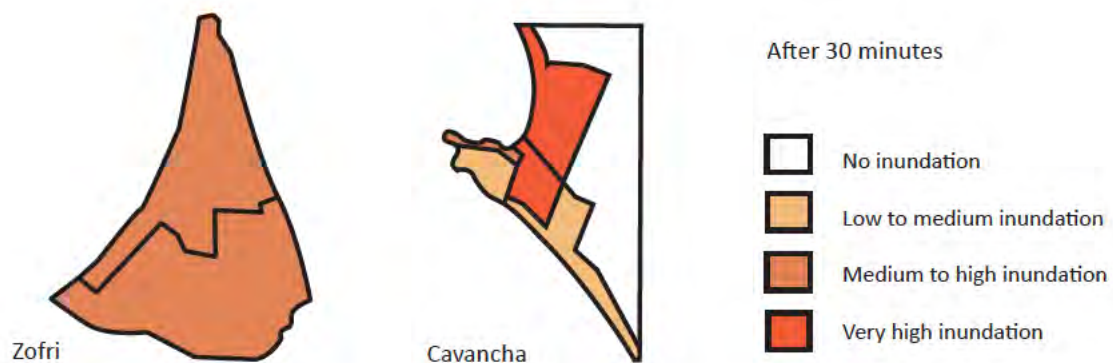


Figure 3.2: Inundation in sub-areas (schematic)

QUALITATIVE ANALYSIS

Based on the quantitative analysis and the results from part one, a qualitative analysis is performed. The predefined design criteria are related to the sub-areas as discussed in the previous chapter. The results of this analysis can be found in appendix F.

3.2.3. CORRELATION OF MITIGATION MEASURES AND DESIGN CRITERIA

In this section the proposed long list of mitigation measures are correlated to the design criteria. In appendix G the results are represented. Noticeable is that for many of the listed mitigation measures (figure 3.3) many criteria are not relevant as a rating system. On the whole all criteria are met by a representative amount of mitigation measures for the authors to move forward with the system.

3.2.4. DETERMINING A SHORTLIST OF MITIGATION MEASURES FOR IQUIQUE

In order to create a substantiated shortlist of mitigation measures specifically appropriate for each sub-area, the results of the previous two sections are combined. In figure 3.4 the shortlist of mitigation measures as used in the following chapter, is presented.

Tsunami Impact Reduction Matrix						
Strategy	Mitigation measure	Method				
		Retaining the water	Delaying the water	Diverting the water	Escaping the water	Preparation for aftermath
Reduce exposure	Dikes and embankments					
	Dyneema tsunami barrier					
	New vertical evacuation building					
	Offshore vegetation barrier					
	Onshore vegetation barrier					
	Tsunami breakwater					
	Tsunami flood gates					
	Tsunami seawall					
	Assigned reinforced buildings					
	for tactical vertical evacuation					
	to steer water forces					
	Evacuation bridges					
	Integrated flow channels					
	Pallafita housing					
Raised infrastructures						
Design and adjustment of evacuation routes						
Reduce vulnerability	Local logistical centres					
	Regulation for hazardous objects					
	Reinforcement of existing structures					
	Education on tsunami risk and course of action					
	Implementation of crisis communication system					
	Implementation of crisis team to instruct and guide					
	Specific hardcopy information and signs					

First level of implementation

Second level of implementation

Third level of implementation

Main design function

Additional function

Figure 3.3: Feasible mitigation measures can be classified using the framework.

Mitigation of Choice per Area			
<i>Cavancha</i>	<i>Mitigation measures</i>	<i>Zofri</i>	<i>Mitigation measures</i>
Cavancha North Peninsula	Tsunami breakwater	Coastal zone & industry	Tsunami flood gates
	Tsunami seawall		Tsunami seawall
Cavancha South Peninsula	New vertical evacuation building		Assigned buildings for vertical evacuation
	Assigned buildings for vertical evacuation		Assigned buildings to steer water forces
	Evacuation bridges	Lower Zofri inland	Assigned buildings for vertical evacuation
	Local logistical centres		Assigned buildings to steer water forces
Playa Brava	Raised infrastructures		Evacuation bridges
Playa Casino	Dyneema tsunami barrier		Pallafita housing
	New vertical evacuation building	All Areas	<i>Integrated flow channels</i>
	Evacuation bridges		Design and adjustment of evacuation routes
	Pallafita housing		Regulation for hazardous objects
	<i>Submerged Tsunami breakwater*</i>		Reinforcement of existing structures
	<i>Tsunami seawall (delaying)*</i>		Education on tsunami risk and course of action
Playa Cavancha	Dyneema tsunami barrier		Implementation of crisis communication system
	<i>Submerged Tsunami breakwater*</i>		Implementation of crisis team to instruct and guide
	<i>Tsunami seawall (delaying)*</i>		Specific hardcopy information and signs

Figure 3.4: Shortlist of tsunami mitigation measures per sub-area.

3.3. A COMPLEX SOLUTION TO REDUCE TSUNAMI IMPACT

The short list obtained in the previous section contains separate concepts of mitigation measures. As stated before in the chapter methodology 2, it is believed that a truly suitable mitigation solution is a complex solution. That addresses multiple strategies, methods and implementation levels. In this section, multiple designs for such a solution are elaborated and substantiated. Each complex solution is derived with the aid of a system of mitigation.

3.3.1. SYSTEMS OF MITIGATION

The use of the systems originate from the *choice* or *need* of the client to deal with the tsunami in a certain manner. Within this choice of action (system), the best possible complex solution can be designed. As input, the short list is used. Therefore, in this section, the authors will not express a preference for a specific system but strive to generate the most suitable complex solution within the boundaries of the system.

The following figures illustrate the proposed systems of mitigation, where the main focus of the system is indicated in blue. The principles of the framework, developed in the previous chapter, are used as a base. Several options for a complex solution are given, for Zofri and Cavanha.

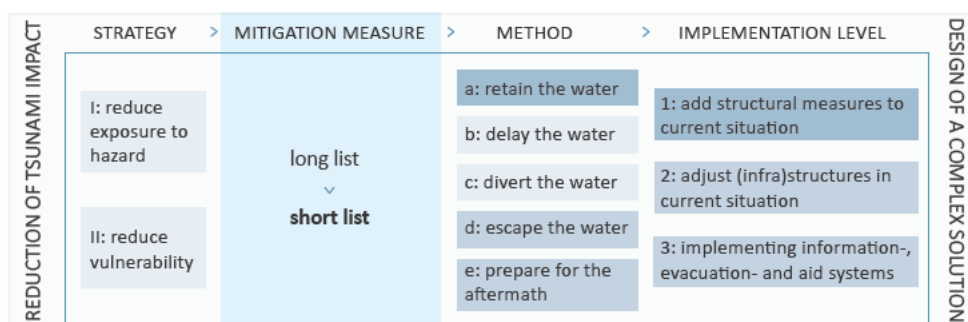


Figure 3.5: System A

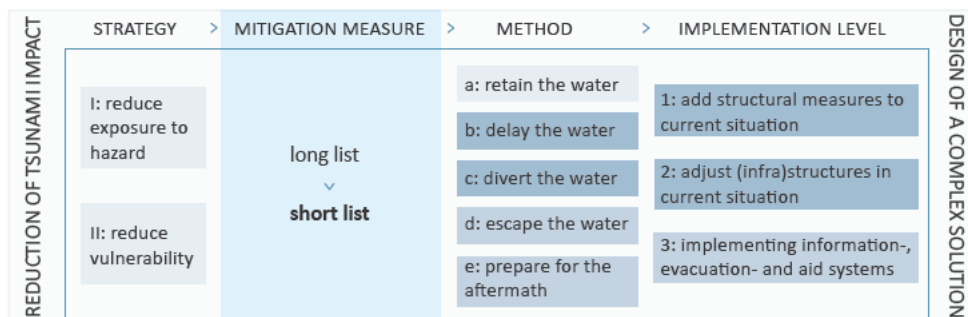


Figure 3.6: System B

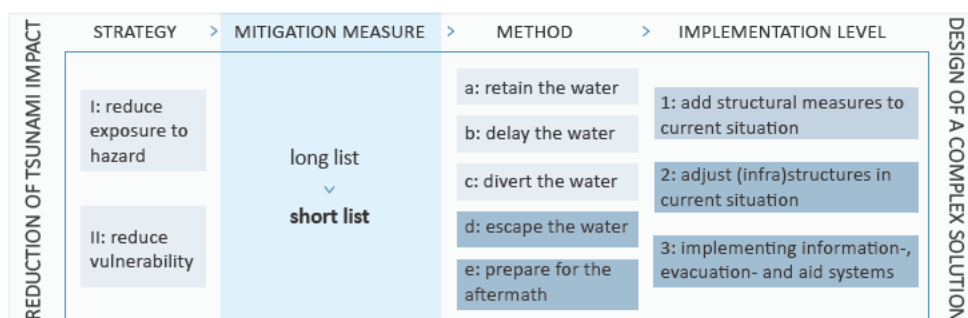


Figure 3.7: System C

SYSTEMS APPLIED TO IQUIQUE REGIONS

The shortlist of mitigation measures specified for the sub-areas can be used to create complex solutions. In figure 3.8 examples of solutions are given. In the following section, in a more detailed analysis, possible solutions within systems are addressed separately. The authors strive to design a suitable complex solution for each system. Stakeholders within the tsunami mitigation process can assess what system they consider most feasible. This assessment is considered to be outside of the scope of this research.

In the following section, various options within systems will be addressed for both Zofri and Cavancha. For Cavancha, one of these options will be further elaborated in the section system design.

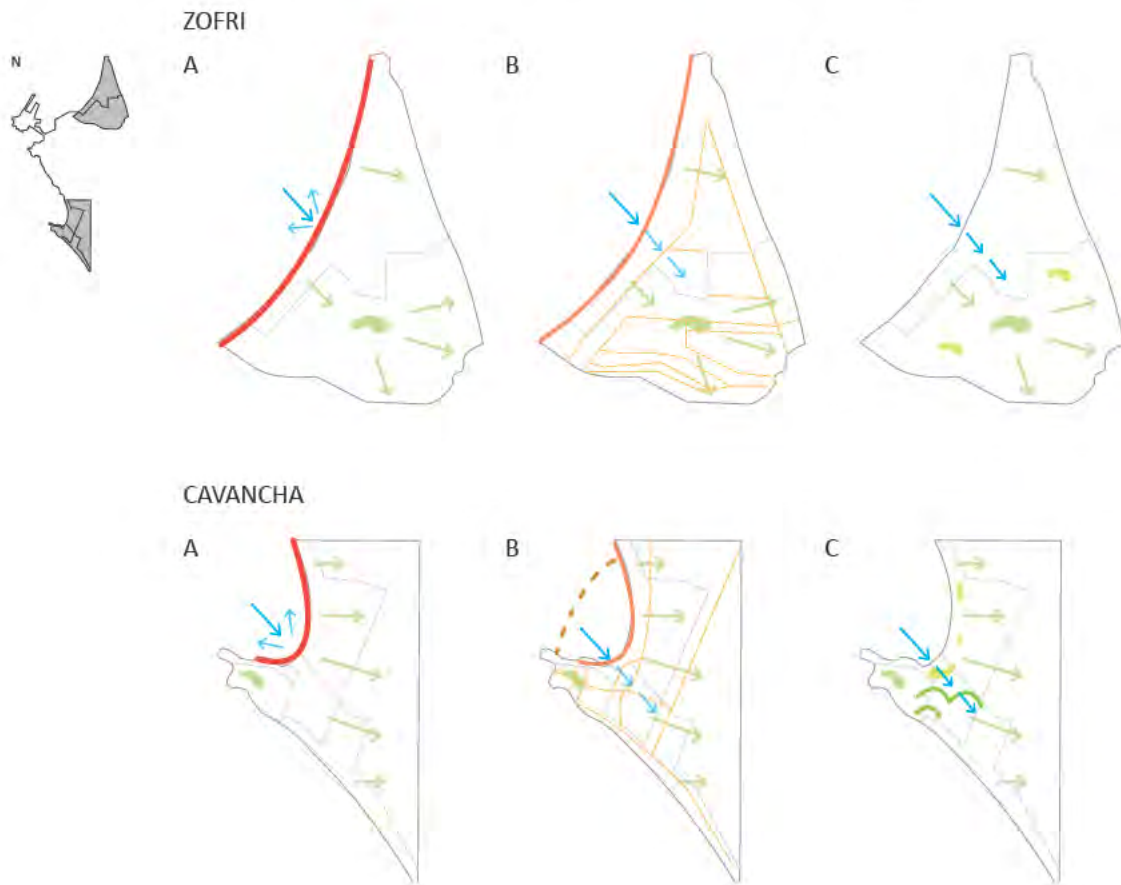


Figure 3.8: Three concept systems of mitigation in Iquique.

3.4. SYSTEM A

3.4.1. INTRODUCTION

A system is designed in order to retain the water 2. When the retaining method is fully achieved the tsunami will have minimal impact. In the lessons learned (part zero, chapter III) is mentioned that the consequences of a failing retaining system are huge because people assume the tsunami is mitigated. Therefore the escaping method is essential to complement the system as to present a full integrated safety plan.

According to the recommendations of part one the water should be retained at the Playa Cavancha, Playa casino and the North side of the peninsula. When this is achieved no inundation will reach the hinterland. Therefore the retaining method will be applied in these regions.

3.4.2. VARIOUS OPTIONS

With the proposed methodology, combinations of measures are evaluated. From this evaluation the considerable options are presented and elaborated to choose the best design option. This option is then compared to the inundation map to check the feasibility of the option. In the system design one system will be fully elaborated and the possible variations will be identified.

CAVANCHA

For the retaining method in the Cavancha region only one combination of measures is found desirable based on the design criteria. The best fit solution is shown in table 3.1. The option consists of two retaining measures, a Dyneema barrier, concept shown in figure 3.10, and a seawall. To complement the method of retaining, various measures for the methods escaping and preparing are available and listed in the table. The consequences of this combination and the process to obtain the solution is elaborated in appendix I.

Table 3.1: System design for Cavancha based on retaining the water.

Level	Area	Method	Mitigation Measure
1	Playa Cavancha and Playa Brava Cavancha North peninsula	Retaining	Dyneema barrier
		Retaining	Tsunami seawall
2	All areas	Escaping	Assign reinforced buildings for vertical evacuation
3	All areas	Escaping	Design and adjustment of evacuation routes
			Implementation of crisis communication system
			Implementation of crisis teams to instruct and guide
			Specific hardcopy information and signs

ZOFRI

Option 1

This option consists of a seawall in the first line of the Zofri natural barrier. This way no inundation in the area is allowed and full prevention is realised. Due to the natural elevation of the first line this barrier will not be very high. Since the model considers the topography of the Zofri area the height of the necessary wall can be obtained from this data. The wall is just barely overtopped at some points so the maximum run up effect already takes place. Most of the current industrial buildings already use walls in order to protect their grounds. These walls can be used in the system and their height is already in the same order as the necessary tsunami wall height. This implies that only reinforcement of these walls is necessary to create this measure at these locations. Observations also show that some properties have a connection to a jetty or an open fence indicating they are not using a wall on purpose. For these properties their motives have to be considered.

Table 3.2: System design option 1 zofri based on retaining the water.

Level	Area	Method	Mitigation Measure
1	Coastal zone	Retaining	High seawall
2	All areas	Escaping	Assign reinforced buildings for vertical evacuation
	All areas	Preparing for aftermath	Regulations for hazardous objects
3	All areas	Escaping	Design and adjustment of evacuation routes Implementation of crisis communication system Implementation of crisis teams to instruct and guide Specific hardcopy information and signs

Option 2

A different system is based on a double line of defence. The natural barrier is elevated to mitigate medium to low tsunamis. For the design scenario a secondary barrier is used, in the hinterland, where the overtopped volume is retained (similar reasoning as option 1). This option uses the fact that all buildings already use walls/fences. The first line than only needs walls at the lower points, reinforced where necessary. In order to create this wall two points have to be mitigated: there are a lot of fences in the area and the properties often need road access. The fences have to be replaced with walls of a certain height and a solution for the entrances has to be designed. This can be easy solutions like watertight gates or more complex solutions using buoyancy or mechanical options. With the combination of these walls a double layer safety plan is obtained. An advantage of this options is that pollution due to damage of the earthquake is retained within the premises of the responsible company.

Table 3.3: System design option 2 zofri based on retaining the water.

Level	Area	Method	Mitigation Measure
1	Coastal zone	Retaining	Primary seawall
	Coastal zone	Retaining	Secondary seawall
2	All areas	Escaping	Assign reinforced buildings for vertical evacuation
	All areas	Preparing for aftermath	Regulations for hazardous objects
3	All areas	Escaping	Design and adjustment of evacuation routes Implementation of crisis communication system Implementation of crisis teams to instruct and guide Specific hardcopy information and signs

PROPOSED OPTION FOR THE SYSTEM DESIGN

For Cavancha only one option is available. This option will be further elaborated in the next sections.

REMARKS ON THE SYSTEM DEFINITION

Before continuing with the system design of the Cavancha option, a small nuance can be made when regarding the method *retaining the water*.

Initial height of retaining methods

The current set of solutions is based on complete blockage of the water. The inundation map and the set of measures are not yet compared to the inundation. This is done to give an impression of the heights of the retaining methods and the feasibility of these heights. In figure 5.10 is seen that a wave height of six meters is reached close to shore. The maximum run-up in the north peninsula reaches six meters. And the maximum run up in the hinterland of the beach is 6.8 meters. According to the FEMA [25] guideline the design run up should be $1.3 * R - z_w$ therefore the seawall has to be at least 7.8 meters minus the topography of the location. The Dyneema design height is 8.9 meters.

Retaining method: Dyneema For the Dyneema barrier at the Cavanca beach a certain width has to be available to install the barrier. According to Marissen Marissen *et al.* [26] the width of a Dyneema barrier for a wave height of 20 meters is around 35 meters. Since the smallest part of the beach is around 50 meters the Dyneema barrier can fit within the beach area, especially because the expected height of the wave is smaller than 20 meters and the construction width will scale down with the wave height.

Retaining method: Seawall The tsunami seawall does not require a wide area. The wall will be in sight and this property causes is the main constraint for the placement of the seawall. Within the system boundaries, full blockage of the water, the wall should be placed at the shoreline as can be seen with the orange line in figure 3.9. When analysing the required height of the wall it shows a height of at least eight meters is required at specific locations. An eight meter high wall is concluded to be an unrealistic scenario. More to the east a hotel then should be surrounded by a wall of at least seven meters. This entails a serious constraint for hotel activities, reducing the chance such a wall will be allowed on private property. Therefore retaining the wave in the worst case scenario is not an option.

A second trace for the seawall can be found, the red line in figure 3.9. In this trace inundation in the upper part of the peninsula is accepted. Due to elevation of ground level the necessary wall height is lower. To retain the water on this trace a five to six meter high wall should be designed. This is also considered an unrealistic design. Fully retaining the wave is not realistic in the north peninsula of Cavanca.

Combined retaining methods

The system will be designed using two point of views when considering the retaining method. One: retain to the maximum realistic height, implemented on the seawall off the north peninsula. Two: retain the maximum wave height, used in the design of the Dyneema barrier on the Cavanca beach.

This change in methodology adds an extra consideration for the design of the other measures. For the level 2 and 3 measures overtopping of the seawall must be taken into account. With this point of view the system design for the retaining method will be made. Assuming that the retaining method in the peninsula will still contribute to impact reduction in the worst case scenario.



Figure 3.9: The two possible traces for a seawall in the north Cavanca region

Zofri

For Zofri an assessment has to be made in order to obtain the best option. The criteria used for this assessment are expected feasibility and effectiveness.

Technical feasibility of the solution In option 1 the complete wave will be retained. When looking at the topography of the area the natural embankment varies between 3.2 and 4.2 meters from MSL, based on the LIDAR grid data. The incoming wave reaches an average height of 4.5 meters with a local maximum of 5.7 meters from MSL, based on the worst case scenario. The topography at the local maximum is 4.0 meters therefore a minimum of 1.7 meter high wall is required. Using this height over the topography shows that this will be high enough over the entire embankment. Therefore the realisation of a full retaining seawall on the embankment of Zofri is very realistic considering the observations show higher walls than this already present. This means option 1 is a very feasible option.

For option 2 the same wall as option 1 can thus be implemented. The difference is that a lower wall is possible. This only creates a higher secondary wall. As can be seen in figure 5.3 the decrease of wave height is dependent on the height of the embankment. Therefore stopping the water in the first line will require a less high secondary wall. The secondary wall needs to cross the openings off the properties this is the bottleneck of the design since most of the buildings already use walls around their property. For the design of the gates two main considerations rise: The height of the wall highly influences the possibility of the designs and a human factor might be necessary to operate the solution. The last one mainly because high-tech self rising options are unrealistic for this industrial area. Concluding the second wall is possible but not considered a good solution for the scale of the problem.

Effectiveness Taking the previous lines into account it can be directly concluded that option 1 is a very effective option. Most of the walls are already present so reinforcement and completion of the wall is sufficient to prevent the full tsunami impact.

For option 2 is is uncertain whether the secondary wall provides a more complete solution. The secondary wall needs to have a continuous height along a premises. The main reason to design the secondary wall will therefore be to mitigate the possible pollution due to the oil tanks in the intermediate region. The effectiveness of the second option therefore becomes higher than the first because of this extra pollution mitigation effect (relevant design criterion for the region).

Conclusion of the analysis For the Zofri area a secondary wall does not add enough value to the solution because of the increased design efforts. For the mitigation of the tsunami **option 1** is a complete impact reducing option. Added to this conclusion is a recommendation of the possibility for a secondary wall around the oil storage in order to mitigate the possible earthquake damage.

3.4.3. SYSTEM DESIGN

The methods used in this system are: retaining the water, escaping the water and preparation for the aftermath. Measures within these methods are assessed on their aptitude for the complex solution with the aid of implementation levels. The used measures in this design are shown in table 3.1.

In order to create a design combining all measures the location and parameters of the level 1 measures are determined, the level 2 and 3 measures are designed according to the failure of the Dyneema barrier and overtopping of the seawall.

LEVEL 1

For the level 1 implementation it is important to remember that the Dyneema barrier will be implemented over the full length of the beach, retaining the full wave. The seawall crosses the Cavancha peninsula until it reaches the most west point of the peninsula. The seawall will be as high as reasonably possible.

DYNEEMA BARRIER

The Dyneema is a new concept, therefore no implementations are known. The concept is elaborated in figure 3.10. It is preferable to design a straightforward Dyneema barrier in order to minimise the research necessary for implementation. The aesthetics of the beach is the primary design criterion which is conflicting with the straightforward design preference.

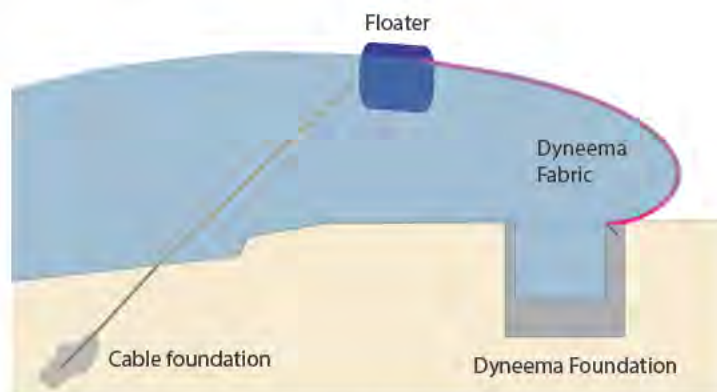


Figure 3.10: The principle of the Dyneema concept. The Dyneema uses a floater to rise above the tsunami wave, the Dyneema fabric retains the wave. These two objects are both founded in the soil. This concept is able to retain tsunami waves until a certain design height and will be in the foundation under normal circumstances.

The tracing of the barrier

In order to define a possible trace for the Dyneema an area analysis of the beach has been made in order to establish possible contours and determine leading factors in the design of the barrier. From this analysis two contours are found which are elaborated in this chapter and shown in figure 1.2. A pros and cons list of these contours is made in table 3.4 in order to determine the better option. The analysis to find the contours is found in appendix 1.2.1.

Comparing the pros and cons of table 3.4, **option 2** is chosen as the best path. Preventing inundation of the casino area is important since no sufficient information is available on the behaviour of the fabric when in contact with debris and large objects (cars). The restructuring of the pathways is achievable. Next the dimensions of the fabric have to be determined in order to conclude whether this path is appropriate.

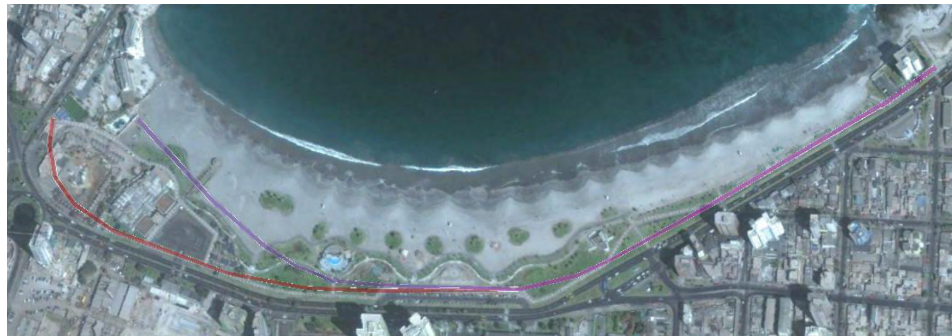


Figure 3.11: The two contour lines for possible Dyneema integration. Where the red represents option 1 and the purple option 2.

Table 3.4: Pros and cons for the two Dyneema contour options.

Option 1	
Pros	Cons
Minimal change of the current infrastructure Space behind the barrier High elevation of the Dyneema floater Increase accessibility of the beach on south side	Casino inundated Objects in the Dyneema fabric Interaction between Dyneema and vehicles Space in front of the barrier Cars need to drive over floater for parking spot
Option 2	
Pros	Cons
Casino in dry zone Objects in Dyneema fabric Space in front of the barrier	Redesign of the side walk and pathways Space behind the barrier Decreases of sandy beach area

The design of the Dyneema

Along the determined trace a general design for the Dyneema barrier is made based on one cross section combining the worst case parameters along the trace. These parameters are the highest wave height, narrowest part of sandy beach, smallest area behind/in front of the barrier and width of the path. Therefore the cross section is representative for the entire trace. The conclusions of the design are: 1) this cross section is feasible and 2) the forces on the cable foundation are the bottleneck of the system. The result gives a good indication of the sizes and forces. The design is shown in figure 3.12. The detailed values and forces are given in table 3.5.

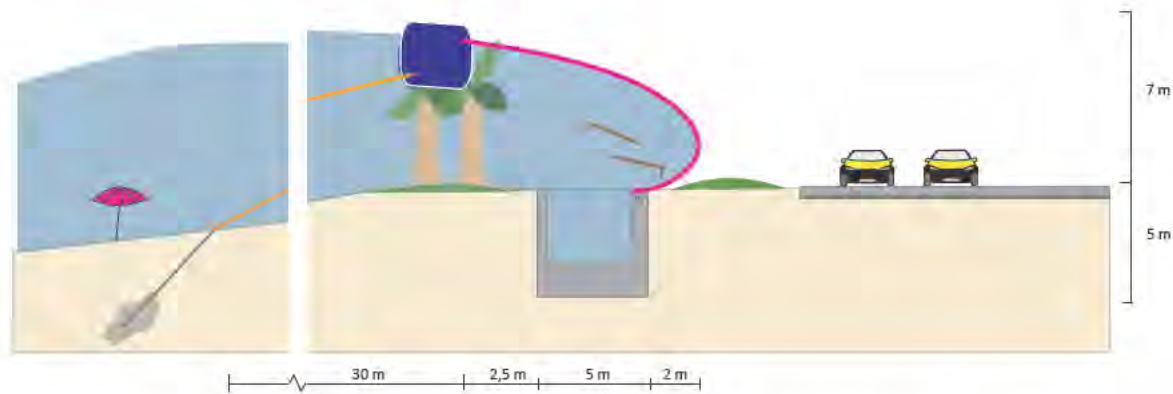


Figure 3.12: The dimensions of the general cross section for the Dyneema design. Based on the analyses in I.2.

Table 3.5: Dimensions and forces of the Dyneema design results based on prior analyses (I.2).

Dyneema fabric		Cable foundation		Floater constraints	
Tension	147 kN/m	Cable		Required buoyancy	72 kN
Contour length	13.2 m	Length	24.4 m	Maximum width	4 m
Bottom		Diameter	5 cm	Minimum emergence	25%
Angle	11.5°	frequency	1 : 10	Floater design	
Horizontal Force	144 kN/m	Stress	1.2 GPa	Width	4 m
Vertical Force	29 kN/m	Foundation		Height	3 m
Top		Resultant force	1.52 MN/m	Buoyancy	100 kN
Angle	10.2°	Angle	17.8°	Density	350 kg/m ³
Horizontal Force	145 kN/m	Distance to Dyneema	30 m	Emerged	84 cm
Vertical Force	26 kN/m			Emerged %	28%

SEAWALL

For the seawall in the north Cavanca peninsula a feasible height and trace has to be found. This wall will not retain all the water of the worst case scenario but is designed in order to have a feasible height, this means that aesthetics of there area are more important than tsunami mitigation. The terrain along the peninsula will be analysed in order to determine the feasible height a description of the terrains is given in appendix I.2.3. The wall trace is shown in 3.13 and the design is given in table 3.6. For this design basic strength calculations are made in appendix I.2.4 these forces correlate to feasible wall designs.

The seawall is designed to retain 3.9 meter run up scenarios, as concluded in appendix I.2.3. This implies that the retaining scenario will be fully effective in the majority of the scenarios. The effectiveness for the worst case scenario should be validated.

Table 3.6: Seawall design heights as determined per terrain

Terrain	Lowest altitude [m]	Feasible height [m]	Necessary Elements	Height from MSL [m]
Undeveloped area	3	3	Wall	6
Club nautico	3.2	2.5	Wall and gate	5.7
Fishing pier and market	3	2.5	Wall and gate	5.5
Cocktail bar	3	2.5	Wall	5.5
Parking spots	2.8	2.5	Wall	5.3
Terrado suites	3.2	4	Watertight building	7.2
Cavanca hotel	2.6	2.5	Wall and gate	5.1



Figure 3.13: The final seawall trace is shown in orange. From this trace a raise from mean sea level of five meters can be realised. For this the wall height will vary between 2 and 3 meters. In purple the final Dyneema barrier trace is shown.

THE DYNEEMA SEAWALL CONNECTION

The traces of the two retaining measures meet in a connecting point. Both scale-tested and implementable options for this connection are not yet developed. A small evaluation of a possible scenario is made in [1.3](#). For the connection of the two elements a part of the Cavanha area has to be reclaimed from the owner in order to extend the Dyneema barrier in order to connect it to the wall. The connection point should continue as high as possible in order to prevent or delay overtopping. A detailed design of this part is not considered within the scope of this report, since too limited information is available.

LEVEL 2

A measure that is suitable to be implemented as the second level is a reinforced and adjusted building for tactical vertical evacuation. This measure is implemented to ensure a safe situation in the case that not all the water is retained (failure). Additional information on the level two solution is given in appendix I. In order to quantify the possible failure some assumptions related to this scenario are made related to the seawall and Dyneema barrier:

1. When the seawall is overtopped, this will create a comparable inundated area in the north and south peninsula areas as the unprotected case.
2. The seawall will delay the inundation. Therefore more evacuation time is available.
3. Dyneema barrier failure is possible. This failure is assumed to happen when the water level is high. In case of failure, also more evacuation time is created than in the unprotected scenario.

These changes in the scenario are debatable and very difficult to validate. Especially the assumption of the equal inundation map is unsubstantiated. It is possible that the blockage of the water by the Dyneema barrier raises the water level in the bay. A situation is created where the wall receives a higher flow depth than without the barrier. If this happens, the inundation of the peninsula can be bigger than without the wall. This can change the effectiveness of the proposed system because when the inundation reaches the hinterland of the Dyneema barrier, the investment of the system might not be worth it. This possibility is taken into account in the validation of system A.

LEVEL 3

In the previous sections, the main structural elements for this system are elaborated. The proposed structures for level will retain the water. In case of failure the evacuation time is increased (with respect to the default situation). Multi-story buildings in tactical places on the peninsula are reinforced and adjusted in order to host evacuees. The measures, categorized in implementation level three, should anticipate on these system specifics. An example of anticipation are the tailor made evacuation routes for system A. The adjusted routes can be found in appendix I.

On level three many well-functioning measures can be implemented. The authors have formulated a default concept for level three mitigation that can be applied for systems A, B and C. The default concept can be found in section *system C, system design for level three* 3.6.3.

GEOTECHNICAL CONSIDERATIONS FOR SYSTEM A

A few remarks can be made on the foundation of the structural measures in level one and the possible related failure modes. A more elaborate consideration of the technical design of the structures is considered to be outside the scope of this research. The mentioned failure modes serve mainly as a reminder of the risks related to the local subsurface and conditions with respect to system A.

The dyneema barrier foundation consists of two elements; the gravity based main foundation, in which the the floater is kept, and the tension anchor. As discussed in part zero, the subsoil contains mainly sand and rock. Therefore, it is assumed that the subsoil is firm enough to hold the gravity based structure. The main considerations for the design are captured in table 3.7. A more elaborate description of relevant geotechnical failure modes can be found in appendix M.

VARIATIONS

Within the proposed system numerous variations are possible. The Dyneema idea can be introduced in many different concepts. In this section two ideas are presented in which the concept of the system is slightly changed and thus the effectiveness.

Floating wall principle

The floater of the dyneema principle takes a lot of space. This floater can be altered into a seawall, with a low density, connected to Dyneema fabric and founded in the structures. This way the seawall can gain additional height during the tsunami event. The wall can align with the upper angle of the Dyneema increasing its horizontal surface when the water rises. This will not work for a very high wave but the concept shows that alternatives on the static hard wall can be found. When such a concept is implemented for a location where overtopping of the wall occurs, every centimetre the wall rises will increase the effectiveness of the scenario.

Table 3.7: Geotechnical considerations for system A

Structure	Element	Main failure modes	Enduced by	Prevention
Dyneema Barrier	Gravity based foundation	Uplift	Vertical upward tensile forces (tsunami)	Safety factor in design
		Settlement	Seismic forces	Safety factor in design
		Scour	Eroding forces (wind and water)	Periodic check up
		Piping	Seepage (tsunami, tide)	Preventative reinforcement Deeper foundation
	Grout anchor	Uplift	Vertical upward tensile forces (tsunami)	Safety factor in design
		Scour	Erosion (water)	Periodic check up
Seawall	seawall	Earth pressure failure	Excessive waterforce (tsunami)	Safety factor in design
		Scour	Erosion (tsunami)	Preventative reinforcement
		Piping	Seepage (tsunami, tide)	Preventative reinforcement Deeper foundation

Dyneema without a floater

The Dyneema fabric can be implemented in a lot of different ways. Considered here is a covered walking path, which are used in Chile to provide shelter for rain, with reinforced foundation and steel beams. Dyneema can be installed on the floor with cables along the beams of the shelter so that it can be pulled over for the tsunami event. This concept is also applicable on fences. When installing reinforced fences the fabric can be pulled over to convert this fence into a seawall. This would be a good solution for the unwanted seawall in the peninsula, because the owners are more likely to accept 3 meter, or higher, fence. The proposed sea gates can also make use of this trick, by installing regular fenced gates with some extra ground pins. On a smaller scale this concept can be used as secondary wall for the Cavancha peninsula in order to prevent the inundation from spreading.

3.5. SYSTEM B

3.5.1. INTRODUCTION

The system is designed to delay and divert the water in order to reduce impact and increase evacuation time. When taking the delaying and diverting as a starting point for the design of a system, escaping the water is of great importance because inundation is still possible and allowed in case of a large event. Since the impact criterion of post-disaster disruption of society is defined, also preparations for the aftermath are taken into account. In order to obtain a full scale safe and multilateral approach measures within the system should be implemented on the three levels (2).

According to the recommendations of part one and the local restrictions analyses, the water should be delayed or diverted at the Playa Cavancha, Playa Casino and the North side of the peninsula to reduce the impact on the hinterland. These areas are focussed on in terms of mitigation measures on the first implementation level. Mitigation measures on the second and third level are used to carefully complement the system.

3.5.2. VARIOUS OPTIONS

In this section, various options for a complex solution are proposed and briefly discussed. For each region, a preferred option shall be given. This choice is made based on available literature and the analyses performed in this chapter.

CAVANCHA

Option one: Delaying impact in the city

This option consists of onshore mitigation measures. In table 3.8 the measures are listed as well as a description of the location, the level of implementation such as defined in the framework and the main functionality. In figure 3.14 an overview is given of the measures that are compiled in this system. The system is based on the method of delaying by implementing small sea walls onshore at the Playa Cavancha and a bit higher sea walls at the Northern side of the peninsula. The choice for smaller walls at the beach is mainly based on aesthetic requirements. By designing the height of the wall (especially at the Northern peninsula) such that it gets only over topped by the highest waves it is possible to delay the impact and increase the evacuation time. On a second level flow channels will be integrated in the city by replacing the coastal roads by caissons. These caissons can store and divert the inflowing water through a network of connected channels. The benefit of this solution is the wide range of design possibilities to implement them in the city. Along the Playa Cavancha the existing dunes will be extended to delay any incoming water and form a natural barrier which should be able to retain smaller tsunamis. At the south side of the peninsula the pedestrian path along the coast will be raised to function as a small sea wall which can retain until a certain height. Assuming the water will be delayed, evacuation time will be increased. Vertical evacuation buildings will be assigned at the peninsula to escape the water. As described in the introduction of the section the second and third level are of great importance when delaying or diverting the water because inundation is still allowed and the people need to evacuate. That is why a clear evacuation protocol is compiled in the option and logistical centres are assigned at the peninsula. Furthermore there has to be some regulations on hazardous objects in the area to make sure debris forces on the sea walls will be limited. This is of vital essence for the system since the delaying and diverting principle is maintained by the sea walls. When they break down, flow velocities could increase rapidly around the breach and the system could fail.

Table 3.8: System design for Cavancha - option B1

Level	Area	Method	Mitigation Measure
1	Playa Cavancha	Delaying and diverting	Small sea wall
	Playa Casino, Peninsula North	Delaying and diverting	Medium sea wall
2	All roads	Delaying and diverting	Integrated flow channels
	South peninsula	Delaying and escaping	Raised infrastructure, pedestrian path
	South peninsula	Escaping	Assign vertical evacuation buildings
	Playa Casino, Playa Cavancha	Delaying	Align existing dunes
3	Peninsula	Escaping	Emergency and logistical centres
	All areas	Escaping	Clear evacuation protocol
	All areas	Escaping	Reinforcement existing structures
	Around sea walls	Secure chosen method	Regulation for hazardous objects

Option two: Decrease the wave and delay the impact

The second option contains most of the same elements of the first option however a few functions are added in order to make the measures on a second level more feasible (see table 3.9). This system holds a submerged breakwater in combination with the integrated flow channels which are combined with a lower sea wall. This gives three levels of delaying the water. The most important difference is the submerged breakwater which is implemented at the entrance of the Cavancha bay. The breakwater is used to reduce the incoming tsunami wave in order to decrease the amount of water that is propagating inside the bay. By this means the flow depth should be reduced and the total inundation area should decrease. Because the integrated flow channels have a finite storage volume and the incoming discharge is assumed to be lower due to the breakwater, the evacuation time available is assumed to increase. The casino at the Playa Cavancha is reinforced to withstand the water forces since the smaller sea wall does not protect it. At the North peninsula reinforced buildings steer the water inside the integrated flow channels. Also here the amount of water that enters is decreased by the breakwater. At the south peninsula a vertical evacuation building is assigned at the tip of the peninsula. This is possible since less inundation is expected at the peninsula due to the reduced tsunami wave by the breakwater. One of the main benefits of the breakwater is that it 'protects' the entire bay instead of needing local structures in each area along the coastline, this benefit meets the restrictions of urban planning. The measures which focus on escaping the water are based on the same principle of the first proposed system (B1).

Table 3.9: System design for Cavancha - option B2

Level	Area	Method	Mitigation Measure
1	Cavancha bay	Reducing (and delaying)	Submerged breakwater
2	All roads	Delaying and diverting	Integrated flow channels
	Playa Casino, Playa Cavancha, South peninsula	Delaying and diverting	Integrated flow channels with small wall
	North peninsula	Diverting	Reinforce existing buildings to steer
	South peninsula	Escaping	Assign vertical evacuation buildings
	Playa Casino, Playa Cavancha	Delaying	Align existing dunes
3	Peninsula	Escaping	Emergency and logistical centres
	All areas	Escaping	Clear evacuation protocol
	All areas	Escaping	Reinforcement existing structures
	Around sea walls	Secure chosen method	Regulation for hazardous objects

Option three: Diverting the water in the city

The third option is mainly based on the method diverting the water. By using the existing infrastructure deep open channels can be implemented to steer and divert the water. An overview of the measures that are composed to create the system is given in table 3.10 and figure 3.14. The largest channels are lowered roads in the area where the most inundation is expected. Here the channels have to be designed such that they can store enough water to decrease the total inundated area. In fact this system uses the principle of cutting of the peninsula and transforming it into an island by deepening the expected inundated area in order to decrease inundation in the other areas. Because the roads are normally used with a different purpose, in the case of a tsunami alarm the entrance of the channels should be cut off in order to evacuate the channels with people and cars. To make sure the water will enter the deeper channels existing structures and tactical buildings like the casino are reinforced and used to steer the water into the deeper channels. By means of evacuation bridges over the channels it is possible to evacuate the people from the peninsula to higher grounds. The system is vulnerable due to the limited storage capacity of the channels. The storage can be increased by placing caissons under the secondary roads. Besides the possibility to evacuate the peninsula also other evacuation buildings are assigned to give more options for evacuation than only the pedestrian bridges. When applying evacuation bridges a clear evacuation protocol is essential, this can be supported by adding signs and distribute specific information. Especially tourists should be instructed since they do not have experience with earthquakes and tsunamis.

Table 3.10: System design for Cavancha - option B3

Level	Area	Method	Mitigation Measure
2	Playa Casino, North peninsula	Diverting	Steering buildings
	Main road	Delaying and diverting	Open channel to divert the water
	Main road	Escaping	Pedestrian bridges over the channel
	Secondary roads	Delaying and diverting	Integrated flow channels to increase storage
	South peninsula	Escaping	Assign vertical evacuation buildings
3	All areas	Escaping	Clear evacuation protocol
	All areas	Escaping	Specific hardcopy information and signs



Figure 3.14: System B options for Cavancha

Proposed system

All various options of mitigation systems to delay or divert the water have their pros and cons for the implementation in the Cavancha bay. Of course dimensions and the other governing design criteria can be modified within each system according to the level of safety that is desired.

The third system, which is based on diverting the water in the city, assumes that the open channels will be able to store and divert enough water to decrease the inundation area in and around the peninsula. Because there are no mitigating solutions on other levels which can fulfill the same method, the inundation area will increase in the case that the channels do not have enough storage capacity or get constipated (for example by cars, boats or other debris). If that occurs the pedestrian bridges will be flooded or are not able to meet the required capacity. This is why the system is vulnerable to the main function of the open channels. In order to make this system succeed the channels and the steering buildings need a careful design or to be integrated a design with a level one measure.

The first system is based on the principle of delaying the water in the city by using sea walls and integrated channels. The function of this system is limited to the height of the sea wall and the storing capacity of the integrated channels. In order to make this a effective option the height of the sea wall should be increased or the storage capacity of the channels should be increased, which are both not favourable. Another option is to reduce the amount of water that is propagating towards the shoreline. This can be obtained by implementing a submerged breakwater at the entrance of the bay as proposed in system two. Now the height of the sea walls can meet the aesthetic design criteria and the integrated flow channels can store and divert the remaining water.

Based on Irtem *et al.* [27], who did experimental research with the effect of submerged breakwaters on tsunami run-up heights, reductions varying between 19% - 43% can be realised. This gives reason to believe that a submerged breakwater could work in case of a tsunami.

One of the downsides of a submerged breakwater in the bay of Cavancha is the influence on the wave climate. Besides the reduction of the tsunami wave, the breakwater will also reduce the swell waves (surf waves). This could make the beach less interesting for surfers, which is one of the main tourist attractions at the Playa Cavancha. The reduced wave height will also influence the sediment transport by which the topography of the beach could be changed.

However, the effect of the submerged breakwater on the swell waves can be minimised by optimising the design. Since the effectiveness of the submerged breakwater is mainly depending on the relative freeboard F/H_i (Irtem *et al.* [27]), the freeboard can be optimised in order to reduce the tsunami wave height and minimise the effect on the swell waves. Another benefit of the submerged breakwater is that it 'protects' the entire bay instead of needing local structures in each area along the coastline. This solves the problems of a medium wall at the North peninsula and at the Playa Casino in the first system. Besides the impact of hazardous object on the sea walls will have less impact on the failure of the entire system.

In general the strong part of the second system is that there are multiple mitigation measures on several level with the purpose to full fill the same method (delaying and diverting), this makes system is less vulnerable to the function of one element. Especially within this system, this is a desired property because there are there are many uncertainties in the exact delaying functions of each element. Figure 3.15 gives an overview of how the second system should work. Based on the considerations discussed above the second system (B2), which includes the submerged breakwater to reduce the wave height and acts on multiple levels, is proposed to obtain a reduced impact on the Cavancha area.

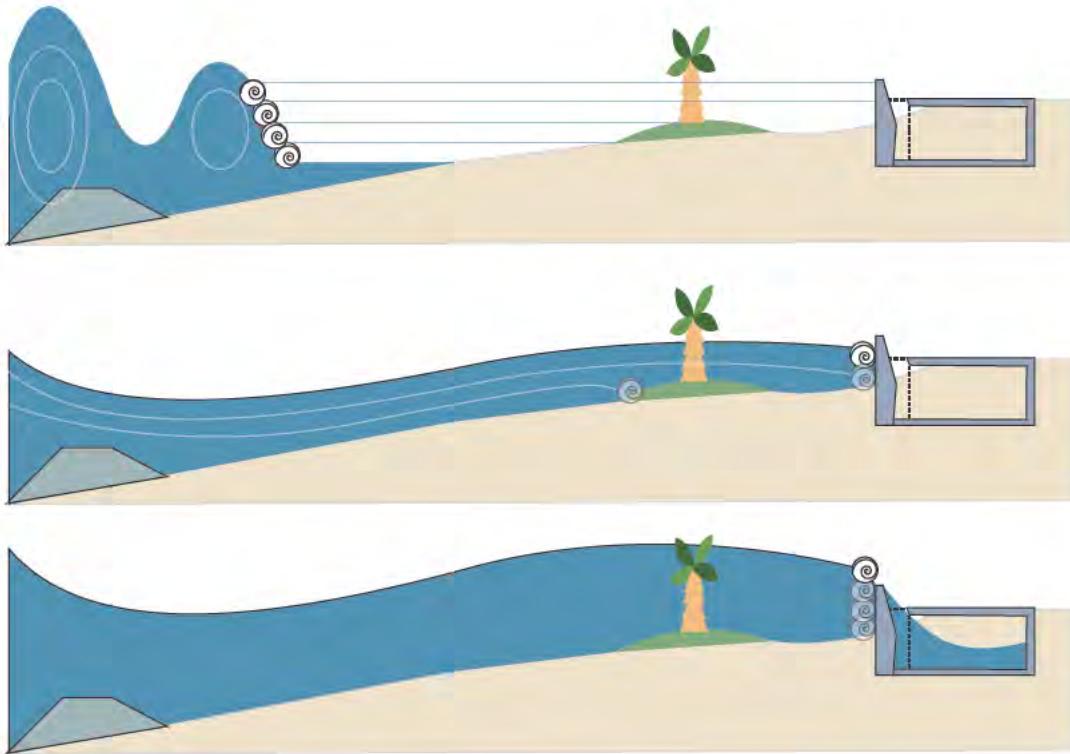


Figure 3.15: A schematic overview of the principle of system B2 when it arrives on the shore of Cavanca.

ZOFRI

The Zofri area is transformed into a bathtub when inundated by a tsunami, this makes it difficult to propose mitigation measures with a method of delaying and diverting. Two options are proposed, the first one is delaying the water when the embankment is already overtopped. The other one proposes to delay the water before it gets the opportunity to overtop the embankment.

Option one - Delaying onshore

This proposed system for mitigation in Zofri is based on delaying the water inside the Zofri area. It is designed to divert the water after the embankment is overtopped. To do so the integrated flow channels are introduced in all roads in the inundated area, see figure 3.16. The channels aim mainly to store and divert the water from the evacuation roads in order to increase evacuation times for the Zofri mall. The integrated channels at the Arturo Prat Chacón will be combined with a sea wall. This sea wall will replace the fence of the factory that is situated between the coastline and the Arturo Prat Chacón. The wall will delay the flooding of the Zofri area since a buffer has been created. When the wall is overtopped the water will be steered into the channels, this system uses the same principle as the small sea wall implemented with the integrated channels along the Playa Cavancha. Combined with the integrated channels the pedestrian roads will be raised to secure evacuation routes. Besides the structural measures also attention should be paid to escaping the water. When infrastructure is raised the evacuation routes will be changed, that is why a clear evacuation protocol should be designed and the people should be informed about this protocol. Both are essential in the case of delaying and diverting in Zofri. An overview of the proposed measures is given in table 3.11

Table 3.11: System design for Cavancha - option B1

Level	Area	Method	Mitigation Measure
1	Along Arturo Prat Chacón	Delaying (and retaining)	Reinforce sea wall
2	All roads	Delaying and diverting	Integrated flow channels
	All evacuation roads	Escaping	Raised infrastructure
3	All areas	Escaping	Clear evacuation protocol
	Zofri Mall	Escaping	Specific hardcopy information and signs

Option two - Delaying offshore

The second proposed system for Zofri tries to delay the impact by means of offshore situated measures and smaller measures inside the Zofri area. By using a system of breakwaters like in the simulation of Jahromi and Sidek [28] the wave height can be reduced to limit the overtopping in the first place. Since the coastline is not used for tourist activities changes in the wave height are not much of an issue here. A reduction in wave height will reduce sediment transports so sedimentation is expected, this could even be beneficial for the system. Figure 3.16 and table 3.12 give an overview of the measures. With a limited overtopping the amount of water to delay inside the Zofri area is reduced so measures inside the Zofri area (where not much space is available) can be designed smaller. To delay the water inside the Zofri area large 'thresholds' are introduced to create zones. Buildings in line with these speed bumps should be reinforced to retain the water till a certain threshold to close the zone. Also it is recommended to assign vertical evacuation buildings around the Zofri area since here the density of people is large compared to the rest of the area. Since there are no other evacuation possibilities besides the road this could be a good solution. Also, as in case of the first proposed option, the people should be aware of the evacuation possibilities so a clear evacuation protocol, hardcopy information and signs are of essential importance.

Table 3.12: System design for Zofri - option B2

Level	Area	Method	Mitigation Measure
1	Offshore the Zofri coast	Reducing (and delaying)	Submerged breakwater
2	In the roads	Delaying	Speed bumps
	In line with the speed bumps	Delaying	Reinforce buildings
	Around Zofri mall	Escaping	Vertical evacuation buildings
3	All areas	Escaping	Clear evacuation protocol
	Zofri Mall	Escaping	Specific hardcopy information and signs

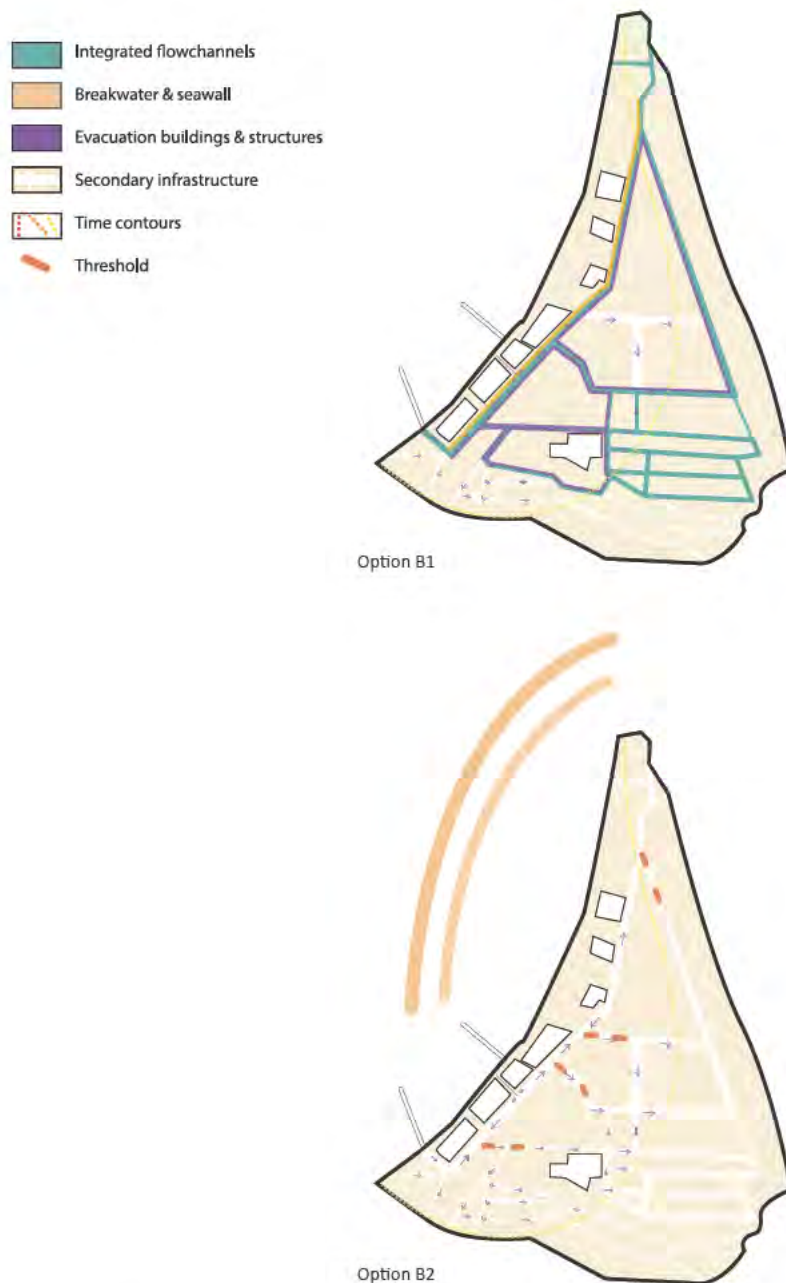


Figure 3.16: System B options for Zofri

Proposed System for Zofri

In general the Zofri area is not suitable to delay the water since the bathtub will make sure the entire area is inundated rapidly. Since building breakwaters is a rather expensive solution this is not the best way to reduce impact on Zofri when it is only used to delay the water. When proposing a breakwater it is recommended to build it high enough to retain the tsunami instead of reducing its wave height, so actually a system A solution. So when talking about delaying the water the first proposed system, delaying onshore, is thought to be the most feasible. It is relative easy to implement since the existing infrastructure is used and the caissons are easy to construct. In general the evacuation of the Zofri area is of great importance since there is a fast propagation of the water in case of over-topping. However this aspect will be dealt with in system C.

At a first estimation based on the length of the available roads (8,5 km), the available width (15 m) and a possible depth (5 m) the total storing capacity is assumed to be 630.000 m^3 . Extra storing capacity could be necessary to increase evacuation times. For example below the parking place of the Zofri mall. This is approximately 12.000 m^2 which could increase the storage capacity with another 50.000 m^3 .

3.5.3. SYSTEM DESIGN

In the previous section, both for Zofri and Cavancha options of mitigation are proposed. In the following section the option for Cavancha will be further elaborated.

In this section the elements of the proposed system (B2) will be designed in more detail. The design is based on the three different levels. The most important structures in this system are the submerged breakwater (level 1) and the integrated flow channels in combination with a seawall (level 2). In this section of system design, the authors will focus on those elements. In order to give a preliminary design the design criteria, tracing, dimensions and knowledge gaps for both elements are discussed. Also some geotechnical considerations are briefly mentioned for the structural elements within the system.

LEVEL 1 - SUBMERGED BREAKWATER

On the first level the system contains the submerged breakwater at the entrance of the Cavancha bay. The aim is to reduce the tsunami wave height in order to lower the flow depth and decrease the inundation area in the city. The reduction of the flow depths is necessary to increase feasibility for the level 2 solutions (like the integrated flow channels). Normally a breakwater is designed to dissipate wave energy and reduce the wave heights of all waves. However in this case the submerged breakwater should only effect the tsunami wave. Based on physical experiments by Irtem *et al.* [27] and simulations by Jahromi and Sidek [28] it can be concluded that a submerged breakwater can have a significant effect on a tsunami. To make a sufficient design there are several criteria which must be taken into account. Below the most important ones are listed, these are based on the system design. If requested by local authorities more criteria can be added.

- Most reduction on tsunami wave height
- Minimize effect on normal wave climate in the bay for tourist activities
- Minimize effect on beach topography
- Allow small fishing boats (max. draft 1 meter) to enter the bay
- Minimize effect on water quality for swimming and ecological purposes

Tracing

In order to reduce the tsunami wave height in the Cavancha bay the breakwater should close the bay along the entrance. The proposed tracing of the submerged breakwater will be from the tip of the North peninsula to the Northern point of the Playa Cavancha. Both connection point are already an existing rock formation at mean sea level. The depth contour along this tracing varies between -2 meters along the connection points and -13 meters in the centre, see figure 3.17. The slope of the bathymetry is roughly 1:42 and is almost constant over the depth contour, however its direction with respect to the breakwater changes. The length of the tracing is approximately 800 meters.

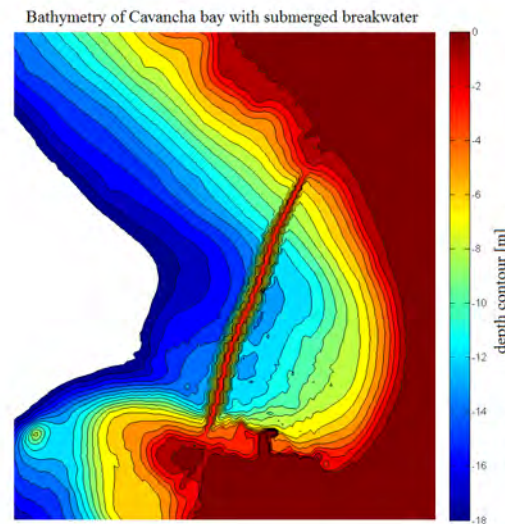


Figure 3.17: Depth contour of Cavancha bay, based on LIDAR topography used for the NEOWAVE model. Location of the proposed submerged breakwater is indicated.

Preliminary design cross-section

A preliminary design is given in figure 3.18. The focus is on the first order estimation of the dimensions of the cross-section. Literature has been found of physical experiments and modelling results for the effect of submerged breakwaters on tsunami waves. In order to give a preliminary design most dimensions are based on these physical experiments and modelling results. A more detailed description on the choice of several parameters can be found in appendix J. In this design the structural stability is not taken into account. First the proposed design has to be tested by modelling the results assuming it will preserve its structural stability to check if it has the desired effect. A first estimation of the stone size is based on the rule of Burcharth (2003) unless this rule gives a rather large stone size ($D_{n50} = 3,2m$) the individual stability of the stones is an important aspect in case of extra debris. For a first estimation the slope of the breakwater is assumed 1:3. However also this value has to be recalculated to make sure that it is sufficient for the overall stability and interlocking of the armour layer. Taking these dimensions the cross-section around the -13 m depth contour is $440 m^2$ and the total volume of the breakwater is approximately $210.000 m^3$.

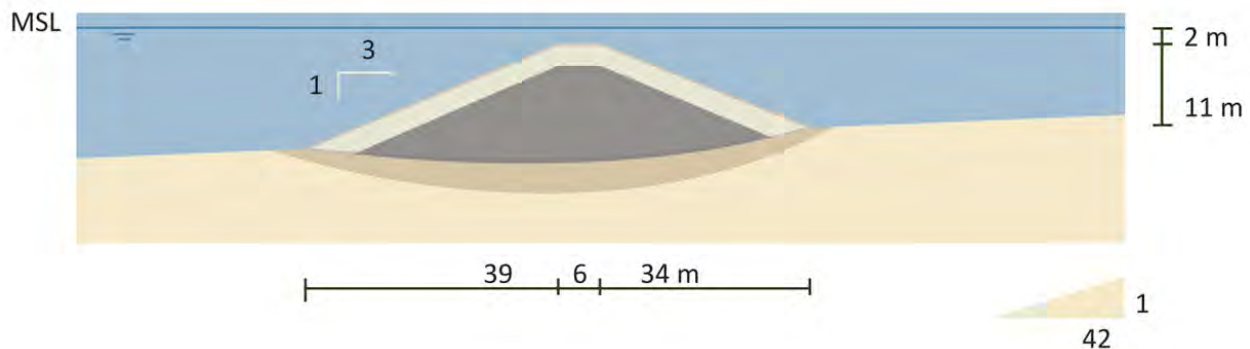


Figure 3.18: Preliminary design of the submerged breakwater

Variations

Besides the classical rubble mount submerged breakwater it is possible to make the submerged breakwater out of a caisson. For example a active breakwater a active submerged breakwater like the REWEC1 as described by Filianoti and Piscopo [29] could be implemented, see figure 3.19. This caisson contains an air pocket which can be used as an gas spring to absorb the wave energy. By regulating the amount of air inside the caisson the natural frequency of the gas spring can be close to the period of the waves that you want to reduce. In this way the regular swell waves (which are nice for surfers) can propagate unhindered towards the shore and only the long tsunami waves will be captured by the active breakwater. Knowledge gap to this system is how the large amount of air that should be needed can be stored, this needs further research.

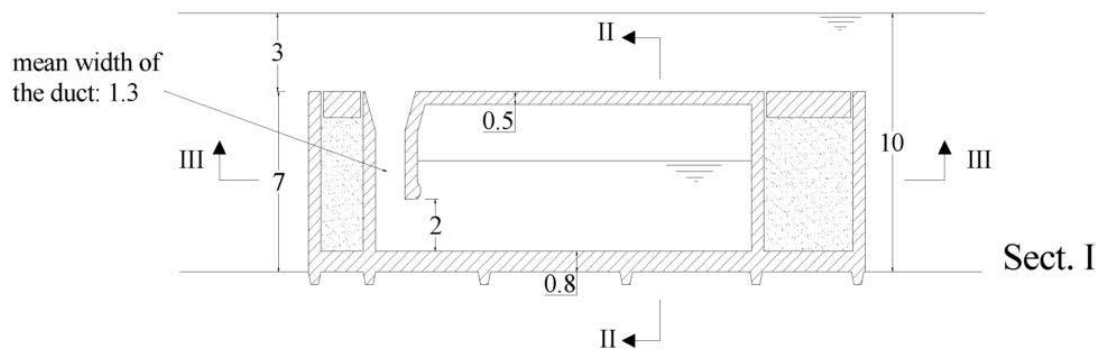


Figure 3.19: Cross-section of REWEC1 active breakwater.

This concept could be extended with a system that predicts the exact wave period for example with a wave buoy offshore. In that way the system can be adjusted to the exact wave period that is propagating towards the bay. Feasibility of this concept needs further research and is mainly depending on the amount of air needed to reach the same period of the tsunami wave. Disadvantage of this concept can be the large running costs since the caissons should be equipped with a control system for tuning, and must be connected to a pumping system. Large benefit to the REWEC1 submerged breakwater compared to the classical rubble mount breakwater is the possibility of a lower freeboard which is convenient for the minimal effect on swell waves.

Another variation is a submerged breakwater made of reefballs, like in figure 3.20. These hollow structures are mainly used to create an artificial reef. However it is possible to use them as a submerged breakwater. These elements will increase the permeability which enhances the possibility for the water to flow inside the bay. This benefits the ecological downside of closing the bay.



Figure 3.20: Overview of a reefball breakwater.

Knowledge gaps

The influence of the submerged breakwater has some knowledge gaps that need further research, these are listed below and should be taken into account when making a more detailed design.

- **Influence on natural period of the bay**
Due to the submerged breakwater the dimensions of the bay change which may influence the natural period of the bay. There is not yet any information of the subsequent resonance effects.
- **Tsunami forces on a submerged breakwater**
It is assumed that the tsunami wave is already broken before reaching the breakwater. The tsunami can therefore be considered as a bore acting on the breakwater. The behaviour of the bore and the impact on the breakwater are still unknown.
- **Wave height reduction**
The effect of a submerged breakwater on the reduction of a long wave (like a tsunami wave) is not well understood yet. Based on physical experiments and a simulation the assumption has been done that it will reduce the wave height.
- **Environmental impact**
To make sure that the water within the bay stays of good quality for swimmers there should be openings to allow water and the tide to flow in and out the bay. The breakwater may negatively influence this. In that case this could also have a negative ecological effect.

LEVEL 2 - INTEGRATED FLOW CHANNELS

On the second level a design is made for the integrated flow channels which are combined with a small sea wall. Its main purpose will be to store and divert the inflowing water. In figure 3.21 a more detailed overview of the principle is given. The design criteria for such a integrated flow channel are listed below and based on the system design. Most governing criteria for the dimensions is the available space to integrate the channels in a nice way. The first two design criteria are qualitatively described because there is no required time to delay the tsunami yet, this has to be evaluated based on the combined effectiveness of the different elements in the system.

- Sufficient storage capacity to delay the tsunami for several minutes
- Sufficient inflow and outflow capacity to meet the first design criteria
- Sea wall should be able to hold hydraulic forces
- Nicely integrated in existing infrastructure
- Easy to construct

Tracing

The caissons will replace the existing roads in the Cavancha area. By connecting the caissons together a network of integrated flow channels will be formed by which the water can be stored and diverted. In front of both beaches (Playa Cavancha and Playa Brava) the road is wider so here the width of the channels can be increased in order to increase the capacity. Since this is the most critical area, because the first and biggest wave will enter here, the extra capacity is really convenient. The total length of the tracing as presented in figure 3.21 is approximately 13,2 kilometres. The dimensions of each section along the tracing can be found in 3.13. Here the Playa Cavancha refers to the area where the integrated flow channels are implemented in the road along the North Peninsula, Playa Casino and Playa Cavancha.

Table 3.13: Dimensions and capacity for preliminary design of the integrated flow channel.

Area	Length [km]	Width [m]	Height [m]	Capacity [m^3]
Playa Cavancha	1,18	30	6	212.400
Playa Brava	2,77	30	6	498.600
Other roads	9,24	22	6	1.219.680
Total	13,19			1.930.680

Preliminary design

In figure 3.21 an overview is given of a preliminary design. Here the cross-section is given at the widest locations (Playa Cavancha). The cross-section contains three elements 1) the sea wall, 2) the caissons and 3) a overflow shaft.

The caissons will be designed as two separate caissons which will function as a road (one for each direction) and a channel. It is chosen to use two caissons to decrease the span to 12,5 meters. The caissons will have holes in the walls to allow the water to flow in. Due to the large span and the holes it is recommended to reinforce the caissons. Also because they have to withstand the seismic forces which could induce cracks and settlement of the construction. Next to both caissons retaining walls will be placed. At the seaside this will be a sea wall which extends 1,2 meter above ground level. At the other side the top of the wall will be at ground level. Both spaces between the caisson and the retaining walls will have to be closed with bars to let the water flow in but also allow people to walk over it. The hinter shaft between the retaining wall and the caissons has two main functions first to allow air to flow out the caisson while it is filled with water, second to allow water that flows over the road to enter the caissons form the back.

The dimensions are mainly depending on the available space at each section, in the case of the road along the beach this holds a 30 meter width, at the other roads the width should be decreased to 22 meter. It is believed that the depth of the caissons can be 6 meters, however this is strongly depending on the subsoil and influences also the construction method. The construction method is briefly explained in the appendix also some geo-technical considerations are briefly explained. Most attention should be paid to the connection between the element to make the structure watertight.

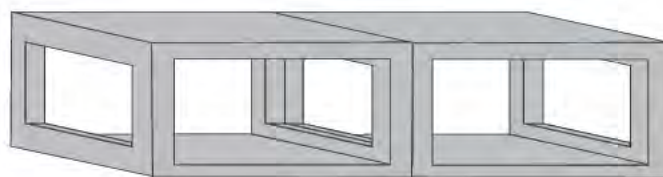
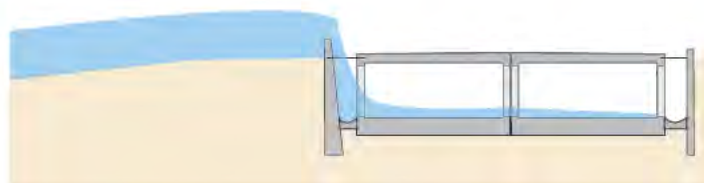
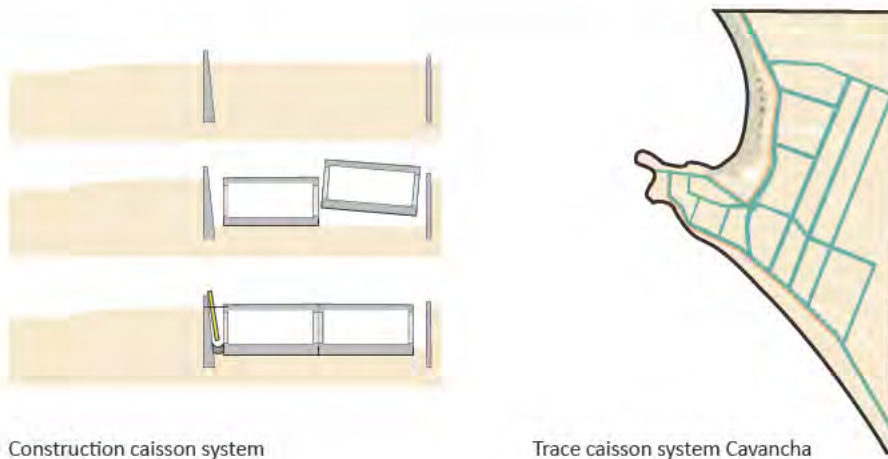
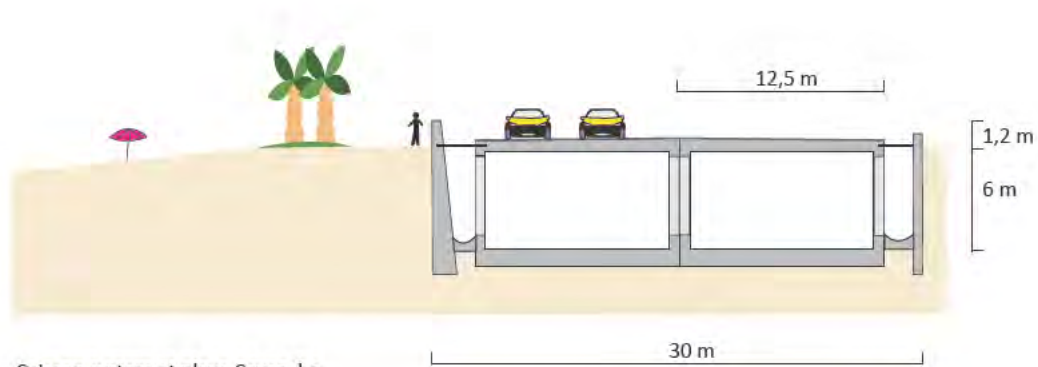


Figure 3.21: Storing and diverting principle of the integrated flow channels (schematic)

Capacity

The required capacity to increase evacuation time is related to the discharge of the incoming tsunami bore. In appendix J the maximum inflowing discharge is estimated based on the modelling results of NEOWAVE, the maximum values found are $6 \text{ m}^3/\text{s}/\text{m}$ and $6,8 \text{ m}^3/\text{s}/\text{m}$ and for location 1 and 2 respectively. The method used to estimate the discharges is a rough approximation since the data is not influenced by the presence of the sea wall.

The available capacity is related to the dimensions of the caisson. Based on the numbers in table 3.13 the capacity for each section can be calculated. Along the Playa Cavancha the storing capacity is 180 m^3 per meter over length of 1,18 km, this gives a total available capacity along the Playa Cavancha of 212.400 m^3 .

For a first order estimation the discharge found can be integrated in time and compared with the available capacity on a section at the beach, this will give approximately 2,5 minutes before the available capacity is flooded with water. However this does not take the outflow capacity of this section into account. To give an estimation of the extra time that will be generated for evacuation the system should be modelled first.

Integrated sea wall

In front of the integrated channel a small sea wall of 1,2 meter height above ground level will be combined with the integrated channels, see figure 3.21. The height of this wall derived from the urban planning discipline as a size for bannisters and other non-view obstructing structures. With 1,2 meter it is still possible to oversee the beach while walking and it does not obstruct the view. The small sea wall have several functions to full fill:

1. **Delay the impact:** By catching the impact forces of the first tsunami bores that are approaching the beach the impact on the channel can be limited.
2. **Steering the water:** When the wall is over topped it functions like a spillway in order to fill the caissons with a more laminar flow, the water will be steered into the caisson.
3. **Sediment trap:** The propagating tsunami will contain approximately 10% of sediment as assumed by the FEMA646 guidelines, especially since the wave first propagated over the beach. The sea wall could act like a sediment trap to decrease the amount of sediment that is flowing inside the channels.
4. **Retain small tsunami:** In case of a smaller tsunami the wall could be able to retain and prevent the water from flooding the city.

The hydraulic forces on the wall can be estimated using the FEMA guidelines and equations according to Yeh *et al.* [30] for tsunami loading on a vertical wall as described in appendix L. When calculating the hydraulic loads it is recommended to take at least two scenarios into account. First a scenario where the small wall is able to retain the water, in that case the flow velocity at the wall will be zero and second the scenario where the sea wall is over-topped, in that the flow velocities should be taken into account. In both cases the debris forces due to objects from the beach and boats from the sea, but also the damming forces of debris, should be taken into account.

Variations

The design that is given assumes that the combined capacity of the channels will be enough to store enough water to delay the impact in the city. However it is possible to increase storage to assign several areas which can be replaced with caissons and can be used to increase the storage area. For example the parking areas along the beach and the foundations of buildings that are going to be build in the near future can be used.

To enhance the spreading of the water through the channels the caisson can be placed under a small angle. Since the topography of the city is already increasing in the hinterland the natural gradient is in the opposite direction. This would mean that the caisson should become deeper when they are implemented in the higher hinterland.

Another modification to the design is to combine the system with a bucking to pump the water out. This will increase the out-flowing discharge and increase evacuation times. It is also possible to connect the caissons with the sea with tubes combined with an one-way valve. By this means the caissons can drain on the sea by a natural gradient during the period that the tsunami wave is retreating and between two incoming tsunami waves.

Knowledge gaps

The proposed design has some knowledge gaps which could be researched with physical experiments or a numerical model.

- **Inflow velocity**

It is assumed the sea wall will act like a spillway when it starts over-topping, so the water will be steered inside the channel. The interaction between the sea wall and the increasing discharge of the tsunami could change the inflow velocity.

- **Influence of construction on discharge**

The design contains elements, like the bars to close the inflow shaft and the holes in the side of the caisson, that could delay the inflow velocity and by that means the inflow discharge. The delaying effect of those elements on the inflowing discharge are not well known yet.

- **Flow velocity inside the channel**

The flow velocity inside the channel is depending on the several parameters like the inflow velocity, the dissipation due to roughness and the local dimensions. Since these are not specified yet the spreading of the water through the channels is not estimated accurately.

- **Subsoil characteristics**

The implementation and feasibility of the concept is highly depending on the characteristics of the sub-soil. For example, in case of rock it becomes harder and much more expensive to excavate the area for the caissons. For this research no accurate information on the subsoil was available.

LEVEL 2 - REINFORCE STRUCTURES TO STEER

At the north side of the peninsula buildings are assigned which will get the function to steer the water inside the integrated channels behind them. The buildings get the same function as the small sea wall in front of the integrated channels at the beach. Between the buildings a larger entrance into the integrated channels (like a 'goal') will be situated to guide the water inside the channels. To make sure that the buildings will be able to withstand the hydraulic forces, the buildings have to be reinforced. To give an idea of the hydraulic forces these building can be assessed based on the equations in appendix L. Since the water is allowed to flow around the buildings the hydrostatic force based on the CCH (which includes the velocity head) should be taken into account.

LEVEL 2 - ASSIGN, REINFORCE AND ADJUST VERTICAL EVACUATION BUILDINGS

A measure that is suitable to be implemented as the second level is a reinforced and adjusted building for tactical vertical evacuation. This measure is implemented to ensure a safe situation since within the system some inundation is allowed and people need to be able to evacuate. Additional information on the level two solution is given in appendix J.

LEVEL 2 - EXTEND BEACH DUNES

Part of the design on the second level is to extend and higher the existing beach dunes at the Playa Casino and Playa Cavanha. This extension will create a larger natural barrier in order to retain smaller tsunamis and delay the larger tsunamis. The existing dunes are separate grasslands with palm trees which can easily be connected. In this way the beach still has its natural view but the resilience of the beach will be increased.

LEVEL 3

In the previous sections, the main elements for this system are elaborated. The proposed structures will divert and delay the water, thereby reducing the damage and increasing evacuation time. Measures, categorized in implementation level three, should anticipate on these system specifics. An example of anticipation are the tailor made evacuation routes for system B. The adjusted routes can be found in appendix J.

On level three many well-functioning measures can be implemented. The authors have formulated a default concept for level three mitigation that can be applied for systems A, B and C. The default concept can be found in section *system C, system design for level three* 3.6.3.

GEOTECHNICAL CONSIDERATIONS

For system B, the geotechnical considerations for the three structural measures, the seawall, the caissons and the breakwater, are captured in table 3.14. A more elaborate description of relevant geotechnical failure modes can be found in appendix M.

Table 3.14: Geotechnical considerations system B

Structure	Element	Main failure modes	Enduced by	Prevention
Breakwater	Rubble mound	Circular slip surface	Excessive loading (seismic, static, cyclic)	Safety factor in design
		Scour	Erosion of the subsoil (tide, tsunami, flow velocities)	
		Liquefaction	Sudden shearing of soil in undrained conditions	
Channels	Caisson	Settlement	Seismic forces	Safety factor in design
		Uplift	Rise of pore pressure due to tsunami	Safety factor in design
Seawall	seawall	Earth pressure failure	Excessive waterforce (tsunami)	Safety factor in design
		Piping	Seepage (tsunami, tide)	Preventative reinforcement Deeper foundation
		Liquefaction	Sudden shearing of soil in undrained conditions (tsunami)	
		Scour	Erosion (tsunami)	Preventative reinforcement

3.6. SYSTEM C

3.6.1. INTRODUCTION

The inundation area is large and a large number of people are present in the inundated area. When there are no investments done to retain or delay the impact of the tsunami, escaping the water and preparation for the aftermath become essential. Safely evacuate all people from the hazardous areas and re-stabilisation are the main focus points of this system.

This implies that the inundation and arrival time-maps must be analysed in order to design an effective, balanced and safe evacuation plan. Also the aftermath of the event must be taken into account, for, since there is no protection, the disruption of the society will be high.

3.6.2. VARIOUS OPTIONS

CAVANCHA

In appendix K the mitigation measures from the short list are evaluated for this system. From this, two options for system C are derived, option 1: vertical evacuation and option 2: horizontal evacuation as shown in table 3.15 and 3.16.

Option C1: Vertical evacuation

In this option a new vertical evacuation building is added to the normal evacuation routes (see table 3.15). This building will be tactically places in the Playa Casino area, here extra capacity is needed to evacuate people on the beach and in the casino. The new building enhances the safety of this area. The peninsula is evacuated by assigning vertical evacuation buildings. The buildings that qualify to be vertical evacuation buildings can be seen in figure 3.22.

Table 3.15: System option 1 - Vertical evacuation, CavanCHA

Implementation	Area	Method	Mitigation Measure
Level 1	Playa Casino	Escaping	New vertical evacuation building
Level 2	Peninsula South	Escaping	Tactical vertical evacuation - Public
	All Areas	Escaping	Tactical vertical evacuation - Private
	All Areas	Escaping	Regulation for hazardous objects
	Safe zone	Preparation Aftermath	Local logistic centres
	Peninsula South	Preparation Aftermath	Small local logistic centres
Level 3	All areas	Escaping and Preparation Aftermath	Education
			Crisis communication system
			Crisis team
			Hardcopy information and Signs

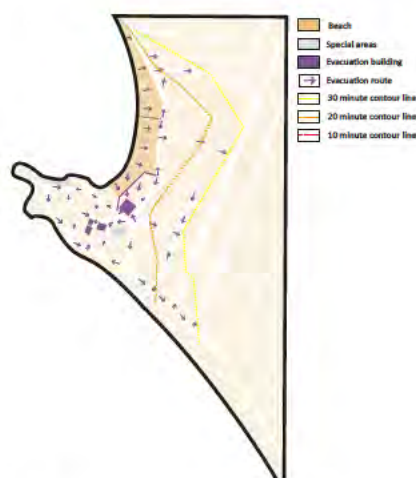


Figure 3.22: System option 1 - Vertical evacuation

Option C2: Horizontal evacuation

For this option the peninsula is not evacuated by assigning vertical evacuation buildings, but by horizontal evacuation via an evacuation bridge. The playa Casino will also use this evacuation bridge to safely evacuate and therefore a new evacuation building is not implemented in this option. The option is shown in table 3.16 and figure K.1.

Table 3.16: System option 2 - Horizontal evacuation, Cavancha

Implementation	Area	Method	Mitigation Measure
Level 2	Peninsula and Playa Casino	Escaping	Evacuation bridge
	Peninsula South	Escaping	Raised infrastructure
	Peninsula South	Escaping	Tactical vertical evacuation - Public
	All Areas	Escaping	Tactical vertical evacuation - Private
	All Areas	Escaping	Regulation for hazardous objects
	Safe zone	Preparation Aftermath	Local logistic centres
	Peninsula South	Preparation Aftermath	Small local logistic centres
Level 3	All areas	Escaping and Preparation Aftermath	Education
			Crisis communication system
			Crisis team
			Hardcopy information and Signs



Figure 3.23: System option 2 - Horizontal evacuation (using bridges), Cavancha

PROPOSED SYSTEM

To be able to select the more suitable option, first the need and possibility of vertical versus horizontal evacuation must be assessed.

The two areas where vertical evacuation might be implemented (see appendix K), the Cavancha Peninsula and the playa Casino, are analysed. There are several criteria that can be of influence. The amount of people present, the time available to evacuate and the flow direction of the water (the progression of the inundation) are essential parameters.

Playa Casino The water reaches the area behind the casino within 10 minutes, granting a short evacuation time for the beach and casino area. Subsequently the water flows in the direction of the roundabout. This causes the area to be partly closed of and only leaves one evacuation route open. This route has a distance of approximately 700 meters from the 20 minute contour ¹, which is very close to the maximum length as discussed in appendix K. An additional difficulty for this particular area is the amount of obstruction near the beach and the casino.

Approximately a 1000 people (see appendix K) need to be evacuated out of this area and there are no high-rise buildings present that can be used as vertical evacuation buildings.

Peninsula This area becomes an island within 20 minutes. At the same time parts of the peninsula are also inundated in 20 minutes. After this time it is not possible to evacuate of the island and an alternative should be introduced. As mentioned in appendix K approximately 1750 people must be evacuated, the area has three high-rise buildings that are in the small inundation free zone of the peninsula and therefore are suitable for vertical evacuation.

As the analyses of the two areas implies, the peninsula has enough capacity to assign (reinforced) buildings for tactical vertical evacuation, making evacuation bridge obsolete. Since, in this system, the possibility of using existing evacuation possibilities is preferred over adding new structures, option 1 is the best option.

¹The 20 minute contour is the edge of the inundated area 20 minutes after the event. This line confines the most immediate danger zone.

ZOFRI

For Zofri there is no need for a new evacuation building. The 20 minute contour is close and therefore easily reachable. The 30 minute contour lies on maximum distance of 1000 meters, this is lower than the maximum allowable length (see appendix K). In figure 3.24 the evacuation routes are indicated. For the mall, the blue area in figure 3.24, the evacuation is slightly different since this area can be very crowded. The maximum distance from an entrance to the 30 minute contour is approximately 500 meter. Even taking into account 10 instead of 8 minutes of 'start up time', this is still safe. An exception is made for the store owners. For them approximately 20 minute 'start time' is assumed, making horizontal evacuation for them undesirable. Therefore it is advised for the store owners to evacuate vertically in the mall ². In table 3.17 the system is represented.

Table 3.17: System C, Zofri

Implementation	Area	Method	Mitigation Measure
Level 2	All areas	Preparation Aftermath	Small local logistic centres
Level 3	All areas	Escaping and Preparation Aftermath	Education Crisis communication system Crisis team Hardcopy information a Signs

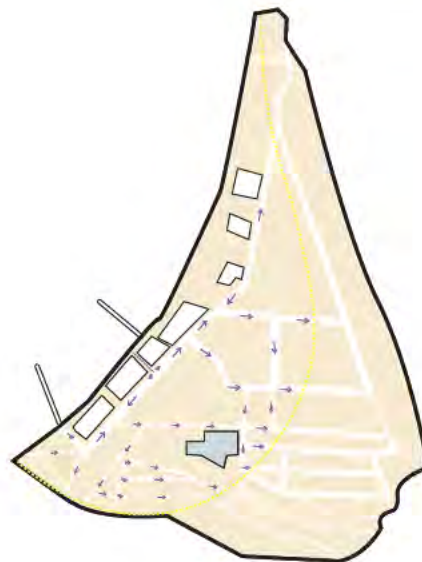


Figure 3.24: System C - Zofri. Evacuation plans.

²For this is not preferred, the people present in the mall will not be given the same advice.

3.6.3. SYSTEM DESIGN

In the previous section, both for Zofri and Cavancha options of mitigation are proposed. In the following section the option for Cavancha will be further elaborated.

In figure 3.25 the complete evacuation plan is shown. In this section the different elements will be discussed to further detail and clarifications on a number of implemented mitigation measures are provided.

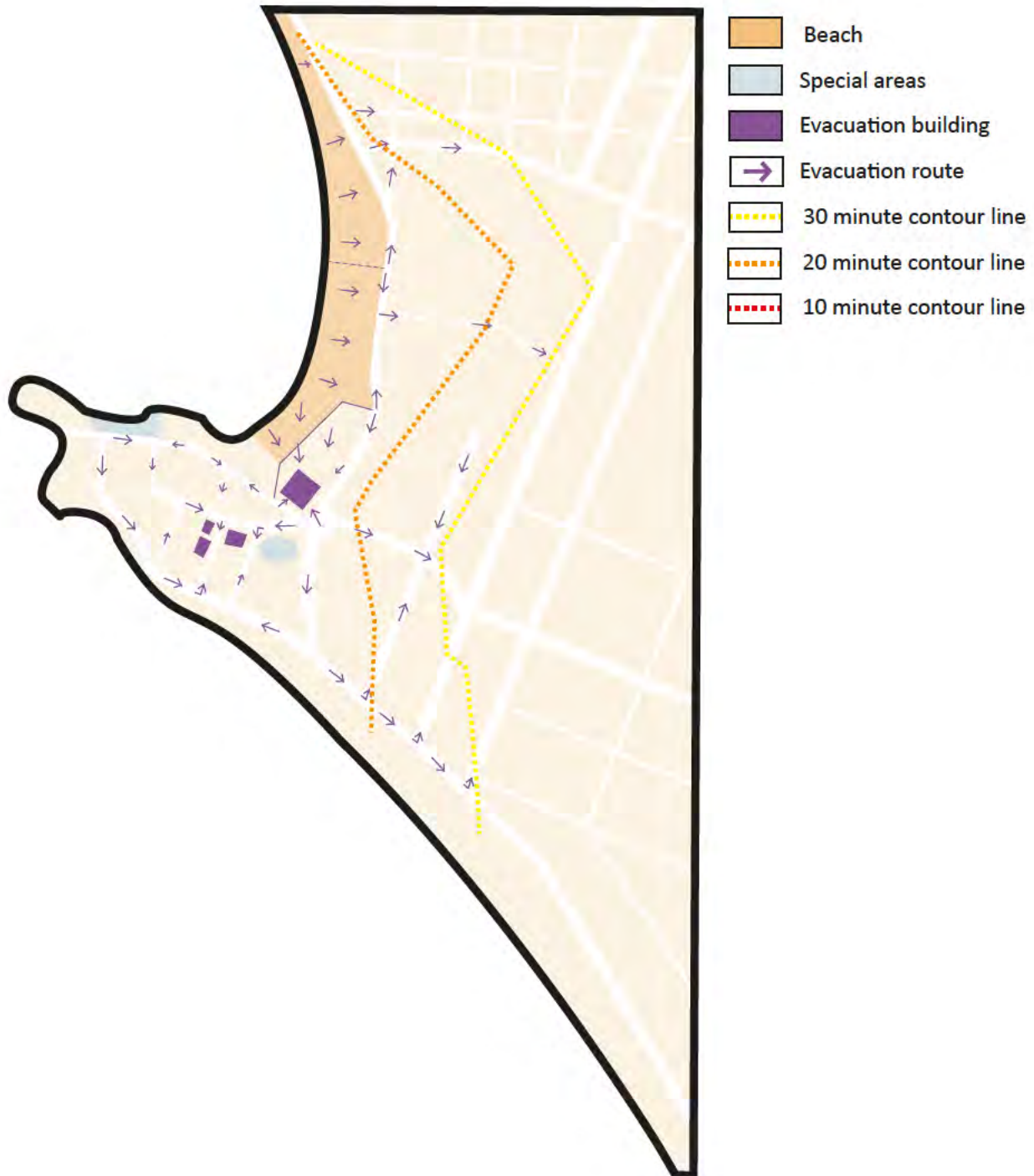


Figure 3.25: System C, Cavancha

LEVEL 1

New evacuation building

As mentioned in appendix K Playa Casino is difficult to evacuate safely, and therefore vertical evacuation is advised. For this a new evacuation building is needed since there is no existing structure that can be used. Currently only one location is suitable. A fallow area next to the casino gives possibility for a new structure. The location is fit for the area it should service, namely the beach and the casino.

To make this building viable it cannot only be used as an evacuation building. There should be an additional use for the building. The design criteria for evacuation must be leading in the design of the building and the needs and desires of the area must be leading in determining the secondary activities.

Design criteria Inundation at this area is maximum 3,8 meters, a safe height for the evacuation area is therefore 5 meter and the evacuation surface area must be 500 m². Next to tsunami forces the building must be able to withstand the earthquake. The latter needs extra attention since the location of the building is not ideal regarding wave and water forces. In order to limit these forces the building will be designed using the Palafita concept, see figure 3.26.

Possibilities for secondary functions There are many possibilities for secondary function, such as a small restaurant on the second floor and a sport field on the ground floor (in figure 3.26 the dimensions of a beach volleyball field are used).

Possibilities local logistic centre implementations The location of interest is not optimal for a large logistic centre. A small logistic centre however is needed for every vertical evacuation building (see small logistic centres below). Therefore when designing this building a storage area should be taken into account.

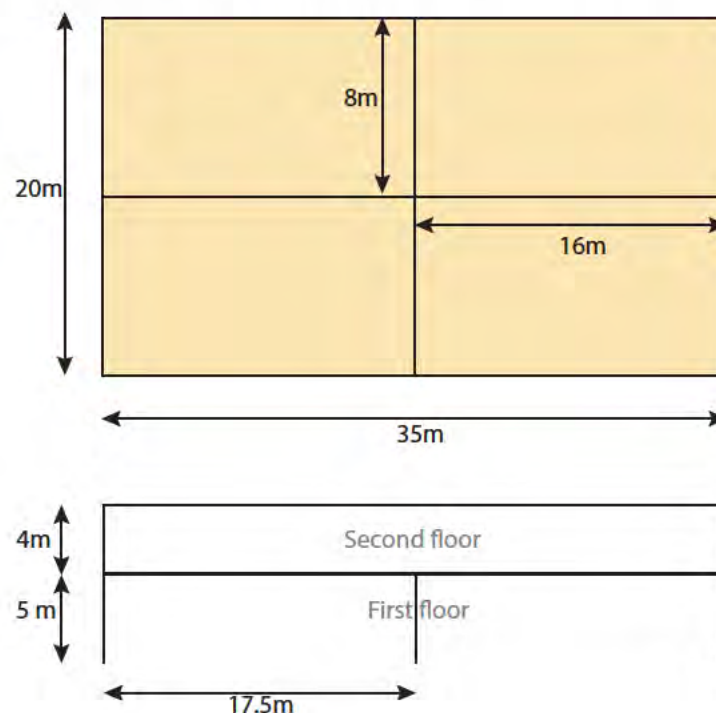


Figure 3.26: Dimension of Palafita evacuation building.

Geotechnical considerations A very conceptual design for the vertical evacuation building is given. Further development of the technical design is considered outside the scope of this research. Nonetheless, a few remarks on the implications of the location can be made for future elaboration of the design.

Since Chile is a very seismic country, the current building regulations are already very apt to ensure a - in seismic terms - safe building. The relevant geotechnical failure modes are captured in table 3.18.

Table 3.18: geotechnical considerations system C

Structure	Element	Main failure modes	Enduced by	Prevention
Vertical evacuation building	Shallow foundation	Piping	Seepage (tsunami)	Deeper foundation
				Preventative reinforcement
		Scour	Erosion (tsunami)	Preventative reinforcement
		Settlement	Seismic forces	Safety factor in design
	Piles	Liquefaction	Sudden shearing of soil in undrained conditions	
		Liquefaction	Sudden shearing of soil in undrained conditions (extreme conditions)	Safety factor in design
		Cracking	Seismic forces	Safety factor in design
		Scour	Erosion (tsunami)	Preventative reinforcement

LEVEL 2

Assigned buildings for vertical evacuation

The public vertical evacuation buildings are on the higher ground of the Cavancha Peninsula. For this location the maximum distance is lower than the maximum allowable distance, these two characteristics make the position of the three high rise buildings optimal.

Assumed is that not only rooftops, but also an extra floor can be used, the three indicated high rise buildings have a surface area of approximately 850 m², this creates sufficient capacity (see appendix K).

Location of logistic centres

Two types of logistic centres are taken into account; small centres with only basic needs and larger ones, that can be used for the weeks after the event.

Small local logistic centres Small centres should be implemented in every area that is cut off from help for several hours, until the threat of new tsunami waves is over. All private vertical evacuation buildings therefore should have their own small storage area with potable water, blankets and first aid kits. For the public vertical evacuation buildings these storages must be larger and checked by authorities.

Large local logistic centres These are located in safe zones for the obvious reason that once inundated their functionality decreases. These centres will be used for coordination in the aftermath, this is coordinated by ONEMI and is already implemented in their evacuation plans.

Regulations for hazardous objects

The essence of this measure is to prevent damage to surrounding properties and obstruction of evacuation routes. To obtain this goal regulations are in place. In many areas parked cars are an issue, for this stricter regulations can be issued. Another hazard are electricity pools. Due to the earthquake and tsunami forces these are prone to block the routes. This may not only cause hazardous obstruction but also fires. Therefore in the inundated area electricity should be relocated, preferably to the subsurface.

LEVEL 3

The following section describes the default concept related to the methods escaping the water and preparing for the aftermath of the event. In the system design sections for system A 3.4.3 and system B 3.5.3 this default concept is already referred to.

When regarding level 3 measures ONEMI is in charge of the regulation and coordination. The structure of their approach is elaborated in appendix D. Almost all the measures are mentioned in their current plan to enhance the coordination of the evacuation and aftermath. In order to emphasize the importance of these measures and due to minor adjustments that must be done (because of changes in the evacuation plans) the measures are mentioned in the option. They are not further elaborated here.

The measures discussed in this level are newly implemented or adjusted mitigation measures.

Default situation for horizontal and vertical evacuation

The default situation for evacuation is the standard manner that is overall applicable, the exceptions to this rule are discussed in the next paragraph. There are two ways to evacuate, horizontal and vertical.

Horizontal To guide horizontal evacuation, clear signs must be in place. Horizontal evacuation will be coordinated by the life guards, police and fire fighters (see appendix D). In figure 3.25 the evacuation routes are indicated, from the 30 minute contour the evacuation maps of ONEMI with small adjustments can be used³.

³ONEMI uses a 20 meter contour line for allocation of the safe zones, the authors use inundation maps as guidelines. Therefore after the 30 minute contour line a medium safe zone is reached. This will be indicated on the signs in this area. The safe zones will remain according to the ONEMI map.

Vertical, public and private Vertical evacuation can be divided in two, public and private. *Public evacuation* is the vertical evacuation for the public, this does not necessary mean that the building assigned for this is public property, the existing vertical evacuation buildings used in this system are privately owned, the new evacuation building will be public property. *Private evacuation* is the default vertical evacuation of going up in the building where one is present. These buildings can be public or private property.

For vertical evacuation the position of a person when the alarm sounds is crucial. At first the private vertical evacuation is discussed, this implies the situation when present in a high rise building. Because of little evacuation time it is advised for everybody in a high rise building to evacuate vertically in the same building to above the fifth floor⁴. The buildings where this is applicable should have a sign and home owners or hotel visitors must be informed. This is a small adjustment on present advise distributed by ONEMI (see appendix D).

The second situation discussed is when following a route that ends in a public vertical evacuation building. The procedure is similar to horizontal evacuation, except that the safe zone is on the higher floors of an evacuation building.

Special cases of horizontal and vertical evacuation

In 3.25, the light blue areas indicate areas where the default evacuation is not acceptable. The area in the North-Peninsula is quickly and heavily inundated. In this area the building present, club Nautica, is not safe to use as a vertical evacuation building and therefore people present here should evacuate horizontal.

The second light blue area indicates a building that may appear suitable, however the roof is not at a safe height and therefore people present in this building are also advised to evacuate horizontal to another vertical evacuation building.

Specific hardcopy information

Important is that hardcopy information is not only available for and focussed on local inhabitants, but aims to inform non-locals (tourists in hotels but also apartment owners that use it as a second house). Ho(s)tels should hand out a informative folder by check-in and apartment owners when buying or subscribing in the municipality.

To be able to inform this target group the folder should contain:

- Evacuation map
- Information on vertical evacuation
- Information on the alarm system
- Information on the evacuation protocol
- Background information on earthquakes and tsunami

An additional use of hardcopy information can be to indicate exceptions to the default system and whether you enter a certified vertical private evacuation building. In other words, when does the default evacuation changes to vertical evacuation for a specific case.

⁴ This is higher than the maximum inundation depth

A new approach for evacuation: signs and color schemes

Signs are used to present information in a clear, self explanatory and unambiguous manner. Items that are important to process in the image on the signs are mentioned in table 3.19. An example design is shown in appendix K. Also the implementation of the color scheme is shown here. This is based on the 20 and 30 minutes contour line from the NEOWAVE model. The safe zones (green) are located on the 20 meter contour line as used by ONEMI (see appendix D).

Table 3.19: Information evacuation signs

For which event	Earthquake Tsunami Fire	Indication of zone	Safe zone Medium safe zone Danger zone
Evacuation mean	Horizontal Vertical	Direction of evacuation route	

The above combination of measures, implemented in various levels, is considered a suitable proposition for a complex solution to mitigate tsunami impact.

3.7. VALIDATION OF THE RESULTS

3.7.1. SYSTEM A

EFFECTIVENESS

The system is designed to retain the maximum wave based on realistic aesthetic implementations. The effect for the worst case scenario is not fully mitigated, however the system is expected to significantly reduce the worst case scenario impact. In order to verify this expectation the level 1 implementations of the system are modelled to see their effect on the impact of the worst case scenario. Based on this model, the effectiveness of the system is estimated. For the reason that level 2 and 3 are not applicable in the model, these levels are not discussed.

Model alterations and expectations

For the validation of the system, the retaining layer is implemented in the grid. The seawall is added as a 5 meter high wall, as concluded feasible. The Dyneema barrier as a wall with an altitude of 20 meters, the reason to do so is that the bag will not allow over topping. In this way the maximum run up can still be obtained. Using this run up, the FEMA guidelines can be verified. The grid is shown in figure 3.27.

Adding the walls will create a situation which is not ideal for a NEOWAVE simulation. This is due to the fact that the model works in its limits and the low inundation values create errors in the simulation. These errors have no effect on the run up against the Dyneema barrier and the over topping value of the seawall. They do effect the spread of the inundation and the flow velocities after over topping the seawall. The model is expected to give good results of the wave in the bay and close to the wall.



Figure 3.27: The implementation of the Dyneema barrier and the seawall in the grid. The contours of the 0, 5 and 10 meters are given in blue green and red respectively.

Results

The results of the model show that inundation is significantly smaller and that the wall is merely over topped by the second and largest wave. The altering of the grid also lead to numerical errors and therefore the final inundation map, and thus corresponding heights, is not realistic. The different aspects of the results will be elaborated. The results are shown at six different moments in time in figure 3.28.

All observations made from the validation results are given in appendix I.5. It is concluded that the system is fully retaining for tsunamis with a modelled run up of less then 3.9 meters. Even though the run up effect in the center of the Dyneema is higher than expected. The run up over topping the wall is slightly lower than expected, therefore the assumed run up is still realistic. The inundation maps following from the over topping of the wall are not reliable. It is observed that the inundation area is different, but numerical errors make the final inundation map unrealistic. The wall is over topped with a maximum of 2.5 meters in the east, it created a delaying effect of 8 minutes.

Concluding, the system is very effective since the worst case scenario inundation is delayed and the majority of scenarios will be fully mitigated. The current bottleneck lays in the east side of the wall where inundation will be the highest.

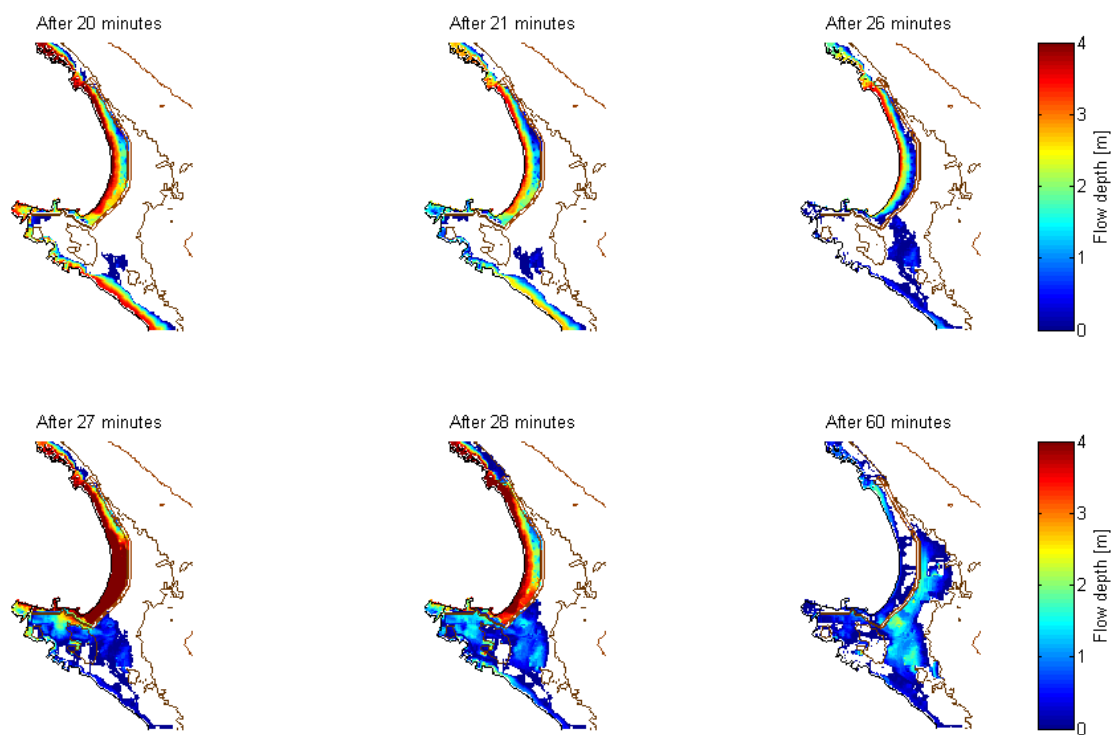


Figure 3.28: The modelled results through time. All figures contain the same flow depth scale and contour lines. The contour lines represent the zero, five and ten meters contours in black, brown and light brown respectively. Minutes 20 and 21 represent the repelled first wave. The minutes 26, 27 and 28 contain the effects of the second wave where overtopping of the wall occurs. The 60th minute shows the evaluated the flood map of the model, here conservation of mass is not properly applied since the minute 28 inundation is the only inundation which arrives in the peninsula. Note that inundation from the first wave from the south occurs, this data is analysed and is a result from the same model errors as the sixtieth minute.

Proposed validation steps

This method is validated using multiple assumptions, some of which must be validated for this system to work. Therefore the extra validation steps necessary for this system are listed. Separating the Dyneema related validation from the seawall.

Dyneema barrier Since the Dyneema technique is currently an unproven concept. A lot of knowledge gaps and uncertainties are related to this solution. The important points of validation are listed:

- How does the earthquake damage correlate to the chance of damaging the floater, the rise of the floater is essential for the system and cannot fail. This is highly related to the design of the floater and should therefore be validated when a full design is made.
- Is the runup behaviour against walls comparable to the Dyneema system, also, the occurrence of other effects.
- A full validation of the behaviour of the Dyneema fabric to all kinds of damage has to be done. Failure of the fabric will cause major damage and is an unacceptable side effect. Hereby taking unexpected object in front and behind the barrier simultaneously.
- Test the tsunami behaviour around the seawall connection. Side effects are highly likely to occur in that area.
- Validate the foundation on all failure modes. The forces of the water are large and therefore multiple failure modes of the soil are possible.

Seawall For the seawall validation of the effects of the worst case scenario are more relevant as well as the run up effects for smaller tsunamis. The necessary validations are listed:

- The inundation in the peninsula is important for evacuation procedures, this data obtained with the current model is not accurate enough. Validation with a different model is therefore advised, in order to quantify the amount of water entering the peninsula. This is also very relevant when looking to the aftermath of the event.
- Run up effects against the wall are difficult to assess due to the non-linear behaviour of the topography. In order to find the maximum retained wave multiple scenarios have to be modelled. This information is very relevant when calculating the effectiveness of the mitigation.
- The forces on the seawall have to be validated. In this research the width of the wall is assumed to be compliant with the trace. However, if the forces turn out to be much higher the width of the wall and foundation will increase.

3.7.2. SYSTEM B

In this section the effectiveness of the proposed system B based on the method of delaying and diverting will be validated. Also several side-effects will be mentioned. To validate the system as a whole, both the breakwater and the integrated channels will first be treated separately. Besides the evaluated validation the main purpose of this section is to give an overview of how the proposed system and compiling elements can be validated even further.

SUBMERGED BREAKWATER

The submerged breakwater is part of the system which aims to delay and divert. The purpose of the submerged breakwater is to reduce the wave height in the bay and in that sense reduce the flow depths and runoff onshore. To validate the effectiveness the submerged breakwater has been modelled with NEOWAVE. The approach and results of this validation are presented in appendix J. The simulation was performed assuming the highest astronomical tide of +0,8 meters.

NEOWAVE simulation of submerged breakwater

The results in the appendix show that the submerged breakwater has the desired effect. The reduction on the wave height in the bay is on average 35% in the first 50 minutes. Also there are no higher waves found inside the bay when the submerged breakwater is applied. The period of the waves with a breakwater correspond to the periods without a breakwater, this gives reason to believe that the results of the validation are reliable. The reduction in the wave height also results in a smaller inundation area. This can be observed on figure J.7 in appendix J. The maximum runoff is decreased with 1,1 meter, to 5,7 meters and the flow depths decreased equally. However it must be mentioned that this is the reduction effect at high tide. At low tide the freeboard will be lower so the reduction on the tsunami wave will increase.

Based on the results of the NEOWAVE simulation also negative side effects can be mentioned. Due to the implementation of the breakwater the water is steered to other locations. This creates extra inundation north of the playa Cavanca compared with the situation before implementing the breakwater. Also some higher flow depths are found at the playa Brava.

Influence wave climate

The influence on the wave climate can not be estimated based on the NEOWAVE model since this model only simulates the tsunami wave and does not take the wind induced waves or the tide into account. To give a first estimation on the transmitted wave height the transmission coefficient K_t can be calculated. This has been explained in appendix J. Based on the parameters corresponding to the proposed design the reduction on the wave height in the bay is varying between 39% and 24% with a freeboard of 2 meters compared to MSL. During low tide the free-board is smaller which will result in a higher reduction and vice versa for high tide.

Side effects

There are several side effects which could occur, some are already mentioned during the design phase. One of them is: higher flow velocities in the bay due to the smaller cross-section at the entrance of the bay. This could lead to more sediment transport in the case of a tsunami. Also hydrodynamic forces and debris forces could increase due to the higher flow velocities. Other side effects are the changes in the natural frequency of the bay due to the changes in the size of the bay. This could have negative side effects on the wave heights in the case of resonance. Also the ecological impact could be mentioned as a possible side effect which is not known yet.

INTEGRATED FLOW CHANNELS

The integrated flow channels aim to store and divert the water to reduce the inundation area in the city. The effectiveness can be validated by using advanced numerical models however a first estimation of the delaying effect can be estimated based on a simple calculation of the change in storage through time. This method has been explained and elaborated in appendix J.

Increase evacuation time

The method used for validation is a simple model based on the change in the required storage according to the inflow and outflow discharge. Taking the tsunami flow velocities and flow depths, the design dimensions of the caissons and some assumptions on the distribution of the water in the network an estimation of the cumulative overflow can be given. When this value is negative the channel is able to discharge the incoming tsunami. When this value is positive the channel will overflow and inundate the city. The time before the cumulative overflow gets positive is the extra time which can be used for evacuation. When looking at the results of the validation it can be mentioned that the integrated flow channels have the desired effect in terms of storing, diverting and delaying. Compared to the system with only a small sea wall the integrated flow channels are able to increase the evacuation time with 7 minutes. Also the cumulative overflow, which is related to the size of the total inundation area behind the Arturo Prat Chacón, is reduced by at least 59%. This is significant more than the reduction by only the submerged breakwater which is at least 23% based on the same method of validation.

Side effects

The small wall will influence both flow depth and flow velocity since it decreases the cross-section. Also when the water will start to flow over the wall, the wall will act like a spill so flow velocities will further increase as long as water can flow freely inside the channel. Another side effect occurs when the channels start to overflow and the inundation area is subject to higher flow velocities. In that case the run-up can be higher depending on the sequence of tsunami waves.

Another side effect to mention is the possibility of sediment inside the channel. Since the tsunami propagated over the beach and contains already a high concentration of sediment the channels can easily fill up with a large amount of sediment. When the sediment is captured by the channels this is beneficial for the city since less sediment is on the street. However the available storage capacity of the channels will be decreased which influences the extra time that is available for evacuation.

Besides the storing and diverting of the tsunami the channels are also used to drain the city after the event. However in the case of a small wall the water is not able to drain over the beach to the sea and has to flow through the channels. When the channels are constipated with sediment the drainage could be a problem.

COMBINED EFFECT

To validate the entire system the most important elements of this system, the submerged breakwater and the integrated flow channels, should be combined. This validation is possible with the same method used for the integrated channels. By using the flow velocities and the inundation depths of the NEOWAVE model with the modified bathymetry the combined effect can easily be validated. The result of the validation gives an estimation of the extra evacuation time that is available in the case the worst case scenario (combined North, Centre, South) would happen during high tide. This method of validation is explained and elaborated in the appendix J.

Delaying effect of the combination

The combined effect on the reduction of the cumulative overflow are 72% and 88% for the two design locations. This can be interpreted as a reduction of the total inundation area behind the Arturo Prat Chacón. It must be mentioned that the drainage of the city over the road is not yet taken into account in this model. This means that the values presented are a conservative estimation. Besides the decrease in maximum cumulative overflow there is an increase in evacuation time of 7 minutes. In the case of the second location this is even extended with another 2 minutes to 9 minutes extra evacuation time.

Influence on other implementation levels

The submerged breakwater and the integrated flow channels are considered to be the most important elements in the case of delaying and diverting however the escaping of the water is almost as important. The elements have to work together to obtain the complex solution. The extra evacuation has a positive effect on the evacuation routes. More evacuation time reduces the necessary capacity of the evacuation routes and makes it possible to leave out some vertical evacuation building which would be necessary in the case of a shorter evacuation times.

The delaying effect of the level 1 and level 2 measures have hardly any effect on the precautions like emergency and logistical centres at the peninsula. Also the regulations for hazardous objects to mitigate debris forces on the level 1 and 2 structures are not influenced by the delaying effect, it is even required to let it function. Reinforcement of existing structures to increase the resilience of the buildings against the water can be downscaled in the case that the expected inundation is reduced. Especially when a combined reduction in the order of 72% is expected the buildings further away from the beach need little reinforcement.

3.7.3. SYSTEM C

EFFECTIVENESS

Validated effectiveness

Validation using experts opinions has been done. The results are a summary of the comments from experts in the field. For the entire conversation see appendix D.

Proposed validation

To be able to validate the whole system several validation proposals are given to validate different parts of the system design.

What effects should be further validated? To evaluate the system different parts can be evaluated separately. From the answers on the following list the overall view of the effectiveness of the system can be generated.

- Are the assumptions on reaching the safety lines feasible?
- Is the hardcopy information adequate for tourists?
- Is the hardcopy information adequate for inhabitants?
- Are the signs clear?
- How do people react on designated safety zones?
- Are people prepared evacuate vertically?
- Are people prepared to evacuate in an orderly manner?

How could this be validated? The evacuation process can be *modelled*, as mention in Mak [31]. However, these models are not particularly made for tsunami evacuation and therefore the differences in the evacuation processes must be investigated before applying such models.

In section 2 different type of *drills* are mentioned, these can be used to assess the ability of people to orderly evacuate. This can be linked to the preparedness of the people in the area and thus to the effectiveness of the information distributed.

Questionnaires can be used to evaluate effect of signs, hard copy information, vertical evacuation reluctance and the impact of zone indication.

4

CONCLUSIONS

4.1. ANSWERING THE SUB-RESEARCH QUESTIONS

In this chapter the sub-research questions as described in chapter 2 will be answered, each question will be evaluated based on the modelled results in chapter 4 and 5. Based on these conclusions, the main research question will be answered.

4.1.1. WHAT AVAILABLE MITIGATION MEASURES ARE SUITABLE FOR THE IQUIQUE REGION?

An elaborate method to obtain a short list of mitigation measures is discussed in chapter 2. This method gives us a list specific for each defined sub-area in Iquique. In the table 4.1, the available and suitable mitigation measures are represented.

Table 4.1: Answer to the first sub-research question of part two: a shortlist of mitigation measures, suitable for the Iquique sub-areas

Mitigation of Choice per Area			
<i>Cavancha</i>	<i>Mitigation measures</i>	<i>Zofri</i>	<i>Mitigation measures</i>
Cavancha North Peninsula	Tsunami breakwater	Coastal zone & industry	Tsunami flood gates
	Tsunami seawall		Tsunami seawall
Cavancha South Peninsula	New vertical evacuation building		Assigned buildings for vertical evacuation
	Assigned buildings for vertical evacuation		Assigned buildings to steer water forces
	Evacuation bridges	Lower Zofri inland	Assigned buildings for vertical evacuation
	Local logistical centres		Assigned buildings to steer water forces
Playa Brava	Raised infrastructures		Evacuation bridges
Playa Casino	Dyneema tsunami barrier	All Areas	Pallafita housing
	New vertical evacuation building		<i>Intergrated flow channels</i>
	Evacuation bridges		Design and adjustment of evacuation routes
	Pallafita housing		Regulation for hazardous objects
	<i>Submerged Tsunami breakwater*</i>		Reinforcement of existing structures
	<i>Tsunami seawall (delaying)*</i>		Education on tsunami risk and course of action
Playa Cavancha	Dyneema tsunami barrier		Implementation of crisis communication system
	<i>Submerged Tsunami breakwater*</i>		Implementation of crisis team to instruct and guide
	<i>Tsunami seawall (delaying)*</i>		Specific hardcopy information and signs

An important conclusion is the note that within concepts of mitigation, additional demands on their properties (e.g. functionality, aesthetic value) can be made in order keep the list complete and true.

4.1.2. WHAT COMPLEX SOLUTIONS OF MITIGATION MEASURES CAN BE PROPOSED FOR THE SEVERELY AFFECTED AREAS?

There are three complex solutions that are design on different methods. The system A, B and C focus on respectively retaining, delaying & diverting and escaping the water. The conclusions per system are given

below.

SYSTEM A

The retaining method of this complex solution is implemented in two ways: full retaining at Cavancha beach using a Dyneema barrier and medium retaining at Cavancha peninsula using a seawall. This system will minimise impact on all the criteria for low to medium scenarios. For the worst case scenario it is designed to minimise the inundation and will additionally cause delaying effects therefore reducing the impact on loss of life and damage criteria. The escaping method is applied in the complex solution which takes failure of the retaining method into account.

SYSTEM B

The delaying method of system B aims to increase evacuation times and thereby reduce the impact on the criteria loss-of-life. Diverting focusses on the reducing flow depths and flow velocities to minimise the economical and material damage. Also diverting aims to prepare for the aftermath since it enhances the water to drain the city during and after the event. The delaying effect is implemented by reducing the wave height in the Cavancha bay by means of a submerged breakwater and temporarily storing the water that is inundation the city with integrated flow channels. The method of diverting is implemented by steering water inside the flow channels with reinforced buildings and a small sea wall in front of the integrated channels. Escaping is obtained by applying assigning vertical evacuation buildings and improving the evacuation protocol.

SYSTEM C

This system focusses on escaping the water and preparing for the aftermath, therefore no structures are build that address the incoming water. In this system the evacuation routes are adjusted to fast inundation, to be able to facilitate a safe evacuation for every area a vertical evacuation buildings has to be implemented. Economical and material damage is not mitigated but the loss of life is. Also, post-event disruption is influenced by implementing a improved system of logistic centers and post-event coordination.

4.1.3. WHAT CAN BE SAID ON THE PROPOSED COMPLEX SOLUTION?

This question is twofold, first the effectiveness per complex solution is discussed followed by the side-effects.

1. What is the effectiveness of the complex solution?

SYSTEM A

The effectiveness of system A can be divided in two situations:

Situation	Methodology	Impact
$R < 3.9m$	Retaining	Minimised
$R > 3.9m$	Retaining + delaying	Less inundation More evacuation time

Form the validation with NEOWAVE it can be concluded that the system is retaining the full wave for tsunamis with a maximum runup of 3.9 meters. In these events the system is very effective, with a small inundation area and no inundation on escape routes. For bigger events the system is overtopped and the effectiveness changes. The inundation is still much smaller and delayed with 8 minutes. Therefore effectiveness is large in the loss of life and damage criteria.

SYSTEM B

The effectiveness of system B relies on the effectiveness of the submerged breakwater in combination with the integrated flow channels and the smaller sea wall. Based on the simulation of the submerged breakwater with NEOWAVE it can be concluded that the submerged breakwater gives a significant reduction on the tsunami wave height of 35% in the first 50 minutes. The maximum wave height decreases from 10,6 to 7,1 meters and due to this reduction the maximum runup at the Cavanha area is decreased from 6,8 meters to 5,7 meters. The validation of the integrated flow channels show a reduction in the cumulative overflow of 68% and 59% for two test locations respectively. This results in a significant reduction of the inundation area since these are related. Also the evacuation time has increased with 7 minutes. This can be considered significant when the time between the earthquake and the arrival of the first wave is approximately 15 minutes.

When combining the small sea wall with both elements it can be concluded that the integrated channels have a larger effect (59% - 68%) on the reduction of the inundated area then the submerged breakwater (23% - 39%). So the integrated flow channels are more effective in terms of loss-of-life and material damage than the submerged breakwater.

Finally the combination of all three elements gives the best reduction effect on the cumulative overflow of 72% and 88% for both locations respectively. It can be concluded that the combination increases the reduction on material damage but does not have a significant increase in the reduction on loss-of-life. Overall it can be concluded that the effectiveness of the proposed design of system B is significant in terms of delaying and diverting.

SYSTEM C

The effectiveness of system C relies heavily on having preformed drills for the practical validation, experts opinions and evacuation modelling for the theoretical validation. Practical and theoretical validation was not possible in the time of the project. The experts opinion has been asked via email however there is no reaction yet.

*2. What are the side effects of the complex solution?***SYSTEM A**

The side effects of this system can be listed as:

Effect	Consequence
Runup	Higher flow depths on Dyneema contour
Runup	High overtopping of the seawall
Overtopping	New inundation scenario for the peninsula
Overtopping	Bathtub effect behind Dyneema barrier

Runup effects are found due to the concave shape of the measures. This causes higher flow depths on the retaining contour. The seawall is also subjected to these run up effects causing high overtopping. This overtopping creates a new inundation scenario at the peninsula and a part of this inundation will get trapped behind the Dyneema barrier.

SYSTEM B

Structures like a submerged breakwater disturb the equilibrium situation and will influence the wave climate and by that sense the sediment transport and the beach topography. Also changes in the natural period of the bay, the flow velocity and the ecological equilibrium could be expected. For the proposed design the reduction on the significant wave height is approximately 39%, this reduces the swell waves of 1,7 meter to 1,0 meter. It can be concluded that this is inconvenient for tourists since the playa Cavanha is a popular surf destination. This has to be optimized in the design.

Side effects concerning the flow channels are less far-reaching however the small wall and the caisson itself do influence the hydrodynamics of the tsunami wave which influences the inflowing discharge in the caissons. Another side effect is the sedimentation inside the channel which will reduce the available capacity of the system. This also affects the draining purpose of the channels.

SYSTEM C

For this system hydraulic side effects are not expected since only one aspect is adjusted; the new evacuation building. Because it is implemented according to the Palafita concept, water forces are not likely to change and thereby inundation will not change. Side effects on the level of escaping the water and preparing for the aftermath are not considered in this research.

4.2. ANSWERING THE MAIN RESEARCH QUESTION

In order to answer the main research question the sub-research questions as composed for Part 1 and Part 2 are answered in the report. To conclude the main research question will be answered in this section. The different criteria as mentioned in the main research question are separately evaluated.

How can the impact of a likely future tsunami on the city of Iquique be reduced with respect to the criteria loss of life, material and economical damage and post-event disruption of society. .

The answer to this question is based on the answers given to the sub-research questions. The impact of a possible future tsunami in the city of Iquique can be reduced by implementing a complex solution based on the proposed framework. This complex solution should contain different methods of mitigation on several levels to fortify the solution and create a resilient system of mitigation. The three complex systems as designed in part 2 are effective and have minimal negative side-effects and can therefore be used to reduce the impact in Iquique.

REDUCTION OF LOSS OF LIFE

For all systems designed this criterion is met. To decrease loss-of-life the human contact with incoming water must be avoided. New evacuation routes and possibilities are implemented in all systems to meet this requirement. For system C this implies a new evacuation structure, for systems A and B the retaining and delaying of the incoming water makes a new structure obsolete since evacuation times are increased.

REDUCTION OF MATERIAL AND ECONOMICAL DAMAGE

Systems A retains tsunamis with a wave 4 meters, which provides a hinterland free of material and economical damage. More severe tsunamis are for greater part and therefore the material and economical damage is reduced. System B delays the water which considerably decreases the material and economical damage. Systems C is not mitigating the incoming water and therefore this system does not reduce material or economical damage.

REDUCTION OF POST-EVENT DISRUPTION OF SOCIETY

In the hours after the event the crisis centres and coordination improvements are crucial, for the weeks after the event the improved coordination of aid is important, accompanied by the reduction of material damage of homes and workplaces. For the months after the event the decrease of the economical and material damage has a profounding roll in the reduction of the disruption of society.

This means that for the hours and weeks after the event all systems are contributing to the reduction of the post-event disruption of society, for the months after the event mainly systems A and B are contributing.

5

DISCUSSION

5.1. INTRODUCTION

In this chapter, the performed research is reviewed. To increase the readability, a division is made between the sub-research questions that have been investigated in the previous chapters. Based on the validated results, the conclusions and the discussion, this report will be concluded with recommendations.

5.2. RESEARCH QUESTIONS

The objective of the research is formulated in the main research question (MRQ). The research is thus set up, that first the input for answering the MRQ is generated (part one). For the second part, three sub-research questions (SRQ) are formulated to guide the designer through the process of answering the MRQ, completing the objective of the research. The main research question implies a designed solution must be proposed. The sub-research questions are therefore set up comparable to the classical iterative design process, in which three steps can be identified; analysis, design and validation of the design (van Doorn [32]). Very important to note is that the classical design process demands iterations, where the SRQ in this report guide the designer to the answer to the MRQ in one iteration.

5.3. IMPACT CRITERIA

The main research question is posed in order to reduce the impact caused by a tsunami. This impact is defined by three criteria, loss of life, occurred damage and the post-disaster disruption within a society. These criteria are formulated without any attaching or specified weight to them. When assessing a complex solution, no difference can be made in the importance of reducing impact on any of these criteria. When a hypothetical solution X is very apt with respect to the first two criteria, but not at all for the third criterion, and solution Z quite apt for all three, solution Z might now be considered the best solution for all three criteria are met. This may not agree with the wishes or ideas of the client. In applying this research method, one must take into account that in selecting the best solution, a choice must be made by the client.

5.4. METHODOLOGY

The process of designing mitigation measures is an iterative one. Once the Main Research Question is posed, subsequent steps, formulated as the SRQ, must be taken to obtain an satisfactory answer. The decisions that are made along the way are guided by a framework. In figure 5.1 a conceptual representation of the design process is given.

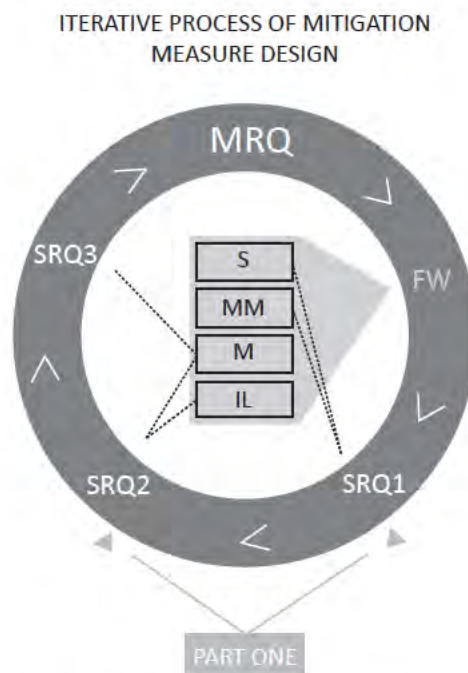


Figure 5.1: In the figure the iterative process of Part Two is represented. The framework and part one are vital elements to complete an iteration. In order to perfect the solution, more iterations might be necessary.

In the following section, elements within the completed process are reviewed.

5.4.1. FRAMEWORK

The framework is developed from various existing calamity frameworks in order to create complete guidance for tsunami mitigation design. The used frameworks address the phase to which the disaster has evolved (*strategies*), techniques that can be applied with respect to the event (*methods*) and the concept of safety ensured on multiple *levels*. The new framework makes use of these elements with some alterations.

The first alteration that is discussed is the addition of a fifth method, the preparation for the aftermath. This can be justified when looking at the third design criterion. Since the solutions will be judged by the reduction of society disruption, it is fair to implement a method that takes this aspect of disaster mitigation into consideration.

The second alteration is less straightforward. The multi layer safety (MLS) approach is developed as a leading mechanism for the design of a solution (Tsimopoulou *et al.* [23]). In this framework, *methods* are used as a guiding principle, and the idea of levels is used to ensure balance within every proposed complex solution, a system.

The authors deem this to be an allowable alteration since new definitions are given. A main concern for this altered framework is that, since the original MLS approach is very well known within mitigation design, the new application may not always be properly deployed. It must be stressed that within this framework, the levels are used for the implementation of selected measures only ¹.

The framework is not yet subjected to an expert opinion and is only tested for this particular research. Therefore, no guarantee for future functionality in a different research project can be given.

¹Some measures are more suited to be implemented in a certain level, therefore, earlier on in the research, the terms are used to categorize mitigation measures.

5.4.2. METHOD OF VALIDATION

Various methods of validation are proposed. Two things can be said on the presented options. First, not all the options are equally realistic for the timespan of the research and the means available. Therefore, elements in the list of methods must be seen as a recommendation for the continued research. An example is the organisation of evacuation drills. This is a very valuable option but could never have been realized within the timespan of the research. Such a drill should be carefully organized in cooperation with the client, in this case the authorities of Iquique and ONEMI. A second observation is that no assessment is made on the aptitude for the method and the value of the obtained validation.

5.4.3. ITERATIONS IN THE DESIGN PROCESS

As mentioned before, the process of designing mitigation measures is an iterative one. Within the scope of this report only one iteration is made. The main reason for this limitation is the time span in which the research had to be performed. The objective of the research can be considered twofold; first to find an answer to the main research question, second to create a precedent for the process of designing tsunami mitigation measures. The research has been set up in such a way that the methodology can be repeated in future research on the subject. In that case multiple design iterations must be performed.

5.5. RESULTS

The results are obtained with aid of the framework and the conclusions of Part One (1. The framework is discussed in the previous section. The input from Part One is in Part Two taken as an absolute truth. Wrongful output and interpretations in Part One will therefore also influence the results of Part Two. A more elaborate analysis on the output of Part One and used models is done in the discussion of Part One 1 and appendix C.

5.5.1. SRQ1: SUITABLE MITIGATION MEASURES FOR IQUIQUE ?

The main objective for SRQ1 is to obtain a selection of mitigation measures that are suitable for Iquique sub-areas. A starting point is developing a large list of available options. Hereto literature and expert opinions are consulted. This list is per definition not complete since new measures are thought of every day. In order to be as complete as possible, concept terms such as breakwater and seawall are used, within which tens of options can be subdivided.

Whether a measure is suitable will always be a somewhat subjective call. In the case of Iquique, many stakeholders can be identified, that are entitled to an opinion on this suitability. The authors have strived to take most angles into consideration by determining the suitability on three main criteria, the necessity for a measure in case of a tsunami, the possibility to implement a certain measure and the desirability of a measure. These criteria are divided into sub-criteria such as amount of inundation, need for protection of a sub-area and the desired aesthetics of a solution to take all opinions into account. These criteria will never completely cover the situation and it is certainly possible to find flaws in the logic of some decisions. The next step in the analysis, the suitability of measures per sub-area, gives the most reason for discussion. Since for each concept term of mitigation, many variants are available, this classification is not immune to subjectivity.

Finally, after cross-referencing the results of the previous two steps, a short list the most apt mitigation per area is found. For each of these steps, no exact quantification is given. The compatibility of two compared elements are rated by the means of low, medium and high aptitude. Objections to this rating system are conceivable. Yet the authors deem this rating system the most appropriate taking into account the assumptions made and ever present risk of bias. It is stressed that this method is not free of subjectivity. The use of the criteria provides a tool for the designer to come to a substantiated short list. Also the criteria-method makes it possible to repeat the selection process for a different area, in Iquique or a different city.

5.5.2. SRQ2: PROPOSED COMPLEX SOLUTIONS

In this section, the process of designing complex systems is discussed. First the process of composing the systems is reviewed. Subsequently the separate systems are reflected upon.

Composing systems of mitigation

The framework is used as a basis for the system composition. Since the objective of the research is to propose a complex solution, the authors chose not to develop a system per method, but search for valuable combinations that give layered solutions. This process has culminated in the systems A, B and C. The question may rise why not the methods of delaying and diverting are considered separately. Working with the obtained short list, combining these two methods in one system seems a logical move. In a future mitigation design, this is not necessarily the case. Therefore the step of creating system combinations is crucial to come to a high quality complex solution for a certain location.

Assessment of the systems

The systems that are designed are not compared nor is preference by the authors formulated. This is a key element for the functionality of the framework. A client should express on forehand their wish to deal with a tsunami in a certain way, with a certain system. Subsequently, the designer can come up with the most adequate complex solution within the system. Since this preference is deemed governing, the systems can not be compared one to one

System input

A critical point in the review of the results is why the design and realisation costs are not taken into account. This may well be crucial information for the feasibility of a measure within a system. As mentioned in the previous section, the choice of system should be made by the client. Within the design, the best possible solution is proposed. In subsequent design iterations, criteria such as costs may be introduced.

SYSTEM A

The discussion points related to the origin of the design of the system are listed. First the mindset of the process is discussed, followed by the specific parts of the system.

Inundated area

The system is designed to retain the tsunami, thereby minimizing the inundated area. This method made many mitigation measures unsuitable. When designing the system for different retaining traces, other solutions will follow. If these measures are not implementable an analysis over a different retaining trace can be made.

Secondary defenses

This system is created with the mindset to retain as much as considered feasible within the design criteria. The consequence is that the system will not fully retain the water. A second line of mitigation measures can be implemented to achieve full retaining. This not applied in this system for three reasons; 1) to see the effectiveness of the single line defence, 2) because no simple solution is present for a second trace and 3) implementing a third structure is not considered realistic.

Other retaining methods

The Dyneema barrier and seawall are used to retain the water. No other options were considered suitable according to the analysis for SRQ1. However the seawall can be fully omitted by integration of the Dyneema on the sea floor or under the streets of the peninsula. This option is not elaborated in this project for the technical implications were too uncertain.

Social feasibility

The solution meets the aesthetic demands (design criteria). But besides aesthetics, the social feasibility of the solution is not taken into account. The authors have too little information to make assumptions in this matter.

Elements of system A

The most controversial elements within system A are briefly reviewed.

The seawall In the current system a solid seawall is implemented. More variants can be considered. Knowing what the local community is willing to accept in order to prevent tsunami damage should be leading in the design and implementation of the wall.

The sea gates The sea gates are not elaborated in the report. The biggest question for these gates is the 'human error factor' allowed when designing these gates. An open gate will cause the entire system to fail. This can not be allowed. The system must be designed so that they always work. Also the seagates can be designed to be invisible in daily life. However, increasing the invisibility might also increase the 'human error factor'.

The Dyneema barrier The diversity of the infrastructure makes a full detailed design time-intensive thus the design is based on a generalized cross section. The concept is only elaborated on the most straightforward implementation method and no alterations to the foundation and bag shape are tested. This method is not ideal for the design of a complex structure. Details in the surroundings are not taken into account as well as possible opportunities to improve the design. Also the discussed social feasibility must be taken into account in the design; the new concept might generate distrust.

SYSTEM B

Design process

The various options for system B are the result of a design process where assumptions and choices had to be made to come to a complex solution. Not all choices are substantiated and should be validated to prove the effectiveness. The various options are compiled from the short list, with limited options to delay and divert.

When talking about a tsunami wave almost all (hydraulic) structures will be able to delay or divert (some of) the water. Their design parameters will determine whether they are effective or not. Many combinations of elements are possible and different solutions can be proposed which are not taken into account yet. Only three viable options are considered and elaborated for system B.

Within the considerations for the three proposed options, the aesthetics and tourist activities at the beach are a large restriction to build new structures along the beach. This has been governing in the choice for the (invisible) submerged breakwater and the integrated flow channels. The implementation of measures on the predefined levels (framework) is an important consideration. When at the three levels a function can be obtained, the system is more resilient. This is the case in the proposed complex solution of system B.

Feasibility

Taking a closer look at the design the feasibility could be discussed. Here a difference is made between the economical and technical feasibility. Both are also depending on the acceptance of the property owners. Since costs are not taken into account it is difficult to elaborate the economical feasibility of the solution. However it can be concluded that the implementation of a submerged breakwater and integrated flow channels will be expensive. In this research, too little information is available to estimate the willingness to invest. Due to the vulnerability of the valuable tourist regions there is reason to believe that the willingness to invest is not lacking. It can at least be concluded that from an economical point of view the method of delaying and diverting is not the most feasible option.

Innovative ideas like integrated flow channels as mitigation measures for tsunamis are not technology proven yet. This makes it difficult to implement these measures. Not only due to the technical difficulties but also due to the acceptance of the local population, especially in combination with the significant investments that are required to construct them.

Alternative options

For a broader perspective on the system, several variations are given. It is possible to change the design of certain elements or replace them with other elements without changing the function of the system as a whole. A submerged caisson breakwater could be implemented instead of the rubble mount submerged breakwater. Both are invisible and able to reduced the wave height. In the case of the caisson it is possible to add a damping effect by making it an active breakwater. This could reduce the waves even further. The same is possible within the design of the integrated flow channels by compiling extra storage areas and pumps to discharge the channels. Other alternatives are the location of the proposed measures, by relocating and validating those locations the most effective solution can be obtained.

SYSTEM C

The results are based on estimation on the amount of people present in an area and the length of evacuation routes. The estimations of the amount of people is of great importance when calculating capacity of horizontal evacuation routes and vertical evacuation area. The length of the evacuation routes is used to decide if a route is feasible or to long and thereby not safe. This estimation must be done with more sophisticated means than are available for this research.

Another uncertainty is the capacity of the evacuation routes. The capacity is assumed to be sufficient, based on estimations. More accurate numbers must be gained.

In the report the willingness of people with respect to vertical evacuate is not taken into account. It is assumed that people will follow and trust the signs and the evacuation routes/buildings. This may not be the case. The authorities should be aware of the willingness, positive or negative, so that the education and even the coordination of the evacuation can address such issues.

For Zofri similar issues are identified. This area is easier to evacuate since less obstacles are present, but the issues addressed above must be taken into account when a more detailed design is made.

5.5.3. SRQ3: EFFECTIVENESS AND SIDE-EFFECTS

In the following section, the validation of the proposed systems is reviewed. The validation is performed in terms of effectiveness and possible occurring side-effects.

Choice of criteria for SRQ

The aim of the research is to propose methods to reduce the impact of the tsunami. Whether a solution is adequate is something the designer must advice on in terms of effectiveness (with respect to the applied mitigation method). Also unexpected side-effects of the solution must be investigated in order not to overlook large negative aspects of a solution. However, the feasibility² of a solution should be assessed by the client. Feasibility can be interpreted in various manners, and to each interpretation a different value can be appointed. Therefore the term is not used to assess the systems within SRQ 3.

²An exception is technical feasibility. This should be accounted for in the design.

SYSTEM A

The validation of entire system is based on a single model. The output is discussed below.

Reliability of the validation method

The NEOWAVE program is reliable for approximating tsunami impact. The downside of this program is that it creates numerical errors around low inundation values. For this reason this program is considered reliable for the run up approximation but is not used for the inundation map. The model generates low values of inundation on the edge of the wall. This is a known side-effect of the model and is not considered consistent with reality.

Run up The effects are assumed to be higher on a wall than on the Dyneema system. Therefore the run up of the wall is considered as the maximum run up. The real behaviour of the Dyneema in relation to run up is unknown.

inundation map The map is altered by the numerical errors of the model. Therefore the final inundation map is not used. The estimations are made using the first minute after the overtopping of the seawall has ended. This gives an approximation but neglects the progress and certainly does not gives a good view of the total inundation.

Substantiated data to conclude effectiveness

For the conclusion of the effectiveness the method is tested with the model. The validation should indicate whether this system retains the water and with that decrease the impact. Considering this definition, one can conclude that the system is effective (even though the final inundation information is not used). This is based on the assumption that the errors in the model create more inundation and therefore the real inundation would be lower than the results of the model. The results of the model are already much lower with respect to the default situation. The effectiveness is thus expected to be higher than the results of this model.

Method to indicate side effects

From the validation two effects have been collected: the overtopping of the wall and the runup effects. Both were expected results of the validation. The model did not gave any extra unexpected results. This is considered a good result because the model did not produce errors in that area of the simulation. For side effects of the inundation procedure another model can be used to check if more effects occur.

Validation gaps

In the current model the Dyneema is considered as a seawall. These two are in reality not comparable since the water behaviour is significantly different. The run up effects, generated with the model, on the Dyneema are debatable. The run up against the Dyneema affects the run up against the seawall. Therefore the Dyneema run up influences the entire scenario.

SYSTEM B

Reliability of validation method

The expected reductions in system B are validated based on the NEOWAVE model and a simple storage capacity model. The results of the NEOWAVE model can be assumed reliable since the time series of the wave inside the bay corresponds with the time series of the simulation without the breakwater. The model used to validate the integrated flow channels is a simple calculation based on the principle of change in storage which uses mainly assumptions for the inflow and outflow discharge. The results of this model only give a first estimation of the effectiveness of the system.

Substances data to conclude effectiveness

The effectiveness of the breakwater is based on data of one time series in the centre of the bay and an overview of the new inundation area. Since the bay is relatively small the assumption that the time series holds for the entire bay is allowed. However it is possible that closer to the shoreline the time series will differ due to shoaling effects.

For the validation of the integrated flow channels the data from only two locations along the tracing is used. Since the data (flow depth and flow velocity) differ in time and place the result of the validation will be limited when only two locations are used. To minimize the impact of this simplification, the locations are the ones with the highest flow depths. This gives reason to believe that these are the worst case locations and the result of the validation gives an overestimation.

Method to indicate side effects

The side effects mentioned in the validation are found by the simulations with NEOWAVE. The results give a good understanding of the impact of the submerged breakwater on the tsunami wave propagation. When the influence of the submerged breakwater on the general wave climate is required, the NEOWAVE model is not sufficient any more. In that case a more advanced and accurate numerical model should be used which takes the different wave directions and the tidal elevation into account.

The channels can not be modelled with NEOWAVE. In the first place it is not possible to add such a hollow structure in the bathymetry, so the side effects can not be obtained. Also it is not possible to obtain side effects from the simplified calculation based the principle of change of storage since this model has already to many assumptions which do not allow any side effects in the first place.

Validation gaps

Both validations on the structures are only applied for the worst case scenario with the highest tide which is defined in part 1. The system is not yet validated for the other possible scenarios or with different tidal ranges. Both could have an impact on the effectiveness of the system.

For the breakwater only the proposed design is validated. Other configurations and other tracings could be modelled as well to see the effectiveness can be improved. Also different values for the freeboard, crest width and stone size can be used to improve the effectiveness of the breakwater. Especially the variation of the freeboard is of great importance to minimize ratio of the reduction of the swell wave over the reduction of the tsunami waves. Another gap in the validation is the possibility of resonance in the bay due to the change of the natural period. Another gap in the validation of the breakwater is the extra inundation at the Playa Brava. More inundation south at the Playa Brava gives reason to believe that the inundation extends further south. This area is not contained in the fifth grid on NEOWAVE, therefore in this stage further research is not possible for this issue.

In the case of the integrated flow channels there are a lot of assumptions in the simplified model which can be identified as gaps in the validation. Such as the influence of the sea wall on the flow velocity and flow depth, the dissipation of energy due to the construction, the flow velocity inside the channel, the influence of the finite volume of the network on the outflow discharge, the drainage over the road to the sea and the sedimentation inside the channel. All aspects are either not taken into account in the model or simplified.

SYSTEM C

For the validation it is of uttermost importance to test the system. This can be done in theory, however the more important method is to perform evacuation drills. This method gives room for unexpected behaviour of human beings, which is very difficult to include in a model. After validation is performed, a verdict can be made on the effectiveness and possible side-effects of the proposed system.

Mainly the scale of the necessary test served as a constraint to the validation process during the research. Experts on the subject have been consulted. However, due to the limited time span of the research, no conclusions have yet been drawn. For future research, more preparations must be made to ensure the validation of evacuation protocols.

5.5.4. ANSWERING THE MAIN RESEARCH QUESTION

As discussed in the first sections of this chapter, the MRQ can be answered after completing the first iteration of the proposed design process. One has to keep in mind that this answer can be improved by performing more iterations. The input of the client with respect to the interpretation of the impact criteria - and their weight - still have to be taken into consideration.

6

RECOMMENDATIONS

6.1. INTRODUCTION

In this chapter recommendations are given that are applicable for all areas and systems that are described in this report. Since all systems are elaborated for the Cavancha area, the recommendation focus on this area and are mentioned for each system. Recommendations concerning the Zofri area are given for all three systems combined. All the topics mentioned can be used to refine the proposed systems or as a starting point for further research.

6.2. ALL SYSTEMS AND AREAS

In general there are a few recommendations that can be applied for all systems, both for the Cavancha and the Zofri area. Most of them are focussed on the improvement of the design and validation.

- **Update short list regularly**

In the beginning of the research a short list is established by using the framework. This is not a static list and should be re-assessed regularly in order to keep it up to date. New mitigation measures are developed and situation may change, in order to have a reliable starting point of your designs phase.

- **Check construction of high rise buildings (vertical evacuation)**

All system make use of vertical evacuation buildings in their complex solution. Before assigning them it must be sure the buildings are able to withstand forces due to seismic loading and the hydraulic loads due to a tsunami.

- **Perform validation methods for all elements**

In this research not all elements have been validated. It is recommended to validate each element in the proposed systems to access whether the systems are feasible or not. Improvements of the validation methods per system or design are given later on.

- **Modelling for specific answers**

Numerical models can be used to answer specific questions that cannot be answered with the NE-OWAVE model. Recommendation for these experiments are given for each system. Alternative models are:

Delft 3D	More detailed information on wave-climate, effectiveness of the de-watering channels, changes in bathymetry
PLAXIS	Ground behaviour and structure - ground interaction
SOBEK	Dimensioning and working of de-watering canals

- **Improve NEOWAVE**

For the numerical analyses with NEOWAVE it is useful to have more detailed information of the inundation and the influence of certain structures. In order to better anticipate the behaviour of water in the city it is recommended to use a higher grid resolution for the structures. These should also be run with the non-hydrostatic assumption which could make a difference when the changes in the topography becomes larger.

- **Physical experiments**

It is recommended to perform physical experiments for the proposed designs. In the case of the sea wall, Dyneema, the submerged breakwater and the integrated flow channels this could be possible to get a better understanding of the involved processes and hydrodynamics. Recommendation for these experiments are given for each system.

- **Perform validation for different earthquake scenarios**

The validations has been performed only for one scenario, to make the validation more solid different earthquake scenarios as described in part 1 should be run and compared to their initial inundation.

6.3. SYSTEM A

In this section the recommendations concerning system A, based on retaining and escaping the water, are specified to the different subjects of its design. The recommendations are mainly focussing on the Dyneema and the sea wall.

6.3.1. SEA WALL

The seawall is overtopped upto 2,5 meters. Therefore a different design of the seawall is recommended. By combining a wall with a Dyneema principle a less visible wall can be obtained with a higher retaining height. The high overtopping occurs in the east side of the peninsula where the most area for implementation is available. Some recommendations of the possible variations are given.

- **Fabric solutions**

These can consist of a small wall with a strong foundation. On top of the wall a high and strong fence. During the tsunami event a fabric can be pulled over the fence to create the wall. These kind of solutions can results into higher walls which are easier to be accepted by the local community.

- **Telescoping solutions**

A different approach is by taking the floating aspect of the Dyneema and implement it in a three layered wall where the middle layer can pop out when the tsunami arrives. This will also create a system which does not reach its retaining height in regular circumstances but can significantly decrease overtopping.

- **Sea gates variations**

For the sea gates the variation types as mentioned above are essential to the implementability of the concept. Research on the implementation of these principles on the required sea gates is therefore coherent for a feasible system.

- **Modelling design**

To get a better understanding of the runup effects against the sea wall and the hydrodynamics during overtopping, the wall should be modelled with a more accurate numerical model. Also physical experiments would be recommended.

6.3.2. DYNEEMA

The Dyneema tsunami seawall is a new concept therefore the recommendations mostly relate to unknown factors in the Dyneema design and the response to the earthquake and tsunami events.

- **Objects in the Dyneema fabric**

The tsunami will breach the beach area and it will catch objects in the Dyneema membrane, these object can be large. The reliability of the fabric may not be compromised by these objects. Objects can also be positioned behind the barrier and the fabric will have to bend around or push away these object, think of parked cars. This can lead to puncture and cutting forces on the membrane. Extensive research on the phenomena is required for safe implementation of the Dyneema fabric.

- **Earthquake impact**

For the floater to rise, open areas have to be available for the water to flow in the foundation and lift the floater along its entire trace. The earthquake forces and displacements can damage the foundation of the floater or block the entrances of the water. Also object can fall over the foundation of the floater preventing it from rising. This factors have to be taken into account when implementing this solution.

- **Bending of the floater**

The foundation follows the altitude of the beach, this creates a slope along the floater. When the water arrives the floater will be lifted out of the lower regions whilst still resting in the upper regions. When the floater is emerged from the foundation it will translate horizontally, creating stresses in the floater since it is not able to extend horizontally in the higher laying regions. This principle has to be investigated when designing the floater.

- **Foundations options**

The foundation force of the cables is the bottleneck of the current design, where a basic foundation principle is implemented. A new foundation can be designed to increase the safety factor of the foundation. It is recommended to use a different type of foundation since the current type alters the beach every ten meters. A detailed study of possible foundations is required to make sure that a decent level of safety is reached.

- **Emerging floater**

The current dimensions fit for a high wave, but does not take the changing area required to rise the floater into account. When the wave is approaching the fabric can extend further backwards than in the fully deployed situation. This extension might require more space. The forces are not maximum at this point but the combination of these forces and potential object can create new scenarios. Analysing this extension and the possible failure mode along this trace is recommended.

- **Aftermath**

What happens after the tsunami occurred, can the Dyneema be restored in the floater? And what are the consequences of the Dyneema floater laying on the beach? For the worst case scenario these consequences should be smaller than the unmitigated consequences. But for small tsunamis the Dyneema might actually cause more trouble than the tsunami. Research of these consequences is necessary for the design of the Dyneema. The floater can be designed to only emerge during significant events.

- **Validation of runup**

In the model the runup effects on the modelled wall are big. If these effects also occur with a Dyneema in this shape the design wave height has to be increased. Research to runup on a Dyneema system can give a more founded design wave height.

- **Numerical validation**

The current scenario is validated with NEOWAVE. In this model errors occur when the inundation reaches low values. In order to get a good approximation of the inundation area, and the effects of the overtopping, a different model must be used for a better estimation.

- **Physical experiments**

Besides validation with a numerical model it is recommended to simulate the Dyneema barrier in combination with a sea wall by performing physical experiments for the Cavancha bay.

6.4. SYSTEM B

This section recommendations concerning the elements proposed for system B based on the conclusion and discussion are presented. Since the submerged breakwater and the integrated flow channels both are designed and validated there are a few special recommendations mentioned for these elements.

6.4.1. SUBMERGED BREAKWATER

The submerged breakwater has been designed and validated for one location and scenario. Recommendations concerning the design and to improve the validation are given.

- **Different configurations**

It is recommended to try different configurations of the submerged breakwater or combinations of several breakwaters to see whether it is possible to find a different tracing or a different design of the cross-section that has more effect on the reduction of the wave in the bay.

- **Optimize freeboard**

By this means the reduction of the swell wave (which are nice for surfers) can be minimized while the breakwater still has a significant effect on the reduction of the tsunami waves. Also other values for the crest width and the stone size could be varied to optimize the design.

- **Resonance phenomena**

Calculate the new natural period of the bay due to the changes in the bathymetry and compare that to the period of the tsunami waves to indicate possible resonance phenomena. In the case of resonance the location of the breakwater should be replaced.

- **Different tidal levels**

Validation with different tidal levels should be taken into account in the case of the submerged breakwater. At lower tides the free-board is smaller which could make the tsunami behave differently.

- **Different locations to obtain data**

Besides different tidal levels also different locations inside the bay should be researched for the effectiveness on the reduction of the tsunami wave. Closer to the shoreline the time series will differ due to the shoaling effects.

- **Reposition the grid**

To be able to observe the influence South of the Playa Brava the Cavancha peninsula should be positioned more in the centre of the NEOWAVE grid.

- **Validate breakwater for the peninsula**

Only the effectiveness of the breakwater combined with the integrated flow channels is validated for the Playa Cavancha. It is recommended to perform the same validation of the breakwater on the inundation of the peninsula since here reinforced buildings are used to steer the water inside the integrated flow channels.

- **Numerical modelling wave climate**

The influence of the submerged breakwater on the wave climate inside the bay can be estimated using an advanced numerical model like Delft3D. This model could also take the sediment transport into account which could give a representation of the changes in the beach topography.

- **Physical experiments**

To get a better understanding of the effectiveness of the submerged breakwater physical experiments could be performed to see how the bay react in the presence of a submerged breakwater. This could be done by simulating the Cavancha peninsula in a wave flume. The experiments could also give information on the influence on the normal wave climate, the sediment transport and the ecological influence.

6.4.2. INTEGRATED FLOW CHANNELS

Also the integrated flow channels has been designed and validated for one location and scenario. Recommendations concerning the design and to improve the validation are given. Also specific recommendation for the improvement of the used model for the validation of the channels are given.

- **Increase storage volume of design**

Increase the available storage by searching for areas that can be used for storage like the foundation of new buildings or parking spaces that can be replaced with caissons. Other possibility is to increase the network of caissons through the city.

- **Increase outflow discharge of design**

The outflow discharge can be increased by adding more outflow cross-sections in the design or adding pumps to drain the channels. However they should be integrated in the design.

- **Slope of the tracing**

If possible it is recommended to place the caissons on a small slope to enhance the spreading through the channels.

- **Numerical modelling**

If a better approximation of the extra evacuation time is required a numerical model which solves the shallow-water-equations like SOBEK or Delft3D can be used. This gives a more detailed understanding of the propagation of the water and the hydrodynamics in the channels. It is also able to indicate side effects that are not earlier discovered.

- **Implement sea wall**

If a numerical model is applied also the small sea wall can be implemented to investigate the influence on the flow depth and flow velocity near the channels. This could assign new side effects.

- **Physical experiments**

Besides numerical modelling it is recommended to perform physical experiments in a wave flume. These could be useful to understand the propagation and distribution of the water through the channels. Also this could indicate unexpected side effects.

IMPROVE STORAGE MODEL

When an advanced numerical model is not available it is also possible to improve the method used for validation in this report. The method applied gives a rough estimation and uses some assumptions, here a few specific recommendations are given which should be taken into account to make the model more accurate.

- **Influence of the sea wall**

The inflow discharge does not take the presence of the wall into account. Both flow depth and flow velocity will be influenced which will influence the discharge. This can be compiled when modifying the bathymetry of the NEOWAVE model and run the model with small wall to obtain better values of the flow depth and flow velocity.

- **Spill effect**

The small sea wall will also act like a spill which increases the flow velocity over the wall even further. The relation between the increasing flow velocity and increasing flow depth due to the tsunami could be interesting to take into account for the discharge.

- **Energy dissipation**

The structure will dissipate energy when the water is flowing inside the channel, this will decrease the flow velocity of the water inside the channel. It is recommended to use a reduction factor on the inflow velocity due to this dissipation.

- **Flow velocity in the channel**

The outflow discharge is mainly depending on the flow velocity in the channel. This value could be estimated using a relation for the local acceleration, advection, pressure gradient and bottom friction. However it is also possible to estimate these values based on physical experiments.

- **Total capacity of the network**

The outflow of the channel assumes an infinite volume where the water can flow towards when it flowed through the cross-sections. Since this volume is limited to the total capacity of the network this should be implemented in the model.

- **Drainage over the streets**

When the cumulative overflow is getting positive this is interpreted as overflow over the streets in the city. The model assumes no other outflow at this point besides the outflow through the channels. However the drainage of the city over the road to the sea should also be taken into account. This also has to relate to the retreating and incoming waves.

- **Divide tracing in sections**

For a more accurate estimation of the critical tracing along the road it is possible to divide this tracing in different sections. For each section the model can be applied. The outflow of one section becomes the inflow of another section. By extending the model for more locations along the tracing an estimation of the extra evacuation time for each section can be given.

- **Take sedimentation in the caissons**

It is possible to take the sedimentation inside the channel due to the tsunami into account this will give a reduction on the available capacity. If this effect is significant this should be considered in the design.

6.4.3. GENERAL RECOMMENDATIONS FOR SYSTEM B

In general there are a few recommendations concerning the overall function of system B.

- **Validate extended beach and steering buildings**

Apply the same validation method with NEOWAVE for the extended beach dunes at the Playa Cavanca and the steering buildings at the North Peninsula. Both can be implemented in the NEOWAVE simulation by modifying the grid, perhaps a smaller grid would be necessary for the buildings. Also new side effects could be observed.

- **Find optimal reduction**

Since system B contains multiple levels with the same methods it is interesting to find the most feasible combination. To do so combinations of all mitigation measures within the system can be made to obtain the highest reduction with the least amount of mitigation measures.

- **Use validation of structures as input for evacuation routes**

The aim of the structures is to increase evacuation times and reduce the inundation depths. The results of the validation should be used as input for the design of the evacuation routes.

6.5. SYSTEM C

Recommendations concerning escaping the water can be applied on all areas, however focus is on the Cavanca peninsula.

- **Adjust function of new evacuation buildings to society**

In order to implement a new evacuation building in an easy and socially accepted manner the needs and wishes of the society must be identified. The function of the building can be adjusted to wishes of society. Especially when implementing in a tourist area like the Cavanca peninsula.

- **Check responsible entities small crisis centres**

There must be a responsible entity for the supply and check of the small crisis centres in the private evacuation buildings. Strict arrangements must be set-up to have these centres in a usable state.

- **Verify available space in evacuation buildings**

There is assumed that public evacuation buildings in the Cavanca peninsula have more area available than the rooftop. This should be verified.

- **Model evacuation routes**

In order to validate the effectiveness of the evacuation routes should be modelled using models described in the validation of system C 3.7.3. However these models should be adjusted for tsunami evacuation. The available evacuation times should be compared with the arrival times of the expected inundation based on the scenario analyses.

- **Improve validation**

Improve the validation of the mitigation measures by means of the methods explained in the validation of system C 3.7.3

6.6. ZOFRI

For the Zofri area no detailed design is made however some recommendations are given based on research in various options of all systems.

- **Raise the embankment**

It is recommended to raise the embankment so the redundancy of the area increases. To retain the water a sea wall is proposed. The seawall is now assumed to cover the entire Zofri embankment. However there is a small area in the south of the embankment where no development is implemented. In this area a raise of the embankment can be more practical. For this small piece of area a different solution should be proposed.

- **Create buffers to delay**

Delaying is proposed by onshore and offshore measures. Onshore it is recommended to create buffers by means of a secondary wall or integrated flow channel. The required size of these buffers can be analysed by the amount of water which will breach the current height of the embankment.

- **Protect oil storage**

In the upper part of Zofri oil is stored. This storage could fail due to earthquake damage. The environmental damage in the Zofri area will be enormous. To conserve this damage a wall can be build around the oil facilities, to prevent the oil from entering the Zofri area.

- **Implement drainage system**

An important aspect of the Zofri area is the bathtub effect as discussed in part 1. It is recommended to implement the function of draining the city, so the method preparing for the aftermath as described in the framework, in the design of the complex solution.

- **Add evacuation routes from Zofri area to the mountain**

The Zofri area has mainly evacuation routes leading more to the center of the city but there are no roads connected to the mountain. It is recommended to add evacuation routes from the Circunvalación towards the mountain to be able to get as fast as possible to higher grounds.

- **Make clear evacuation protocol of Zofri Mall**

It is recommended to give attention to the evacuation protocol of the Zofri mall since the this area has the highest density of people in the area. Besides evacuation routes within the mall and outside are vague and unclear.

6.7. GENERAL RECOMMENDATIONS

General recommendations are given, not specifically for the complex solutions but for the overall processes concerning tsunami mitigation in Chile.

- **Augment acceptance public vertical evacuation (in private buildings)**

In order to implement the solution of public vertical evacuation buildings, using buildings that are privately owned the willingness and awareness must increase. In this way the owners of the buildings are more eager to participate in a vertical evacuation program. On the other hand ONEMI must have more legal options to force owners to open their building for vertical evacuation.

- **Current well functioning mitigation measures, improve and consequently implement**

Chile has experience in mitigation of tsunamis and has developed a number of well functioning mitigation measures. However, these should be improved and consequently implemented.

- **Encourage research for innovative mitigation**

Innovative design of mitigation measures can improve the feasibility regarding the implementation in society.

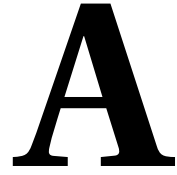
- **Continue research for tsunami (forecast) modelling**

To be able to implemented a suitable solution for tsunami mitigation forecast models are essential. Developing models that have more accuracy is therefore an essential part of mitigation of this natural disaster.

- **Combine multiple mitigation approaches (framework)**

The framework presented in this report enables the user to create unique complex solution of mitigation measures for a location in an effective and sufficient manner. The use of such a framework is advisable when regarding areas with specific requirements and possibilities.

Appendices



RESULTS OF THE SCENARIOS

For the determination of the scenario with the highest impact the proposed scenarios are analysed. In this chapter the proposed scenarios will be ranked on the impact on the city. This ranking will be elaborated according to the differences of the modelled results. In table A.1 the scenarios used in the project are listed with their key parameters.

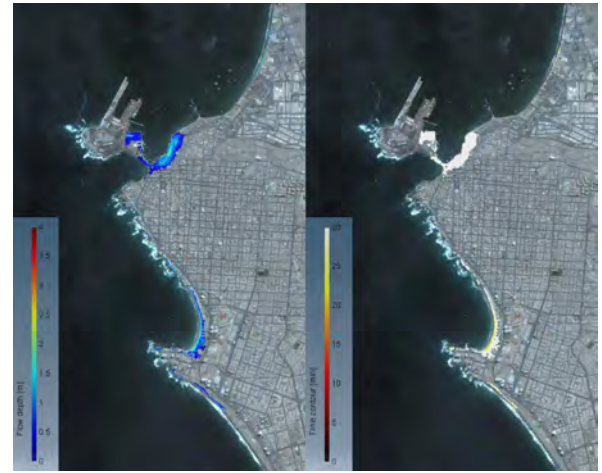
Table A.1: Proposed earthquake scenarios for the Northern seismic gap of Chile

Scenario	Description	Magnitude M_w [-]	Max. co- seismic slip [m]	Mean co- seismic slip [m]	Initial wave height [m]
Scenario 1	8.8 based on Chlieh et al	8,81	7.25	3.20	2,55
Scenario 2	Northern part	8,29	6.59	1.21	1,60
Scenario 3	Southern part	8,51	7.34	3.06	2.14
Scenario 4	Northern + Southern part	8,62	7.34	2.06	2.14
Scenario 5	Centre part (without April '14)	8,45	7.05	2.64	2.07
Scenario 6	Northern + Centre part	8,58	7.05	1.90	2.56
Scenario 7	Southern + Centre part	8,68	7.34	2.96	2.12
Scenario 8	Northern + Centre + Southern	8,75	7.34	2.28	2.53

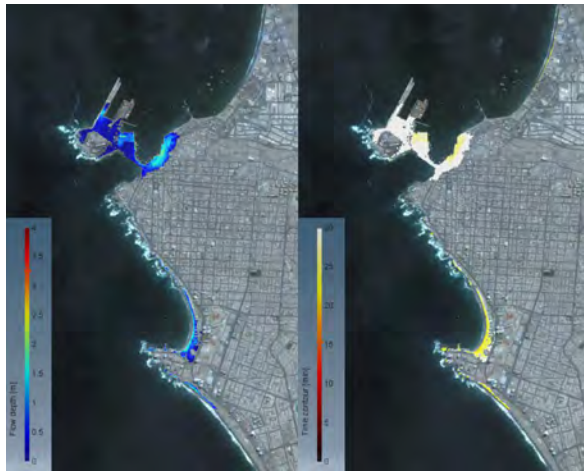
The inundation maps and time contours of this scenario are shown in figures A.1 and A.2. In these figures the left side shows the maximum inundation map and the right side corresponds to the arrival time of the first wave. These figures are used for the elaboration on the ranking of the global impact of the tsunami on Iquique.



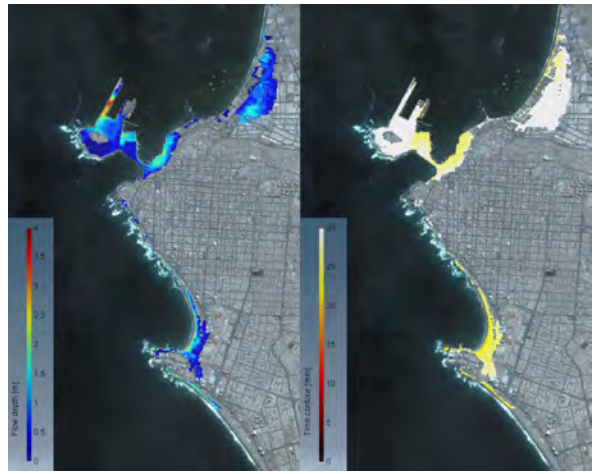
(a) Scenario 1: 8.8 based on Chlieh et al



(b) Scenario 2: Northern part



(c) Scenario 3: Southern part



(d) Scenario 4: Northern + Southern part

Figure A.1: Scenario 1 to 4 of the analysed scenarios. The left sides show the maximum inundation and the right side shows the arrival time of the inundation. The scales on the figures are all equal.

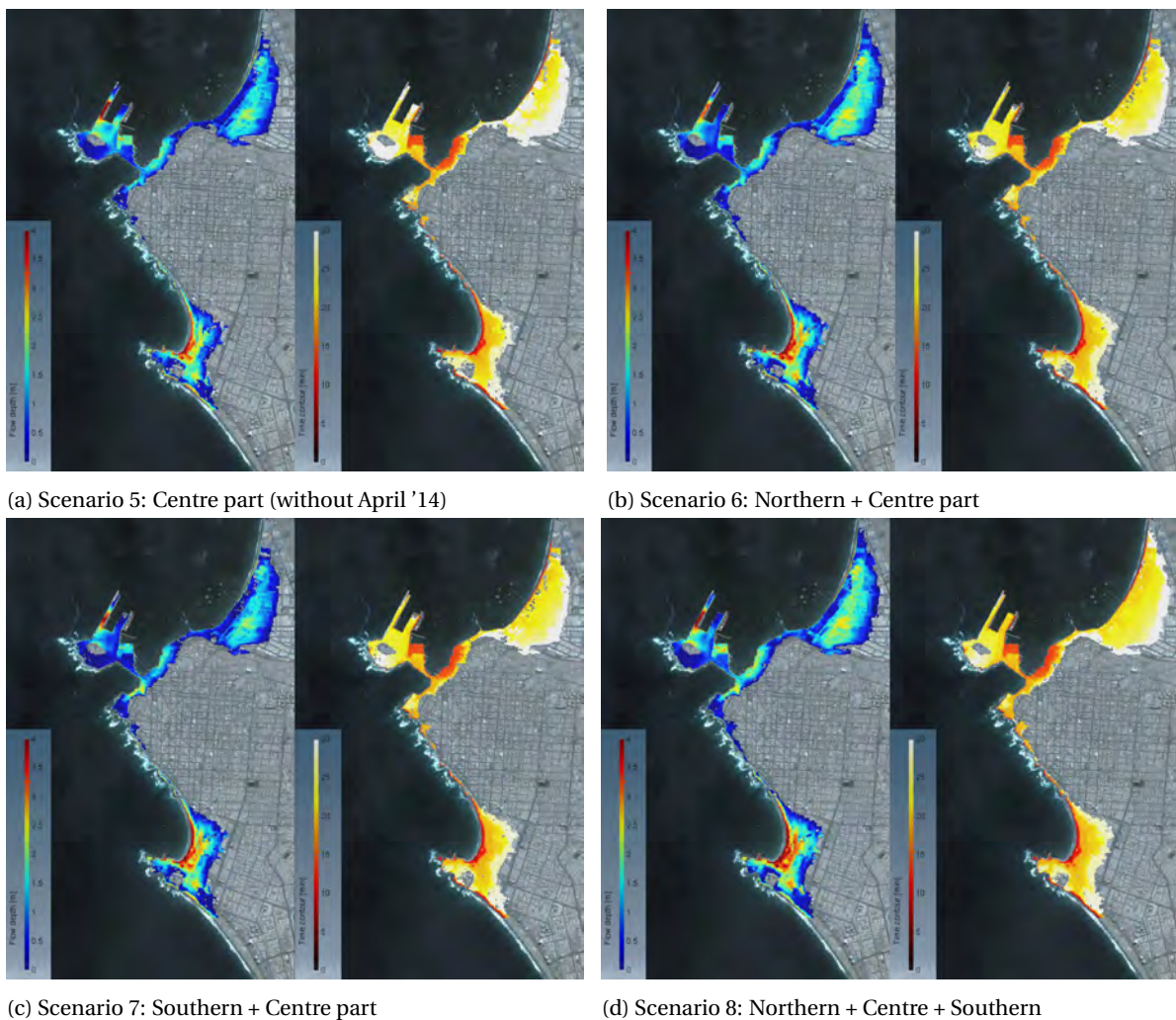


Figure A.2: Scenario 5 to 8 of the analysed scenarios. The left sides show the maximum inundation and the right side shows the arrival time of the inundation. The scales on the figures are all equal.

SCENARIO 2: NORTHERN PART

The northern scenario, figure A.1b, has to lowest global impact on Iquique. In this figure inundation in the harbor area can be identified with a maximum flow depth of 1.5 meters. The Cavancha beach is inundated with maximum 1.5 meters of flow depth which is not enough to reach the road.

SCENARIO 3: SOUTHERN PART

The southern part, figure A.1c, shows more impact than scenario 2. In the port a large area of the piers is inundated and the city side of the port reaches a maximum inundation of 2 meters. The cavancha region looks the same as the second scenario however elevation is slightly higher and the area a bit larger.

SCENARIO 4: NORTHERN + SOUTHERN PART

The northern and southern part, figure A.1d, has a bigger impact than the southern part because of the inundation in the Zofri area. In this scenario the impact on the port and cavancha area is bigger and a new area is inundated, Zofri. The Zofri inundation is reaches by breaching the natural barrier at the lowest point. Here an flow depth of a couple of centimeters is obtained. This causes the model to sea this ground as wet area causing constant head over the Zofri lower laying areas. This error causes a continuous flow from this point to the lower region therefore the total inundation a Zofri grows when no wave is entering the area, this principle will be called the Zofri-error in this chapter.

In Cavancha the inundation also causes a new phenomena. This is called the cut-off it implies that the evacuation route of the peninsula area is inundated. As can be seen in this scenario the roads behind the beach

gets inundated however flow depths are still below the 0.5 meters. And the peninsula is cut-off in 21 minutes with a maximum flow depth of 0.5 meters.

The area of the port inundation also increased and the pier now shows a numerical error as well. The grid at this location is very irregular and this caused an imbalance in the equations. Since this area is not part of this research, as is elaborated in part 1, this error is accepted it does not interfere with the results of the other area. The inundation at the city part of the port is larger and the average flow depth is increased.

SCENARIO 1: 8.8 BASED ON CHLIEH ET AL

In the Chlieh scenario, figure A.1a, the tsunami impact becomes more significant. The Zofri error still occurs only the breaching height is higher, leading to a higher inundation map, but still only one location is breached. The port area now receives a maximum flow depth of 2.5 meters and the streets are now exposed to 2 meters of flow depth. In the Cavancha area the cut-off now occurs with flow depths of 1.5 meters. This implies that the evacuation routes are no longer usable. In the hinterland of the beach area the runup is much higher and the first line of housing is now flooded with 1.5 meters of water.

SCENARIO 5: CENTRE PART (WITHOUT APRIL '14)

The center part scenario, figure A.2a, changes the scale of the impact. The Zofri embankment is overtopped in multiple places, as can be seen in the time contour. The Zofri-error is still significant since the overtopping takes place on a small area where the maximum flow depths are less than 0.5 meters.

For the port the inundation gets smaller whilst the numerical error on the pier is bigger. This error will stay in all scenarios at the same scale and the port inundation also shows no new phenomena, therefore the port will not be mentioned in the next scenarios.

The cavancha region is now severely compromised. With a bigger run up the inundation now reaches 470 meters onshore and the flow depths on the road reaches 2.5 meters. The cut-off of the peninsula now obtains a 2 meter flow depth and continues completely to playa brava. Not only the cut-off occurs at the peninsula also the northern part of the peninsula is significantly inundated.

SCENARIO 7: SOUTHERN + CENTRE PART

This scenario, figure A.2c, has logically more impact than the center part since the source is bigger. In the Zofri area the complete embankment is now overtopped, strangely enough the flow depth over the embankment show lower maxima. Because of the complete overtopping the inundation area shown in Zofri becomes realistic even though the Zofri-error still occurs, the large area where overtopping occurs allows more volume of water to enter Zofri. The flow depth will probably be lower but this is assumed a good design point. For Cavancha a bigger inundation area is obtained and the flow depths are in general 0.5 meters higher which is a significant raise, this does not create any new elements in Cavancha.

SCENARIO 6: NORTHERN + CENTRE PART

The impact difference between this scenario, figure A.2b, and Southern + Centre is relatively small. The biggest difference is that the Zofri embankment receives bigger flow depth creating a more realistic inundation map. In Cavancha the flow depths are around 0.1 meters higher than the previous scenario.

SCENARIO 8: NORTHERN + CENTRE + SOUTHERN

The worst case scenario is defined as the Northern + Centre + Southern, figure A.2d. In this scenario the Zofri area overtopping is higher, when looking at the time contour it can be seen that the waves enters over the complete embankment. The Zofri-error stays but in this scenario the embankment is overtopped multiple times, with flow depths between 0.2 and 1.5 meters. Therefore the error makes the progress of the inundation untraceable but the total volume of inundation is likely. In Cavancha flow depths of 5 meters are observed at the beach and 3 meters on the boulevard road. The cut-off happens in the twentieth minute when the first wave enters the bay. The second wave in the 27th minute the highest wave comes in creating between 2 and 2.5 meters of flow depth over the cut-off.

This is a summary of the impact of this scenario, the detailed analysis of the impact of this scenario is extensively treated in part 1.

B

COASTAL AREAS IN IQUIQUE

The coastal city Iquique has several important coastal areas which should be taken into account when analysing the impact of the tsunamis. Here the most important coastal area up and till the 10 m contour are mentioned from North to South, see figureB.1.

1. Zofri

In the North of Iquique the tax free zone (Zona Franca Iquique or Zofri) is located. With over 200 hectares of industrial and commercial space, there are well over 1600 companies based. The area was established in 1975 and has seen explosive growth thanks to the ideal location and huge interest of China and the US. Sales have more than doubled from 1889 million dollars in 2005, to 4411 million dollars in 2012 (Besserve [33]). The top three selling products are combustibles & lubricants, automotive parts and electronic components of which 45% of the sales are abroad. Due to the explosive growth unemployment dropped from 15% in 1975 to 7% nowadays.

2. Coastal area north of the port

South of Zofri and hinter the port we find the more central and old part of Iquique. This area contains for example one of the main squares (Plaza Prat), the Municipal Theatre and the Parroquia Cathedral. Besides the cultural down-town there are a few newer buildings along the coastline like the municipality. Furthermore there is a navy base situated here along the coastline next to an exact replica of the Esmeralda, a battleship of the pacific war in 1879.

3. Port

The port of Iquique (approximately 600 workers) is Chile's fifth-largest port and handled 244,565 TEU in 2013 (Bonney [34]). Due to the trading in the tax free Zofri area the port is of great importance for the economics of Iquique. Also the agreement between Chile and Bolivia to ship Bolivian exports through this port makes it an important harbour for Chile. Besides there are plans to expand the port for larger ships that will transit the bigger locks build in the Panama Canal. The expansion also includes extending the terminal's berth by 280 feet, dredging the 38-foot-deep berth to 45 feet, and acquisition of cargo-handling equipment like two super-post-Panamax cranes.

4. Coastal area south of the Port

Between the Port and the Cavancha area a large residential area is situated. Here several hostels, museums and houses are situated. The shore is divided by the road that connects the Port to the Southern part of Iquique and the national highway 1.

5. Beach North of Cavancha, Playa Cavancha

The beach north of the Cavancha peninsula is well known for its good conditions for practising outdoor and sport activities, like surfing and swimming. It is the largest beach in the city, it has well maintained walking area, is surrounded by modern urban architecture and is popular by the tourist and home owners of the Cavancha area.

6. Cavancha peninsula

The Cavancha peninsula with its grand hotels, casino, club nautico and adjacent sand beaches is the touristic hart of Iquique. In this area approximately 18.000 people are present in the high season, roughly consisting out of tourist, home owners and exploiters of restaurants and shops.

7. Urban area

This is a more residential area containing several hotels, a library and universities.

8. Beach South of Cavancha, Playa Brava

On the southern shore of Cavancha another large sand beach is situated. The beach is less cultivated then the Northern beach (5). Right behind the beach a road divides the beach from apartment buildings and housing area (7).

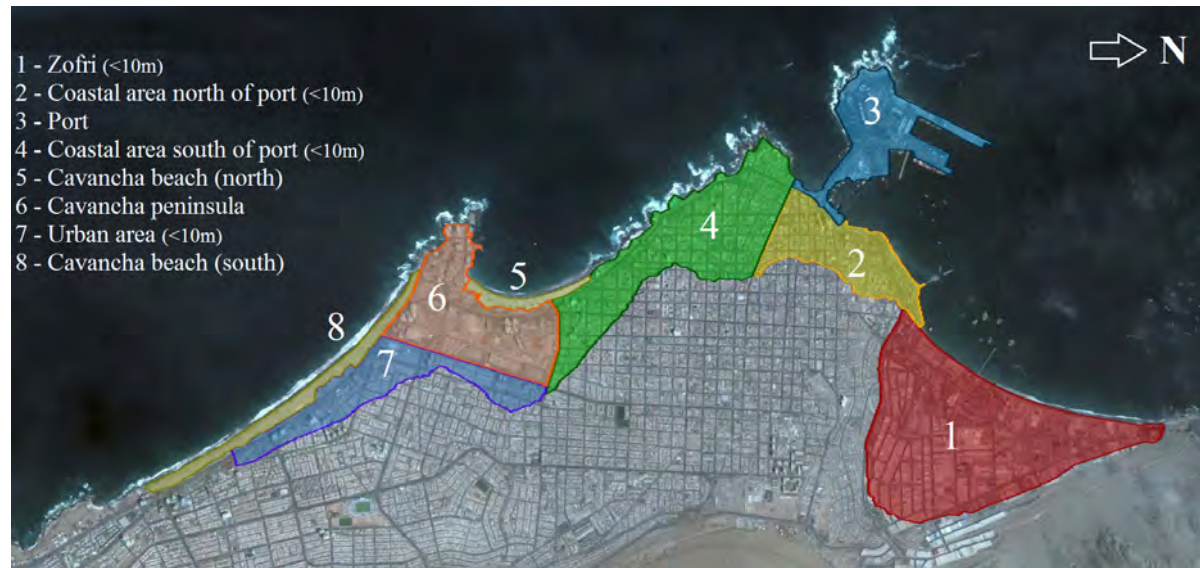


Figure B.1: Overview of the most important coastal areas in Iquique.

C

NEOWAVE METHOD

In this appendix the NEOWAVE model is explained. In the first section the equations and used numerical methods are summarised. in the second part a validation of this model based on the April 2014 Iquique earthquake is given.

C.1. THE NEOWAVE MODEL

NEOWAVE stands for Non-hydrostatic Evolution of Ocean WAVE and is created by Yoshiki Yamazaki from the University of Hawaii(Yamazaki *et al.* [35, 36]). The model is designed for tsunami waves and combines the earthquake dimensions with water propagation. In this section the governing equations and numerical schemes used by the model are summarised followed by the input parameters grid definitions and outputs.

WAVE EQUATIONS

For tsunami propagation shallow water wave equations can be used. The shallow water wave equations are valid when the ratio of the water depth (d) over the wave length (L) is very small. Tsunamis waves have a wavelength of in the order of 100 kilometres and propagate in a water depth of a few kilometres, therefore the shallow water wave equations are valid for this part of the ocean. This model also uses a constant approach for the velocity gradient, this means that no decrease of velocity is taken into account around the sea floor, this is called depth-integration. The full name of the used equations becomes: Depth-integrated non-hydrostatic equations, considering of weakly wave dispersion through non-hydrostatic pressure. In this research the non-hydrostatic approach is compared to the hydrostatic approach to see the differences of the modelled output. The expected difference is small, when this is validated computation time can be reduced by using the hydrostatic equations. The non-hydrostatic equations of NEOWAVE(Yamazaki *et al.* [35, 36]) are:

$$\frac{\delta U}{\delta t} + U \frac{\delta U}{\delta y} + V \frac{\delta U}{\delta y} = -g \frac{\delta \xi}{\delta x} - \frac{1}{2} \frac{\delta q}{\delta x} - \frac{1}{2} \frac{q}{D} \frac{\delta}{\delta x} (\zeta - h + \eta) - F \quad (C.1)$$

$$\frac{\delta V}{\delta t} + U \frac{\delta V}{\delta x} + V \frac{\delta V}{\delta y} = -g \frac{\delta \xi}{\delta y} - \frac{1}{2} \frac{\delta q}{\delta y} - \frac{1}{2} \frac{q}{D} \frac{\delta}{\delta y} (\zeta - h + \eta) - F \quad (C.2)$$

$$\frac{\delta W}{\delta t} = \frac{q}{D} \quad (C.3)$$

$$\frac{\delta(\zeta - \eta)}{\delta t} + \frac{\delta(UD)}{\delta x} + \frac{\delta(VD)}{\delta x} = 0 \quad (C.4)$$

$$F = f \frac{U\sqrt{U^2 + V^2}}{D} \quad (C.5)$$

Where C.1 is the momentum equation for the x direction, C.2 is the momentum equation for y direction, C.3 is the momentum equation for z direction, C.4 stands for the continuity equation and C.5 is the friction term of the momentum equations. In the hydrostatic approach the terms of q are neglected to save computational time, in this project the hydrostatic solution turned out comparable to the non-hydrostatic solution.

NUMERICAL SCHEMES

The numerical simulation is based on a semi-implicit finite difference model. The model is semi-implicit because the non-hydrostatic solution is found with an implicit method and the hydrostatic equations are solved with an explicit model. In the model a momentum conserved advection scheme is applied. These methods are implemented with two-way grid-nesting.

MODEL PARAMETERS

NEOWAVE can handle a maximum of five grids. For the simulations these five grids are used, with a first grid which covers the complete north of Chile until the fifth grid which has a grid size 10 meters. The model uses a manning roughness coefficient of $n = 0.025$, this value is characteristic for ocean floors. No difference in roughness is taken into account in this model .

Besides the grid an earthquake source is required, this source can either be a uniform model or a finite element model. In all the scenarios of this project a finite element source is used. NEOWAVE uses the properties of the earthquake to calculate the corresponding earth displacement. For this the formulation of Okada is used (Okada [37]). The scenarios are designed by seismologists and are based on historical data and tectonic plate properties. The important properties will be supplied in the explanation of the scenarios.

Grid data For the simulation multiple grid configurations are used. For the general analysis a grid with a finest resolution of 10 meters is used. The grids are compiled from different sources. The small resolution grids, 1 and 2, are generated with GEBCO 08 [38], the medium resolution grids, 3 and 4, are built from nautical charts and different topography sources and the high resolution grid 5 is obtained by LIDAR data.

C.2. VALIDATION OF THE MODEL

For the validation of the NEOWAVE model the April 2014 earthquake offshore Iquique is simulated using the proposed scenario by CHAO(Chao *et al.* [39]). The results of this model are verified with known buoy data from the region. This comparison is shown in figure C.1, this figure shows a good comparison of the model with the data especially in the first 2 hours of the event. These comparisons are often made with different models and different source inputs. The NEOWAVE model has been validated for multiple historic events. The 1960 and 1987 earthquake are evaluated in Aranguiz [40], Aranguiz *et al.* [41]. From this is concluded that NEOWAVE is a decent model for tsunami modelling.

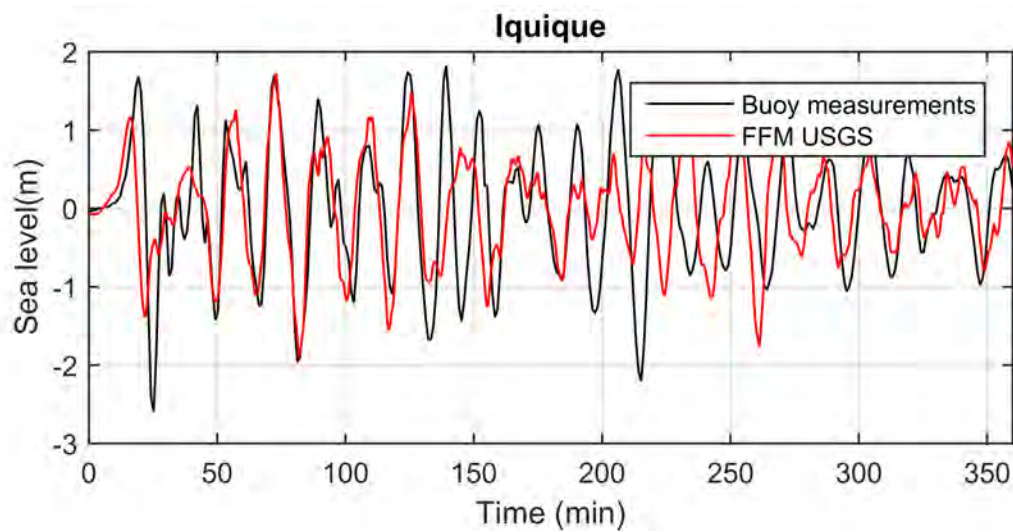


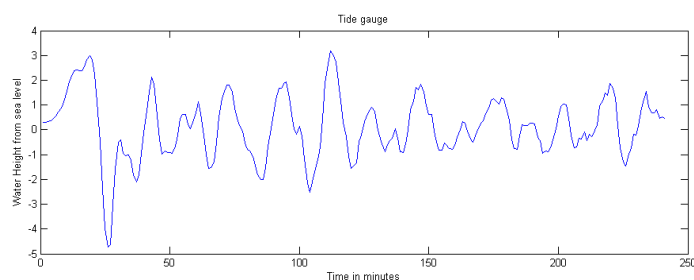
Figure C.1: Comparison of the wave buoy data with the numerical model of NEOWAVE for the April 2014 Iquique earthquake

C.3. IDENTIFIED ERRORS

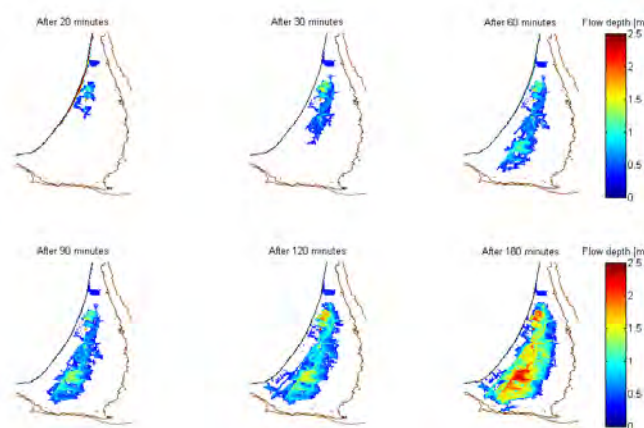
During the project the NEOWAVE model generated numerical errors are found in the results of the scenarios. There were two types of errors which will be elaborated in this section.

CONTINUOUS FLOW

This error occurred in the majority of the scenarios and lead to different interpretation of the results. It consist of a grid point where the water level is just above than the topography, small flow depth, therefore creating a flow towards a lower laying grid point. The volume of this flow is not subtracted from the flow depth. This causes a flow where the mass balance is no longer maintained. This effect is exemplified with an old version of the Chlieh scenario where the effect is clear. In figure C.2a the tide gauge from the Zofri bay is shown in this plot two significant waves are identified around the 20th and 115th minute only these waves overtop the Zofri embankment. The development of the inundation area can be seen in figure C.2b, where it is clear that the inundation level grows significantly from the 30th to 60th minute when no wave overtops the embankment. It can also be seen by the increasing flow depth that the mass balance is off and water is created in this area. This effects plays a large part in the impact analysis.



(a) Tide gauge in the Zofri bay



(b) Inundation through time in the Zofri area

Figure C.2: The old Chlieh scenario data for the exemplification of the numerical error.

GRID INTERPRETATION

A smaller error occurred in the port area of Zofri. Here a very steep rise in bathymetry causes the model to create very local peaks of the water level, likely due to exaggerated shoaling effects. Grid alterations can be made to minimise this effect. Since the port was not part of the project scope and this error does not effect any other area in the model these alterations were not necessary.

D

ONEMI AND FIELD SURVEY

In order to get a better understanding of the area of Iquique a field survey was conducted on 28-29 December 2014. Adjacent to this, a meeting with the ministry of ONEMI has given an inside in the management of emergencies and the structure of the ONEMI evacuation and coordination plans. In this appendix interviews from a beach survey and a summary of the meeting with ONEMI as well as a short explanation on the structure of ONEMI will be noted.

D.1. ONEMI

ONEMI is the ministry of internal affairs of Chile. ONEMI has a sub-office in Iquique with 14 employees. Among other things ONEMI Iquique is responsible for the preparation for and coordination during an emergency. This means that they are in charge when a tsunami occurs, the time in between is used to improve there emergency and awareness plans. ONEMI Iquique works in 11 groups, these groups have their own leader and task, they are coordinated by ONEMI. The 11 groups are; ONEMI, Health service, Environment, Energy, MOP, Education, ITT, Governments, Armed Forces, Justice and Humanitarian aid. In the meeting several knowledge gaps per group identified by ONEMI are explained. Most of these are not within the scope of our research, the knowledge gaps that are important and fall within the scope of our research are summarized in the report. Below first a few comments of ONEMI are mentioned, after this the minutes of the meeting on 30 December 2014 are added.

Opinions ONEMI

A stressed point is the appreciation of the open view on sea and the accessibility of the beach. Changing the current situation regarding this will encounter severe resistance of the inhabitation.

Also, regarding building tsunami mitigation structures on private areas ONEMI has no authority. ONEMI has started talking to owners in Cavancha and Zofri to have more cooperation and to be able to, in Cavancha, use high-rise buildings for evacuation and in Zofri to reinforce structures that are on private property. There are plans to legally strengthen the position of ONEMI.

Internal issues of ONEMI to address

1. Lack of staff in administration and management during the emergency
Not enough staff present to coordinate the emergency plan and the different entities
2. Regional entities did not follow duties and responsibilities as stated in the regional emergency plan
Lfires/rescue operations where addressed, not the bigger picture of the emergency plan. One reason was the lack of coordination
3. Means for communication were inadequate
Absence of radio system, satellite phones and communication plans between different entities

4. Lack of knowledge of documentation needed to request aid from Santiago central government
To be able to request for aid from Santiago certain documents are needed, there was no knowledge present on what documents and how to complete these
5. Mutual aid and resource at community level was inadequate
There was no cooperation between communities in the region
6. Participation of volunteers and local inhabitants was not organized optimal (addressing humanitarian aid)
Different humanitarian groups overlapped in their actions, which resulted in certain groups receiving double aid and some no aid

Issues to address per group

1. Damage and needs assessment
 - (a) Lack of knowledge of mayors
 - (b) Communication systems
2. Health service
 - (a) Emergency vehicles couldn't move through the streets
 - (b) Emergency plans for clinics where unclear
3. Firefighting and other rescue operations
 - (a) Uncoordinated processes for firefighting and rescue operations
4. Electricity and fuel
 - (a) Within the basic service, drinking water was not included
5. Critical infrastructure
 - (a) Overloaded mobile phone network
6. Shelters
 - (a) Shelters did not fulfill minimal need for the situations
 - (b) Insufficient management of the shelters
7. Transport and telecommunication
 - (a) Absent communication plan
8. Communication
 - (a) Poor availability of information and poor management of this poor information
9. Humanitarian aid
 - (a) Lack of commitment of leader volunteers
 - (b) Duplicate delivery of humanitarian assistance to affected
 - (c) Late information about the actual amount needed emergency housing in the region
 - (d) Emergency situations identified for the region

D.2. FIELD SURVEY

In order to get a better understanding of the area and the tourists in this area there has been a field survey in which we interviewed tourists and lifeguards and adjacent to this we analysed the area. The conducted interviews can be read below.

D.2.1. INTERVIEWS

LIFEGUARDS IN FUNCTION; CAVANCHA BEACH

How is the evacuation of the Cavanca beach organized?

On the beach are few signs, how do people know where to go and how are they alarmed that a tsunami is coming?

Routes in the streets are well defined and people of Iquique know where to go from the beach, this means there are no signs needed on the beach. Also, it is our task to evacuate people in the water and on the beach to the evacuation routes.

The people are alarmed via alarms on the buildings next to the beach. The alarm consists of lights and a voice repeating in Spanish and English to evacuate, I don't remember the exact words. There are also emergency teams, but these will be summoned at the moment of a tsunami, these will be later near the beach, we are part of this team and will help to evacuate the beach.

What entity is in control of what element of the evacuation?

The police, fireman and lifeguards (including jetski owners) all have a task.

Fireman are in charge of traffic control. *Police* guide the evacuation in the city. People are forced out of their cars, evacuation by car is not allowed since this will cause accidents and congestions. *Lifeguards* are in charge of beach evacuation. We will go in the water until knee deep, sign everybody out of the water and jetskies are helping to evacuate the deeper water.

The navy also participates where needed. Their main tasks is the early alarm, they will alert the lifeguards and evacuation teams.

Are lifeguards special trained for the tsunami event?

Yes, in the training there is also training for this kind of events. Also lifeguard to lifeguards knowledge is shared. *What was your experience with the tsunami of April 2010?*

We were both there. It was only a small tsunami and the system worked as it supposed to. Within 10-15 minutes the beach was evacuated. *What is your feeling of structural implementations on the beach?*

No structures at the beach, it should remain a natural beach. The view and accessibility is important to the inhabitants of Iquique. *Do you think extra tsunami warning signs are needed?* The local people don't want to talk about tsunami hazards. They already learn about it in school and are not really willing to talk al think about the consequences of a tsunami. They don't care about signs on the beach, there used to be sign but some people of the tourist industry complained and now they are removed. *How is the education concerning tsunami evacuation organized in Iquique?*

In 2005 there has been an inland earthquake that caused a lot of damage in Iquique. After this event education programs in both primary as secondary schools. The hazards of tsunamis and earthquakes are learned in schools and evacuation plans are thought. The people living in Iquique know how to evacuate and what to do. There is no education or awareness program for tourist visiting Iquique.

Figure D.1: Life guard lookout post



INTERVIEW TOURISTS; CAVANCHA BEACH

Interview 1

Where are from?

Belgium, two girls *Do you know that you are in a tsunami hazard zone?*

Yes, locals have told us *Do you know what to do in case of a tsunami?*

Run to higher grounds *Did you receive any information about tsunamis and evacuation?*

We did not get any information, we saw some signs that indicated hazard zones and evacuation routes. *Would you like to have more information about tsunamis and the evacuation plans?*

More information would be nice, it would be good to know what to do. It wouldn't scare us away, just make us aware. *Did you knew in advance that Iquique was a tsunami hazard zone?*

We didn't know, but it would not have influenced our decision to book this.

Interview 2

Where are from?

England and Australia *Do you know that you are in a tsunami hazard zone?*

Yes, we saw the signs. *Do you know what to do in case of a tsunami?*

Run to higher grounds. *Did you receive any information about tsunamis and evacuation?*

No, nothing. *Would you like to have more information about tsunamis and the evacuation plans?*

Yes, it would be nice to get some information at our hostel. It wouldn't scare us. *Did you knew in advance that Iquique was a tsunami hazard zone?*

No, but it wouldn't have effected this vacation.

E

APPENDIX QUANTITATIVE AREA ANALYSES

In this appendix the area division for Cavancha and Zofri will be discussed, this will be the basis of the further function analyses and the population estimation.

E.1. AREA DIVISION

When assessing Cavancha and Zofri in further detail it becomes apparent that within these areas differences in topographic and urban planning, user function, evacuation possibilities and inundation time/depth/direction. For this reason the authors divided the areas in sub areas, see figure E.1.

E.1.1. CAVANCHA

In Cavancha 5 areas have been divided (see E.1a. In table E.1 the different areas with their own specifics is shown.

Table E.1: The five sub areas in Cavancha with their characteristics

1	Cavancha North peninsula	An area with a rock coastline, hotels and few restaurants/bars
2	Cavancha South peninsula	A similar coastline as 1, the area consists of high-rise buildings, both apartments as hotels. In the middle some low-rise buildings and a church is placed. The main function is living in this area.
3	Playa Brava	A sand beach where swimming is not possible ¹ , the hinterland has mainly low-rise buildings with only a few exceptions
4	Playa Cavancha	A touristic sand beach where surfing and sunning are popular, the hinterland consists of hotels, bar/restaurants and touristic attractions such as a park, swimming pool, small zoo, etc..
5	Playa Casino	The beach in this area is less occupied than in 4, this area consists mainly of touristic attractions and a large roundabout/infrastructure. The surrounding buildings are high-rise.

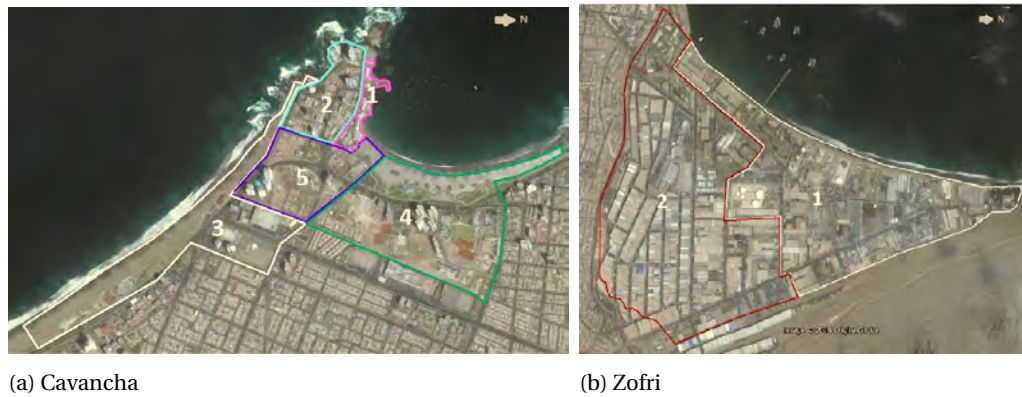


Figure E.1: Sub-areas Cavancha

E.1.2. ZOFRI

For Zofri the dividing of the areas resulted in two sub-areas. In table E.2 this is further elaborated.

Table E.2: The two sub areas in Zofri with their characteristics

1	Coastal Zone	The coastal zone consists mainly of industry and storage for lubricants and combustibles. The coastline consist of a small wall that separates the factories from the sea.
2	Lower Zofri inland	In this areas there is housing and a mall where due to the tax-free zone mostly electronics are sold.

E.2. POPULATION

An estimation has been made by the authors in accordance with the local authorities on the amount of people present in the area in high season. For this the amount of high/rise buildings, the amount of residential areas and the occupation of the beach are taking into account. For Zofri also the amount of people in the Zofri mall has great impact on the people present in the Zofri inland. In the Cavancha area approximately 18.000 people are present, for the Zofri area this is about 30.000. In tables E.3a and E.3b the counting per sub area is added.

Table E.3: Amount of people

(a) Cavancha

Quantitative Area Analysis		
#	Areas	People in area (high season)
1	Cavancha North peninsula	2000
2	Canvancha South peninsula	6500
3	Playa Brava	600
4	Playa Cavancha	5000
5	Playa Casino	5000

(b) Zofri

Quantitative Area Analysis		
#	Areas	People in area (high season)
1	Coastal zone	2000
2	Lower Zofri inland	25000

E.3. FUNCTION ANALYSES

In order to assess the different areas several functions are defined, these functions are evaluated per sub-area of Cavancha and Zofri, this is done in matrix form. Below the different functions are mentioned and shortly explained.

Beach	<i>The presence of a beach</i>
Hotels	<i>The amount of hotels present</i>
Bar / Restaurants	<i>The amount of bars and restaurants present</i>
Historical Value	<i>The presence of historical important buildings or structures</i>
Residences	<i>Residential area, mainly consisting of local people</i>
Environmental Hazard	<i>The storage of hazardous substances</i>
Topographical and urban planning constraints	<i>What are the constraints in terms of urban planning, space available and topographical features</i>
People present in area	<i>Amount of people present in high season</i>

E.3.1. CAVANCHA

For the area of Cavancha the result of the analysis are shown in table E.4.

Quantitative Area Analysis		Functions							
#	Areas	Beach	Hotels	Bar / Restaurants	Residences	Environmental hazard	Historical value	Topographical / Urban planning constraints	People in area (high season)
1	Cavancha North peninsula		+	+	-	-	-	/	/
2	Cavancha South peninsula		/	/	+	-	-	-	/
3	Playa Brava	+	-	-	/	-	-	+	-
4	Playa Cavancha	+	+	/	/	-	/	/	+
5	Playa Casino	/	-	-	-	-	-	/	+

+	High
/	Medium
-	Low

Table E.4: Importance of function per defined area, Cavancha

E.3.2. ZOFRI

For the area of Zofri the result of the analysis are shown in table E.5.

Quantitative Area Analysis		Functions							
#	Areas	Beach	Hotels	Bar / Restaurants	Residences	Environmental hazard	Historical value	Topographical / Urban planning constraints	People in area (high season)
1	Coastal zone				-	+		-	-
2	Lower Zofri inland			+	/	/		-	+

+	High
/	Medium
-	Low

Table E.5: Importance of function per defined area, Zofri

F

DESIGN CRITERIA

F.1. DESIGN CRITERIA

The design criteria are developed in order to objectively obtain a shortlist of suitable mitigation measures per subdivided area. In this appendix these criteria are elaborated and justified. In the actual only the outcome of the analysis is shown. The criteria can be categorised by their nature and objectivity. The first category is the necessity of a mitigation measure at a certain location. If there is no direct reason, should measures be taken? The next category refers to the possibility of implementing a certain measure. When building conditions are not ideal, it might be wise not to construct large structures. The last category is the most qualitative and concerns the desirability of a mitigation measure. Civil objections to a structure or other type of measure can be ground for local authorities to waive an option. An attempt has been made to list such possible objections.

In this section, the authors have chosen not to include any financial criteria. At this stage, too limited an information is available to make proper judgements on this topic. In the chapter Discussion of Part Two of this research, mention is made of possible financial and investment related implications.

NECESSITY

Inundation due to the tsunami This is one of the most important criteria. Characteristics of the inundated area are guiding criteria when it comes to designing mitigation measures. In Part One, the Iquique region is analysed and for the various sub areas the inundation height is determined. This information is roughly translated to the classifications high, medium and low importance. Low importance goes for areas within the analysed region that are not inundated. Since this does not necessarily mean that people will not have to evacuate, the importance level is not set to zero.

Protection hinterland necessary This criterion is introduced to help estimate the importance of mitigation measures. If wasteland is inundated, there might not be an immediate necessity to protect it. In order to better assess the need of protection, some divisions are made.

Dense population If an area within the hazard zone is densely populated, the first impact criterion that becomes relevant is loss of life. Many lives are at risk that need protection. An additional issue is that evacuation of densely populated areas may prove more difficult and time consuming. Also the other impact criteria are affected, since many homes might be damaged and the civil resilience after the hazard decreased. The input for this criterion has been obtained by the authors via a quantitative area analysis in accordance with local authorities.

Significant economic value An additional motive for protection of an area is the presence of property and businesses with high economic value for the area. The assessment of the economic value of the hinterland is done by analysing the main functions in the areas.

Historic value The presence of landmarks and other locations with historic value can be a reason to take extra protective measures in an area.

Area's of historic value can be determined using a functionality analysis.

Limit environmental damage Iquique has industrial zones that, in the case of a combined earthquake and tsunami event, can cause significant environmental damage. The presence of such institutions can be a reason to implement additional mitigation measures.

POSSIBILITY

After one has established the need to implement mitigation measures in an area, the second thing to consider what is possible. In this section, some constraints are listed.

Constraint topography and urban planning Which mitigation measures are appropriate for a region depends on factors such as climate, topography and urban planning. Whether such constraints are relevant for a sub area can strongly influence the type of mitigation measures suitable.

Public function Whether a certain area has a public function or is private property can be a constraint with regard to the implementation of mitigation measures. This can be determined in a quantitative area analysis.

Unobstructed evacuation A mitigation measure, aimed to keep the water away from the city, may also form an obstruction for people fleeing the water. What level of obstruction is allowable can be considered a constraint.

DESIRABILITY

As discussed before, the desirability of a certain measure in a sub area cannot easily be quantified. The assumptions made in this section are based on conversations with UNEMI and local people as well as the opinion of the authors.

Required accessibility Iquique is a city that makes much use of the coastal area. Whether this coastal zone and beach should be kept accessible for all users is considered of high value.

Required aesthetics As every city, the city of Iquique knows more and less well presented area's. The level required aesthetics per neighbourhood can influence one's choice of mitigation measures.

Unobstructed viewlines 'Iquique citizens want to be able to see the beach.' This simple statement, put forward by an ONEMI official, covers a large part of the local opinion on any structure along the coastline. This notion can be taken into account when assembling a combination of measures for the beach area's.

On- and offshore (tourist) activities Iquique has a busy beach life, both on and off the shore, that attracts many tourists and locals. Cavancha beach is a popular surf location. The implementation of mitigation measures might negatively affect these activities.

G

COMING TO THE SHORTLIST

QUALITATIVE AREA ANALYSIS

In this analysis, the design criteria are evaluated for each sub-area. The rating is based on the quantitative analysis and conversations with local authorities. The background information can be found in the appendix ?? and ??. The definition of the design criteria can be found in appendix F.

CORRELATION MITIGATION MEASURES AND CRITERIA

In this analysis an estimation has been made on the aptitude of a mitigation measure for a certain criterion. Often a criterion is not considered relevant for a measure, in which case the rating *no relevance* is given. The authors have attempted to make an objective estimation by consulting literature on the various measures and local opinions. The result is represented in figure G.2.

An example: a seawall is suitable to retain water and is therefore considered apt to deal with inundation. However, the accessibility of the beach and unobstructed viewlines probably will be diminished. For these criteria, the aptitude is low.

CORRELATION MITIGATION MEASURES AND AREAS

Based on the previous two analyses the aptitude of the mitigation measures per sub-area can be backcalculated.

An example of the logic is given: In the case of Cavanha beach, the criteria of necessity and desirability are considered highly relevant G.1. For both these criteria, the mitigation measure of the dyneema tsunami barrier is rated with a high aptitude G.2. Therefore in figure G.3 the dyneema barrier is considered a highly suitable solution for the Playa Cavanha area.

For other examples, the assessment is not as straight forward. In that case the authors have made a judgement call.

The results of the analysis can be found in figure G.3.

Figure G.1: For each area the relevance of a design criterion can be determined.

Figure G.1: For each area the relevance of a design criterion can be determined.

Correlation mitigation measures and Criteria											
Strategy	Mitigation measure's	Necessity			Possibility		Desirability				
		Performance in case of inundation	Protection Hinterland	Limit Environmental Damage	Constraints topography & urban planning	Private property	Unobstructed Evacuation	On- and offshore (tourist) activities	Required Accessibility	Required Aesthetics	Required Unobstructed Viewlines
Reduce exposure	Dikes and embankments										
	Dyneema tsunami barrier										
	New vertical evacuation building										
	Offshore vegetation barrier										
	Onshore vegetation barrier										
	Tsunami breakwater										
	Tsunami flood gates										
	Tsunami seawall										
	Assigned reinforced buildings for tactical vertical evacuation to steer water forces										
	Evacuation bridges										
	Integrated flow channels										
	Pallafita housing										
	Raised infrastructures										
	Design and adjustment of evacuation routes										
	Local logistical centres										
Reduce vulnerability	Regulation for hazardous objects										
	Reinforcement of existing structures										
	Education on tsunami risk and course of action										
	Implementation of crisis communication system										
	Implementation of crisis team to instruct and guide										
	Specific hardcopy information and signs										
	First level of implementation										
	Second level of implementation										
	Third level of implementation										

Figure G.2: For each mitigation measure the aptitude with respect to the design criteria can be rated.

Correlation Mitigation Measures and Areas		Sub area in the Cavancha Area					Sub area in the Zofri Area	
Strategy	Mitigation measure's	Cavancha North Peninsula	Cavancha South Peninsula*	Playa Brava *	Playa Casino	Playa Cavancha	Coastal zone & Industry	Lower Zofri inland
Reduce exposure	Dikes and embankments							
	Dyneema tsunami barrier							
	New vertical evacuation building							
	Offshore vegetation barrier							
	Onshore vegetation barrier							
	Onshore breakwater							
	Tsunami flood gates							
	Tsunami seawall							
	Assigned reinforced buildings for tactical vertical evacuation to steer water forces							
	Evacuation bridges							
	Integrated flow channels							
	Pallafita housing							
	Raised infrastructures							
	Design and adjustment of evacuation routes							
Reduce vulnerability	Local logistical centres							
	Regulation for hazardous objects							
	Reinforcement of existing structures							
	Education on tsunami risk and course of action							
	Implementation of crisis communication system							
	Implementation of crisis team to instruct and guide							
	Specific hardcopy information and signs							

* many measures are thought to have low relevance due to the lack of (high) inundation

First level of implementation
Second level of implementation
Third level of implementation

High aptitude
Medium aptitude
Low aptitude
No relevance

Figure G.3: For each mitigation measure the aptitude with respect to the sub-areas can be rated.

H

APPENDIX: MITIGATION MEASURES

In part two a list of mitigation measures is compiled. This list consists out of words which represent principles of mitigation. These words have various interpretation possibilities. In order to clarify what they mean in this project this appendix will present the projects point of view. All mitigation measures can be used widely and most of them are multifunctional. This point of view is important for the mitigation analysis and therefore the lists main objective is to be able to label everything which comes to mind. And to generalise these ideas and their functions. The mitigation measures are divided with the multilayer safety approach. According to this division they will be elaborated.

H.1. LEVEL ONE MITIGATIONS

The level one mitigations: adding structural measures to the current situation. This measures are elaborated below.

DIKES AND EMBANKMENTS

In this project dikes and embankments are captured under one heading, this heading represents the general idea of man made elevations independent of size, location and construction type. This mitigation measure can be designed for two purposes: to hold back the tsunami wave or the delay the water. The main difference lays in the height of the dike/embankment.

DYNEEMA TSUNAMI BARRIER

The Dyneema tsunami barrier is a new technology. It consist of three main elements: a floater, a fabric 'bag' and the foundation. When a tsunami arrives the elevated water level will raise the floater. At the bottom of the floater the fabric is attached to retain the flowing water. The floater is designed so that the buoyancy force will exceed the downward force of the tension from the fabric bag. The system will be anchored to the foundation on the sea bottom with cables to prevent it from floating away. This is the basic principle of the Dyneema barrier is shown in figure [H.1](#).

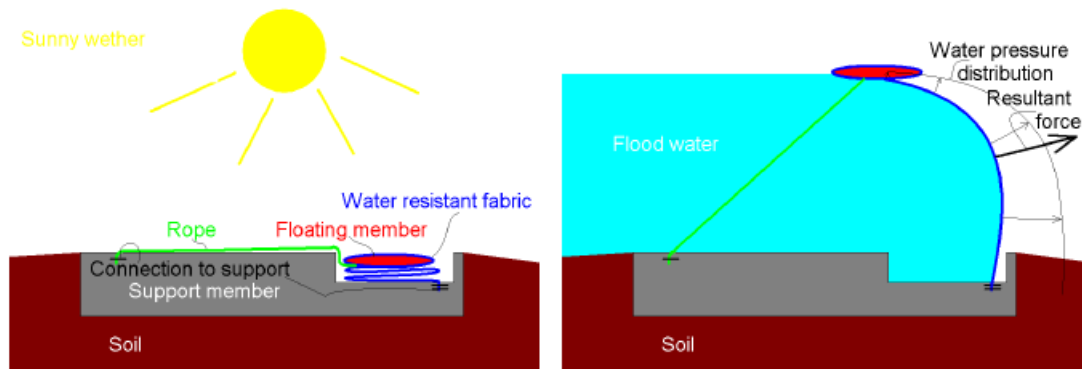


Figure H.1: The principle behind the Dyneema tsunami barrier, where on the left side a sketch of the stored situation is shown and at the right side a sketch during a tsunami event.

NEW VERTICAL EVACUATION BUILDINGS

New buildings with the purpose of vertical evacuation can be designed if the current infrastructure does not allow vertical evacuation or if the capacity is insufficient. This can be combined with other public functions in order to make the design more attractive.

NATURAL BARRIERS

Vegetation can be used to increase the resistance of the coast. This can be done onshore, by the use of forests. Offshore with coral reefs for example. Or in between, mangroves. These barriers will dissipate energy of the tsunami which will lead to less run up and smaller flow velocities.

TSUNAMI BREAKWATERS

A tsunami breakwater is considered an offshore construction which reduces the area through which the tsunami can enter a bay and thereby reducing the tsunami energy in the bay. Two main types of tsunami breakwaters are considered: submerged and emerged breakwaters. Both are able to retain or delay the tsunami depending on their design criteria and the positioning. When applying the structure the influence on the coastal area has to be taken into account since it will influence the wave climate and thereby the sediment transport.

TSUNAMI FLOODGATES

Tsunami floodgates are gates can be used to close pathways for tsunami propagation. They can be used to prevent the tsunami to reach certain vulnerable areas. These gates are not considered stand alone but are used in combination with a tsunami seawall or other elevations, where the gates can be used to keep the possibility of roads and rivers through the elevation.

TSUNAMI SEAWALL

A tsunami seawall is a hard structure build to withstand the tsunami wave. In this project the seawall is interpreted as a hard structure with the function of raising the elevation but can contain multiple purposes. Also it does not have to be able to exceed the height of a worst-case tsunami but can also be used the reduce the tsunami impact and arrival time in the hinterland. Disadvantage of the sea wall is the obstruction in view which is in most vulnerable coastal area a large restriction.

LOCAL LOGISTICAL CENTRES

Whenever to tsunami strikes the damage will cause a lot op people to temporary loose their basic needs of life. In order to manage this loss a logistical center can provide these basic needs. So that everybody who is severely compromised by the damage has enough supplies to survive the period of chaos.

H.2. LEVEL TWO MITIGATIONS

The level two mitigations: adjusting structures in the current situation. These measures are elaborated below.

ASSIGN REINFORCED BUILDINGS

Failure of buildings creates more damage in every criteria. Therefore knowledge on the available buildings, especially how they react on tsunami forces, in the hazardous areas is crucial for mitigation design. By reinforcing buildings on tactical locations this damage can be prevented. The assignment of reinforced buildings can be used for mitigation in two ways: for vertical evacuation and for steering the water forces.

FOR TACTICAL VERTICAL EVACUATION

When the expected inundated area is large it might not be desirable to evacuate everyone in that case vertical evacuation is a very effective mitigation measure. For these scenarios reinforced buildings on tactical locations can be identified as mitigation measure.

TO STEER WATER

The forces on buildings generated by tsunamis are in general large since the flow velocity and flow depths are large as well. By analysing the first line of buildings the impact of a tsunami wave on buildings can be omitted. By steering the tsunami forces away from the weak spots the overall damage can be controlled. This method can also be used to reduce the amount of rubble in the tsunami in order to decrease debris forces. This will also contribute to the reduction in economical damage as well as loss of life.

EVACUATION BRIDGES

Because people have the urge to run when a tsunami risk is real a pedestrian bridge is a good way of guiding the crowd to higher grounds. This is particularly effective when an evacuation route will be flooded. A pedestrian bridge is already a common object in Chile and will therefore not only have a tsunami mitigation aim. This is a level 2 mitigation measure because the implementation will be used to improve an evacuation route.

INTEGRATED FLOW CHANNELS

With integrated flow channels the initial elevation of water can be diverted. By creating large channels underneath the current infrastructure small tsunamis can be captured and bigger tsunamis will be delayed. By implementing this measure over the boulevard of a city large storage areas can be created without changing anything to the current infrastructure of the city.

PALLAFITA HOUSING

In Chile the term pallafita is used to identify a structure with an empty ground floor. This principle is used during the rebuilding process of tsunami damage. When a tsunami strikes these houses will only be damaged when the inundation reached the second floor. This is a very effective way to prevent damage to personal belongings. However this does not mean that the inhabitants of the pallafita house should not evacuate.

RAISED INFRASTRUCTURES

By building infrastructure on an elevated level the tsunami hazard can be mitigated. A lot of different options are available, providing different functions. For example, the boulevard around a beach can be elevated so that the people leaving the beach through this boulevard have more time to evacuate.

REGULATION FOR HAZARDOUS OBJECTS

Many hazards are hidden within a tsunami flow. These hazards can be very big. In order to prevent trucks and cars damaging even more regulations can be made to keep these objects out of the inundation zone when a tsunami is prone.

REINFORCEMENT OF EXISTING STRUCTURES

This difference between this mitigation and the reinforced buildings is that this aims for the locals to have knowledge of the damage which could occur to their property and have then ideas in order to prevent this. Creating this awareness will contribute in the mitigation because of the double effects of this prevention.

Since these structures are reinforced they will dissipate more energy from the tsunami and therefore reducing its total impact.

H.3. LEVEL THREE MITIGATIONS

The level three mitigations: implementing information evacuation and aid systems. These measures are elaborated below.

DESIGN AND ADJUSTMENT OF EVACUATION ROUTES

Within the design of evacuation routes this project focusses on the bottlenecks of the evacuation possibilities. Using the generated inundation maps and time contours critical points in an evacuation plan can be identified. At this point clear designs should be made in order to cope with these bottlenecks. The adjustment of evacuation routes is to analyse the infrastructure and the crowd which will use this infrastructure during an evacuation. With this analysis specific changes of the routes can be made in order to increase the evacuation possibilities. For example, when there is a steep slope next to a facility for elderly people creating stairs instead of a slope might increase their movability.

EDUCATION ON TSUNAMI RISK AND COURSE OF ACTION

In a tsunami prone area it is essential that the community realises this hazard. Therefore the educational system should be designed such that the community becomes aware of the natural disasters. If this is present then the local people will know what to do in case of a tsunami. Since the majority of the people in an area will be locals this is a very effective way of smooth evacuation.

IMPLEMENTATION OF CRISIS COMMUNICATION SYSTEM

When an earthquake happens people do not always realise that a tsunami might follow. For a full scale evacuation this awareness is essential. A crisis communication system can provide information to speed up the evacuation process.

IMPLEMENTATION OF CRISIS TEAM TO INSTRUCT AND GUIDE

The process of evacuation is complex and chaotic. In order to speed up this process a crisis team can be appointed to assist and react. This team can aid and instruct where necessary this will decrease the vulnerability of people not well informed of the situation.

SPECIFIC HARDCOPY INFORMATION AND SIGNS

Tourists might not know that they are in a tsunami prone area or know what to do. This can be mitigated by designing leaflets or other hard copy information informing about the risk and the course of action.



APPENDIX OF SYSTEM A

I.1. PROPOSED SYSTEM IN VARIOUS OPTIONS

In order to compose the retaining system the possible mitigation measures are evaluated according to their methods for each implementation level. Where level the level 1 mitigation measure has to comply with the retaining methodology. The level 2 and 3 mitigation measures are composed taking the level 1 failure into account and thereby using the escaping the water method.

LEVEL 1 MITIGATION

The aim is to completely retain the water in the Cavancha region. In order to connect the possible mitigation measures to this method, the region where the water comes from has to be identified. There are five sub-areas in the Cavancha region, how to protect these areas is related to the approach angle of the tsunami wave. In Part 1, chapter 5 is found that the tsunami wave does not enter from playa brava and the Cavancha peninsula south. Retaining the water in these areas is therefore not necessary. In part 5 is concluded that the wave enters from the Cavancha bay this and therefore protection on this contour is necessary, combining this information with the defined subsections shows that the other three sections playa Cavancha, playa casino and Cavancha north peninsula have to be protected against the tsunami wave. Thus the level 1 mitigation measure has to comply with the constraints off these three areas. Note that it is possible to combine mitigations measures as long as a suitable connection over the boundary can be made.

Using the short list created for the different zones, the following level 1 mitigation measures are suitable for the three areas:

Region	Possible retaining mitigation measure
Cavancha north peninsula	Tsunami breakwater Tsunami seawall
Playa Casino	Dyneema barrier
Playa Cavancha	Dyneema barrier

The tsunami breakwater cannot be applied locally due to the fact that it needs to cross the Cavancha bay in order to be functional. The breakwater is not a desired solution for the Playa casino and Playa cavancha region. This means that only 1 option for each sub-area is applicable, when these options can be combined in the boundaries of the sub-areas a level 1 mitigation measure is found. The Dyneema barrier is the solution for the playa Cavancha and playa Casino, the barrier can be implemented over the complete length of the Cavancha beach. The transition from the Dyneema barrier to a tsunami wall is more difficult but several options are possible. These options are not elaborated in this report.

LEVEL 2 MITIGATION

For the level 2 implementation, the failure of the level 1 implementation is the design parameter. The consequences of different failure modes will identify the necessary method for the level 2 solution. For the failure modes is assumed that the measure is well engineered and failure is due to second order effects. There are two, most likely, second order failure modes of the level 1 mitigation: the forces are larger then the resistance of the structure or the wave height is higher then the design wave for the structure. The two failure modes are addressed as complete failure and overtopping, respectively. Note that both cases are not likely to happen but from previous experience, as mentioned in Part 0, chapter III, it is shown that assuming the level 1 mitigation is sufficient can have disastrous consequences. The method of the level 2 mitigation is determined using an failure analysis of the level 1 mitigation.

Consequences of complete failure

Complete failure is most likely to happen at heigh water level combined with an unexpected impact of a structural object. When such an event causes a collapse of the structure the water will propagate behind the barrier with very height velocities. And the inundation will reach heigh levels around the breach and the surroundings. Since this will be a very sudden change it is not possible for people to see it coming therefore the streets around the barrier have to be empty. The question is whether it is effective to implement diverting or delaying measures for the hinterland in this system.

When considering the suitability of all diverting and retaining methods in the hinterland, they have to be placeable behind the barriers, two options remain: steering the water forces with buildings and integrated flow channels. The first option, steering water forces with buildings, is not applicable for this failure type since the location of the breach is unknown and therefore the flow velocities and directions are unknown. The second option, integrated flow channels, is not applicable for this failure mode since the flow velocities will be so large that the opening of the channels needed for diversion will have an unimplementable size. It can be concluded that the level 2 mitigation has to focus on the escaping the water method based on the complete failure of the level 1 mitigation. Where the most important property is identified as: the prevention of people around the retaining barrier. Additionally The analysis of the overtopping failure mode is not analysed since the level 2 method is already determined.

Using this point of view a list of level 2 possibilities with the escaping the water method is compiled from table ???. These options are evaluated on their function in relation to the complete failure of the level 1 implementation.

- **Assign reinforced buildings for tactical vertical evaluation.** This is a very efficient solution when aiming at fast evacuation. Additionally the size of the additional forces of the possible failure makes the reinforcement of buildings advisable.
- **Evacuation bridges** do not seem to aid this system since a big advantage of this mitigation is that people will use the bridge when they see the water level rise. When full blockage of the wave is realised this will not be visible and therefore people will not have the urge to use the bridge. The expected quick rise of the water will also not allow people reach the bridge in time when failure occurs.
- **Pallafita housing** would save value for all buildings in the inundation area. In this case the inundation area is already developed and new properties are not build on large scale. The principle of this housing is still a valuable recommendation to all property owners in the inundation area. When properties have no valuables on their bottom floors the economical damage due to the tsunami will be smaller. This advise can be given to all property owners and will mainly influence their private property therefore this is not considered a general mitigation measure.
- **Raised infrastructures**, this mitigation measure can be implemented. It would imply that multiple structural adjustments to the city have to be undertaken which will create a big difference in the city in multiple points of view, this is not desirable.
- **Regulations for hazardous objects.** The essence of this measure is to prevent damage to surrounding properties. When retaining the water this problem does not arise but when considering the failure modes of the system hazardous object are critical to the reliability of the system. Therefore this must be considered for the area in front of the retaining structure. However this does not aid the situation

when failure occurs but will only lower the odds off failure. This means that this is a recommended study for this system but cannot act as the level 2 mitigation.

- **Reinforcement of existing structures.** This is still an implementable option since the scenario considers failure of the retaining method. The design for this measure will be a difficult engineering question because the failure modus will create various random scenarios. And reinforcement off all buildings behind the retaining zone is not realistic. There the reinforcement can better be used for the evacuation structures.

This list brings it down to 3 options: Assign reinforced buildings for vertical evacuation, raised infrastructure and reinforcement of existing structures. When comparing the arguments of the measures the best solution for this system is the assign reinforced buildings for vertical evacuation measure because it will support the evacuation of people which is set as the most important goal of the level 2 implementation when considering failure of the retaining method.

Concluding, level 2 mitigation consists out of the **assignment of reinforced buildings for vertical evacuation** combined with the recommendation to move all valuables from the ground floor up to higher floors. Also the objects available in the zone in front of the retaining measure should be analysed according to their possible impact to reduce the risks off level 1 failure, regulations can be made to prevent high impact object from being in the area.

LEVEL 3 MITIGATION

The level 3 mitigation will have to be designed according to the implementations of the level 1 and 2 methods. Also in this scenario it is crucial to consider failure of the retaining method implementation so that the level 3 design will ensure safety in the worst worst case scenario. The available level 3 mitigations are listed and their added value to the system is evaluated:

- **Design and adjustment of evacuation routes.** For an efficient and fast evacuation procedure the level 1 and 2 mitigations have to be taken into account in the evacuation routine. The new situation can change the evacuation possibilities.
- **Education on tsunami risk and course of action.** This is crucial in the awareness of the local community, on this moment this is already well implemented in Iquique. Therefore this mitigation does not require any enhancements.
- **Implementation of crisis communication system.** The presence of a communication system can greatly aid the evacuation and is an essential for a quick evacuation. Fast evacuation is very important and therefore this must be implemented in the design.
- **Implementation of crisis teams to instruct and guide.** With this measure the safe feeling created by the presence of a retaining system can be mitigated. To make sure people evacuate these teams can provide accurate information in real life. When implemented correctly it will be off great value in the evacuation procedure. This measure is also taken into account.
- **Specific hardcopy information and signs.** In order to mitigate the safe feeling this can be valuable to instruct people on the present mitigation measures and what they should do in the event off a tsunami. This is therefore a considerable measure for level 3.

For the level 3 implementation only the educational factor is not taken into account. All other mitigations are considered when designing the evacuation procedures. During this design the most important factor is still the consideration of failure of the level 1 implementation.

I.2. SYSTEM DESIGN

All information which was not presented in the report but which is used in order to find the system design is presented in this section.

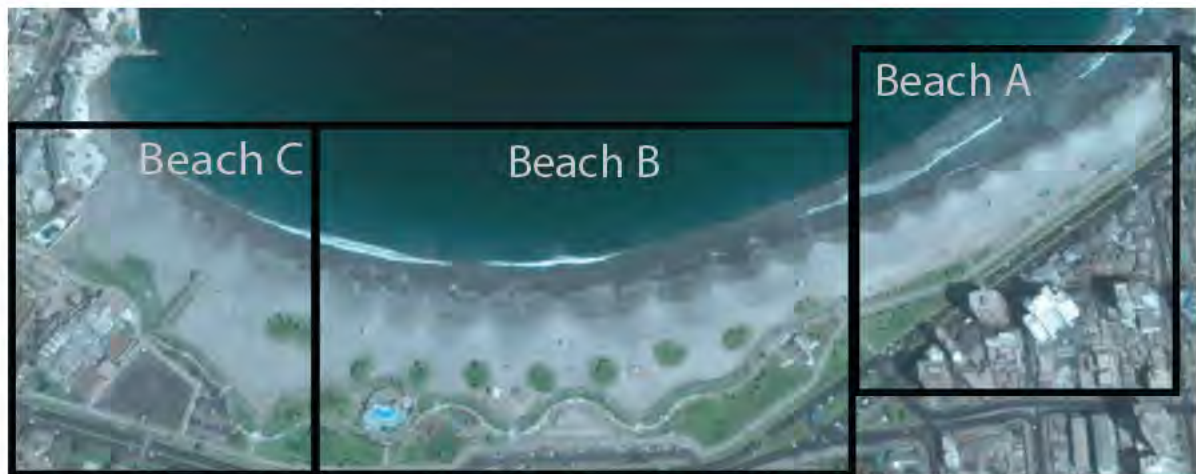


Figure I.1: The division of Cavancha beach in three sections, where A represents the most northern part in this part no additional functions are present. B is the middle section where multiple buildings, dunes and a bikepath is build. And C is the southern section with a lane with shops and the casino.

I.2.1. THE DYNEEMA TRACING

Here the analysis is made in order to generate the pros and cons list as presented in the report.

In order to find the best fit for the Cavancha beach the beach is split into three different sections. The three different sections are used because these section all have different potential for the implementation of the barrier. In figure I.1 these sections are shown and the different parts of the sections are elaborated:

- A The A section is the thinnest part of the beach where no additional functions are implemented. When proceeding from the sea to the road the following dimensions are found: 30 to 75 meters of sandy beach followed by a wooden walkway of 1.2 meters. Than grass, 4 to 11 meters, connects it to the side walk, 5 meters width, followed by 6 meters of grass until you reach the road. This section is relatively straight in the north. In the south some variations start to arise.
- B In section B a lot of public functions are present. Consisting out of 4 buildings from left to right, a amusement show, a swimming pool petting zoo combination, the parking spot as main beach entrance with a fountain and a restaurant/bar. These buildings are considered very important to the local community and the design should comply with this infrastructure or of there is no other option a shift of location. Additionally little dunes are build in order to raise the aesthetic value, these are also considered as essential parts of the beach. The dimensions are more varying than in the A option and therefore these are not summed. The width of the paths are equal only now the pathway has a steep curvature. And a cycling path has started with a width of 4 meters and also a very steep curvature.
- C The C sector has the big difference that the connection to the road is gone and instead the hinterland now is replaced by a casino, a parking spot and an alligator zoo. Between this buildings and the beach is a side walk, the path and the cycling road all with a medium curvature. Additionally this section has an onshore pier where shops are located. the grass widths are comparable to the north.

For the placement of the Dyneema barrier the placement of the foundation is assumed as secondary to the location of the floater. The reason for this is that there are multiple foundation options and therefore a possible foundation is assumed to be found when designing the floater width maximum extension possibilities.

The constraints for the placement of the Dyneema floater are:

1. The floater has to be hidden in stored condition
2. The Dyneema fabric has to be able to acts as a bag, therefore at least 20 meters of width is required. It

is assumed that the location and technique of foundation can be adjusted to this span.

3. Infrastructure has to maintain current functions.
4. Curvature of the floater has to be minimised.

Considering this constraints finding a path becomes rather difficult for section B and the connection to C. In section A the Dyneema can be placed under the side walk. Considering the curvature of the other paths in section B it is best to continue over the side walk. Then the side walk next to the parking spot, left and right, has to be rearranged and the petting zoo needs to relocate. Also in the north the side walk should remain next to the road. All these changes are considered realistic. Looking back at the constraints this path for A and B is only medium compatible with the second constraint since there will not always be twenty meters of space around the floater, the reason why this path is still proposed is because the road is available for extra space. Assuming the Dyneema membrane will not be compromised by the parked cars this is a perfect place for the extension of the fabric. For section C the concept has two possible options.

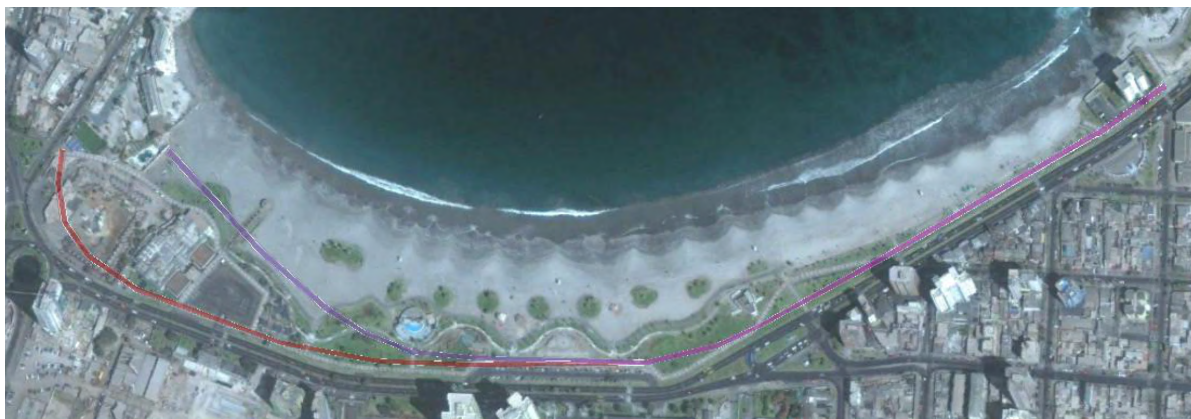


Figure I.2: The two contour lines for possible Dyneema integration. Where the red represents option 1 and the purple option 2.

Option 1: Using this assumption the paths to follow in the C section is defined as the side walk where it will follow the road until it reached the north peninsula. The consequence of this trace is that the inundation of the casino is allowed. Which is not preferable but compared to the feasibility of the design this is considered acceptable. The area next to the casino is a fallow area this can be used in order to create an acceptable curvature without compromising the roundabout for evacuation purposes. The main advantage of this path is that it lays on the highest contour and that the sidewalk is continuous along the trace making the design of the barrier unambitious over the length of the beach. To summarise this path the advantages and disadvantages are summed in table I.1 and the contour is shown in figure I.2.

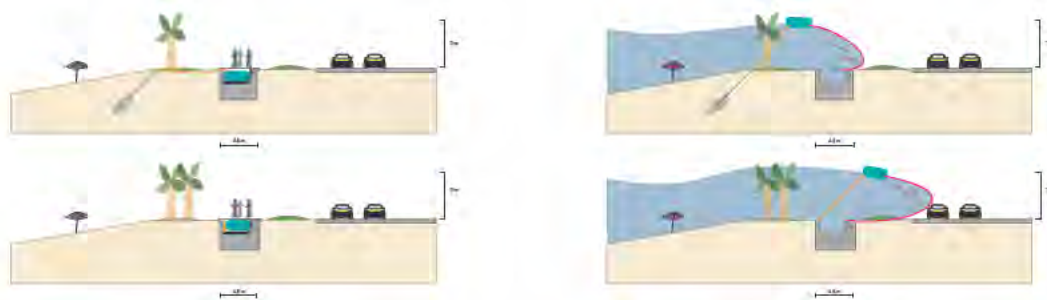
Option 2: The other option is that the side walk is build a little more landward at the end of section B in order to create a curve to fit the barrier in front of the casino. Implementing this would mean a redesign of the pathways and side walk in the area. This will cause a decrease in beach area of ten meters maximum and the pier has to be replaced. The main advantage of this is that the casino is saved. This path pros and cons are summed in table I.1 and the contour is shown in figure I.2.

I.2.2. DESIGN OF THE DYNEEMA BARRIER

In this design two basic methods for the foundation of the Dyneema barrier are considered. An all-in-one solution and a double foundation solution as can be seen in figure I.3. In the all-in-one solution the fabric will extend more behind the foundation while in the double foundation the extension reaches more in front of the barrier. Since the upper foundation is more flexible in design and the space behind the barrier is limited, this foundation is used in the design. The other principle is a good solution because only one foundation is used and therefore no foundation in the sand is necessary, more research on this foundation is therefore recommended.

Table I.1: Pros and cons for the two Dyneema contour options.

Option 1	
Pros	Cons
Minimal change of the current infrastructure Space behind the barrier High elevation of the Dyneema floater Increase accessibility of the beach on south side	Casino inundated Objects in the Dyneema fabric Interaction between Dyneema and vehicles Space in front of the barrier Cars need to drive over floater for parking spot
Option 2	
Pros	Cons
Casino in dry zone Objects in Dyneema fabric Space in front of the barrier	Redesign of the side walk and pathways Space behind the barrier Decreases of sandy beach area



(a) The foundation in stored condition

(b) The foundation in active condition

Figure I.3: Two foundation principles. On the left the all-in-one foundation and on the right the double foundation.

Design height. In order to create a general impression of the forces acting on the Dyneema barrier a test case is evaluated on the lowest elevation point of the barrier. This point has a height of 1.8 meters and is located in south. The evaluation will be done based on to the Marissen *et al.* [26] article. For this the modelled maximum run up height has to be used, which is found in 5.2, and equals 6.8 meters. Therefore the design runup will be $1.3 * R$ which equals 8.8 meters, based on FEMA [25]. The design height is derived using formula L.2 which results in $H = 7m$.

Curvature of the Dyneema fabric. For the design of the Dyneema curvature two parameters have to be chosen. The initial angle of the fabric(α) and the stress factor(f), this is the ratio of the tension versus the maximum tension. These parameters are chosen using recommendations in [26]. The values are shown in table 1.2. With the parameters from table 1.2 and the iterative method as described in [26] the local radius of the fabric is obtained for each height. Combining these radii gives the curvature of the fabric as shown in 1.4. The tension in the fabric is $147MN/m$ and the angle at the floater equals $10.1deg$. Note that these calculations consider hydrostatic force only.

The horizontal expansion of the solution is smaller than assumed for the tracing. This implies that this curvature is implementable over the tracing of the beach. The backwards expansion is smaller then 2 meter while the forward expansion is below 7 meters, considering the width of the side walk the expansion over the side walk is even smaller.

Distance of cable foundation. Now that the shape of the Dyneema is determined. The cable foundation can be analysed. The location is found by taking the narrowest part of the beach, than a minimum is found which can be applied over the full length of the beach. This because a smaller distance increases the angle of the cable which correlates to the required floatation force. From the north part of the beach a distance of 30 meters from the floater foundation is found. To find the tension forces on the cable the horizontal equilibrium of the floater connection is solved. To consider the worst case scenario the 30 meters are assumed between cable

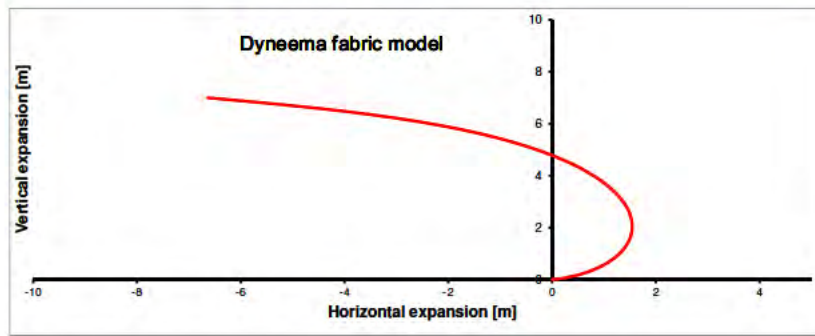


Figure I.4: The slope of the Dyneema system considering the variables of table I.2.

foundation and the Dyneema foundation. Therefore the required length of the cable is reduced by the horizontal extension of the fabric. Solving the dimension equation for this scenario gives a cable length of $24.2m$ and a tension force of $152kN/m$. For a grout anchor with a diameter of 6.4 cm a design force of $1.5MN$ is found. This leads to a cable frequency of 1 in 10 meters. When looking at the stresses on the foundation cable is found that a Dyneema cable of 4 cm is sufficient for the loads. Concluding, the forces on the foundation are manageable however the frequency of cables is quite high which is not ideal. In a more detailed study it is recommended to look into the foundation of the cables to look for a more elegant solution.

Dimensions of floater. With the current curvature the final test for the Dyneema solution is the dimensioning of the floater. This floater has to compensate the vertical forces of the Dyneema fabric and the cables. The vertical force on the floater is found by adding the vertical components of the Dyneema and cable tensions. This is a simple force balance resulting in a vertical force of $72.2kN/m$. The floating capacity needs to exceed this force. For the design of the floater it is assumed that 25% of the floater should be emerged in order to cope with unexpected forces and waves. The material of the floater is not specified in this stage. Therefore the required density based on possible dimensions is calculated. The side walk is 5 meter wide therefore a floater with a maximum width of 4 meters can be implemented. Considering a 3 meters high floater a density of $350kg/m^3$ is required which is more than sufficient. When aiming on a density of $100kg/m^3$ and using the 4 meters of width a height of 2.25 meters is obtained.

Concluding, fitting a floater beneath the path of the side walk is possible. Dependant on the final implementation of the design a floater can be designed by using foam options or air filled tanks.

Table I.2: Input variables for the Dyneema curvature design.

Description	Symbol	Value	Unit
Design wave height	H	7	m
Water density	ρ	1200	kg/m^3
Initial angle	α	0.2	rad
Stress factor	f	0.75	-

I.2.3. TERRAINS FOR THE SEAWALL

The description used to create the seawall trace table is given in this subsection.

Property	Description
Undeveloped area	The first 70 meters are undeveloped and therefore a wall should not be a problem. This area is used to look at the sea but is very polluted so not a lot of effort is put into maintenance of this area. Around the road elevation is around 3.
Club nautico	This is a bottleneck since this club needs access to the beach to reach the boats. Therefore a wall gate combination is necessary. At the moment the club has a wall fence combination of 2.5 meters height if this fence is replaced by a wall the seawall can be implemented with a gate big enough to get the boats through. Around the road elevation is around 2.5 meters
The fishing pier and fish market	This is a place with low aesthetic value. Therefore a wall, 2.5 meters, should be relatively easy. Around the road the elevation is 2.5 meters.
The cocktail bar, parking area and restaurant.	The cocktail bar has no sea view and therefore the wall is able to go behind the bar. The wall will need to extend towards sea in order to go around the parking area to the restaurant. This is possible since the restaurant already has a 2.5 meter high wall so this will easily overlap. Only a bit of sea view will go away but no big issues. Elevation is around 2 meters, a 3 meter high wall should be implementable here.
Terrado suites hotel	This hotel is already closed off so adjustments need to be made to make sure water does not flow through en then only minor adjustments are needed to create a 3 meter heigh wall. Elevation is 2 meters.
Cavancha hotel	A 2 meter wall is already present around the cavancha hotel This is very convenient since the elevation of the road is 2 meters so an elevation of 4 meters is already present. Only the entrance should be sealed with a tsunami gate in order to fully retain the water. For continuity a three meter wall should be implemented in this area. Especially because this is the first area to inundate due to the shape of the bay.

Conclusion of sea wall height. Considering observations made in the Cavancha area a 2.5 meter wall should be acceptable. This is based on the fact that several buildings already got a comparable size wall or fence. This could lead to an average elevation of 5 meters above mean sea level. Which would be able to reduce the impact of the majority of scenarios. The final trace from which a 5 meter high seawall can be implementable as shown in figure 3.13. Using the FEMA [25] guideline, which states that the run up against a seawall is 1.3 times the run up without the wall, an estimation of the retaining height can be made. With this wall a tsunami with an run up of 3.9 meters can be stopped with this seawall. This bottleneck of this element lays in the Club nautico and the wall around the parking spots. The club will currently uses a fence and can loose aesthetic value with the small wall. The parking spots currently have a nice view over the bay, implementing the wall will change that.

I.2.4. FORCES ON THE SEAWALL

In order to give an approximation of the forces acting on the wall. The formulae from ?? are applied where the hydrostatic, hydrodynamic and impulsive forces are taken into account for this approximation. The results of this formulae are given in table I.3. These forces are only to give an approximation of the required strength and are based on the lowest point of the wall at the far east point, here the flow depths are also maximum. They are obtained by using the straightforward formulae from the appendix. The velocity in this calculations is found from analysing the 27th minute in the worst case scenario, since this is the minute from which the highest flow depth is obtained. In reality the wall will influence this velocity reducing its size, this effect is neglected in these calculations. These forces are in the right order of magnitude therefore the wall design is considered feasible and no unrealistic wall thickness's have to be designed.

Table I.3: Inputs for force approximations and the corresponding forces.

Inputs		Forces	
Design wave	$7.8m$	Hydrostatic	$116kN/m$
Design velocity	$5m/s$	Hydrodynamic	$75kN/m$
Density liquid	$1200kg/m^3$	Impulsive	$123kN/m$
Ground elevation	$2.6m$	Total horizontal	$304kN/m$
Wall height	$2.5m$		

I.3. DYNEEMA TO SEAWALL CONNECTION

In this case the Cavancha hotel is in between the two traces, as can be seen in figure 3.13. Connecting them without using the hotel area is not desirable because the concave shape of the Dyneema is wanted to prevent the water from flowing towards the wall. This leaves two options either the wall continues around the perimeter of the hotel. Or the area between the wall and the barrier has to be used for the solution. Both options are not ideal. When looking at the inundation map and the topography of the area it can be seen that this connecting area has a very high inundation because the topography is very low. The inundation even reaches above 4 meters. In order to keep the wall 5 meters from mean sea level it has to become between 3.5 and 4 meters high. This is assumed unrealistic combined with the high inundation the Dyneema barrier should continue over this area.

I.4. ESCAPING THE WATER, EVACUATION ROUTES

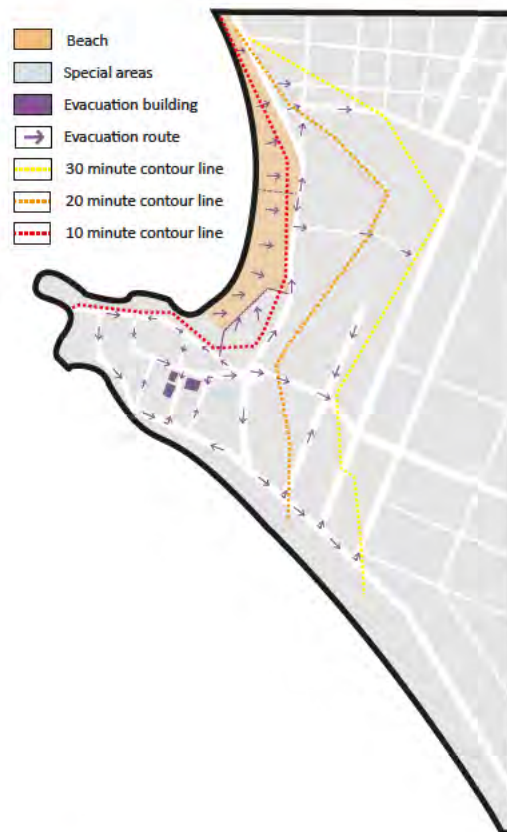


Figure I.5: Evacuation routes for system A

I.5. SYSTEM VALIDATION

From the validation of the model the following observations are made.

Runup The run up against the dyneema barrier shows a much higher peak than the 1.3 times that is estimated with the FEMA guidelines. A runup of 10.2 is observed in the middle of the Dyneema corresponding to a factor of 1.5 as can be seen in figure I.6. This is a lot higher than the FEMA guideline so this means that the Dyneema might need to be higher. When analysing the topography it shows that the area where run up effects exceed the expectation the height of the topography is just height enough to retain the wave however no safety factor is left. When considering run up at the seawall, a maximum of 7.5 meters is found. Which corresponds to a factor of 1.25. This means that the FEMA guideline is quite accurate for this approximation.

Retaining method The wall is overtopped by a wave of 7.2 meters, obtained from figure I.6. So the run up scaled from 6.8, found in part one, to 7.2 which corresponds to a factor of 1.05. However the modelled results around the Dyneema show very high run up values and the water height in the Dyneema close to the wall is 8.2 meters which corresponds to a factor of 1.2. The runup varies along the trace. The Dyneema still has room to increase in height therefore full retaining is verified realistic. For the runup effect over the wall the 1.3 seems appropriate. Therefore this system will fully retain tsunamis with a modelled run up of $5.1 / 1.3 = 3.9$ meters.

Peninsula inundation The inundation in the model with the retaining method is significantly reduced. The flow depths in the hinterland are smaller. When looking of the results of the model through time it can be stated that the model does not handle the amount of water overtopping the seawall accurately. Since the

volume of water grows after the wave has retreated, comparing figure 3.28 minute 28 and 60. This makes the final inundation maps unrealistic however it is assumed that the inundation area of the peninsula can be used for evacuation mapping. This because the source of the water is relocated and the height of entrance is increased, the area touched by the water is realistic. The final flow depths are not used for comparison

Delaying the water The first wave is completely retained by the system therefore the inundation from the first wave is completely omitted. The second wave overtops the seawall in the 27th minute, figure 5.9, compared to the initial scenario where the road gets inundated in the 19th minute, figure ?? . An delay of 8 minutes is achieved with this system.

The borders of the design A possible side effect of the system is the wave surpassing the borders of the system. Since the Dyneema elevation at the north border is not extremely high, this is known in the design and the elevation exceeds the expected height. However the behaviour in the new system can be significantly different. The same principle is applied on the end of the seawall in the peninsula. The two points are analysed. *The Dyneema transition in the north.* In figure 3.28 can be seen that in minute 28 the north border is not surpassed with inundation. It is concluded that the tsunami is stopped by the natural elevation. So the current trace of the dyneema is sufficient to prevent the water from passing the Dyneema. No side effects observed.

The Seawall transition in the west. Figure 3.28 shows. That the seawall gets passed by the first wave but only with a very flow depth, it does not inundate the hinterland. And in the second wave the passing of the wall goes simultaneous with overtopping the wall. Where the water mainly enters the east side of the peninsula. Concluding the east end of this seawall is not the primary source for inundation of the hinterland since the overtopping effects at this part of the wall are smaller.

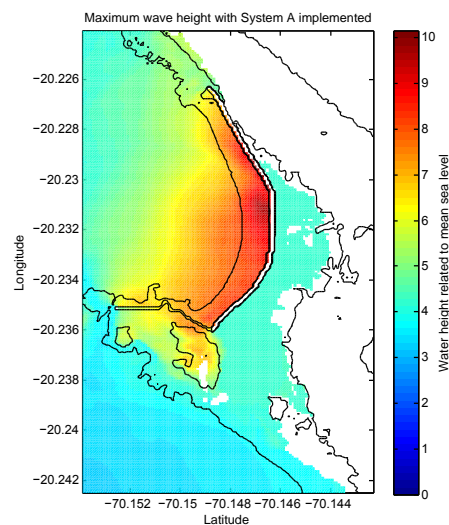


Figure 1.6: The figure shows the maximum waveheight. Where can be seen that runup effects occur in the center off the Dyneema barrier which exceed a height 10 meters.



SYSTEM B

J.1. SYSTEM DESIGN

In this section the design of the submerged breakwater and integrated flow channels are further elaborated.

J.1.1. SUBMERGED BREAKWATER

The submerged breakwater has the purpose to reduce the wave height of a tsunami in the Cavancha bay. However the effect on the normal wave climate should be minimised. This makes it a interesting situation since breakwaters are usually designed to dissipate the significant waves. In this the choice for several parameters is described in more detail. However, most choices are based on the physical experiments of Irtem *et al.* [27] and the simulations of Jahromi and Sidek [28].

EFFECT ON TSUNAMI WAVE

The effectiveness of the submerged breakwater on the reduction of the transmitted wave is depending on several parameters. In general, and in the case of wind waves, two parameters are important which are the B/L and the F/H , where B is the crest width, L is the wave length, F is the freeboard (distance between the water level and the crest) and H is the wave height. Reducing the parameter B/L increases the transmission and thus decreasing the effectiveness of the breakwater. Since the ratio B/L is almost zero because the wave length of a tsunami is in the order of kilometres the effectiveness of the breakwater on a tsunami is thought to be limited. On the other hand, decreasing the value of F/H increases the effectiveness since the space for the wave to propagate over the breakwater decreases.

The physical experiments of Irtem *et al.* [27] showed that submerged breakwaters does have an effect on the tsunami runup if it will save its structural stability. Based on the physical experiments the maximum runup reduction can be in the order of 43% assuming zero freeboard and a permeable surface. However for the implementation of the submerged breakwater in the Cavancha bay a freeboard must be compiled. The physical experiments show that when a freeboard is included still a reduction on the runup in the order of 20% can be obtained. Besides he shows that the crest width is not a governing parameter in the case of long waves. Also simulations by Jahromi and Sidek [28] show an impressive reduction of 83% reduction on the wave height when applying a combination of 2 breakwater segments, one with crest height at MSL (visible during low tide) and one at -2 meter according to MSL (invisible). Based on these two experiments it can be concluded that a submerged breakwater can have a significant effect on a tsunami, however it is hard to estimate the actual effect.

FREEBOARD

The submerged breakwater used by Jahromi and Sidek [28] had a freeboard of -2 meters relative to MSL. For a first design of the submerged breakwater proposed in Iquique the same freeboard is used. When comparing this height to the swell waves ($H_s = 1,7m$) a relative freeboard of 1,18 has been found. This value is rather large compared to the relative freeboard of the tsunami ($H = 7m$) which is 0,29. This gives reason to believe that the effect on the tsunami wave will be larger then on the swell waves.

CREST WIDTH

According to the experiments of Irtem *et al.* [27] the crest width B is not the main parameter in case of transmission coefficient for a tsunami wave since the relative crest width is always very small due to the long wave length (100km). However for swell waves the relative crest width B/L is more important to the effectiveness, that is why a small width will not influence the effect on a tsunami but is desired for swell waves is this design. The primary swell waves in the bay of Cavancha have a peak period of 12 seconds (wav [42]) which corresponds to a wave length of 127 meter according to the dispersion relation in equation J.1.

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{L} \quad (J.1)$$

Taking a crest width of 6 meters the relative crest width for the swell waves becomes 0,047 which is still relative small according to Friebel and Harris [43]. This gives reason to believe that the effect of the submerged breakwater on the swell waves will be small.

STONE SIZE AND SLOPE

To give a first estimation on the stone size the rule of thumb of Burcharth (2003) is used ($D_{n50} = 0.29d$). Using a height of the construction of 11 meters this gives a stone size of 3,2 meters which is rather large, especially since the crest is only 6 meters. Besides the assumption for the rule of Burcharth are breaking waves which is not the case since its aim is not to break the swell waves. This give reason to believe that the Burcharts rule is not applicable and more research has to be performed to calculate the size of the armour units. An important consideration when calculating the stone size is the individual stability of the stones in case of a tsunami wave. When the wave is able to pick up one of the stone and transport it to the shoreline, the debris forces could be catastrophic.

J.1.2. INTEGRATED FLOW CHANNELS

The integrated flow channels are designed with the purpose the store and divert the water. This section looks into the first approximation of the required capacity and the increase of evacuation time due to the available capacity.

CAPACITY

The required capacity to increase evacuation time is related to the discharge of the incoming tsunami bore. Based on specific data of the NEOWAVE model from the worst case scenario the flow depth and velocity can be estimated at a point along the location where the channels will be implemented. This has been done for two locations along the tracing at the Playa Cavancha, see figure J.1. The locations are chosen such that the largest flow depth in the area are taken into account, the results are conservative which is good for a first approximation.

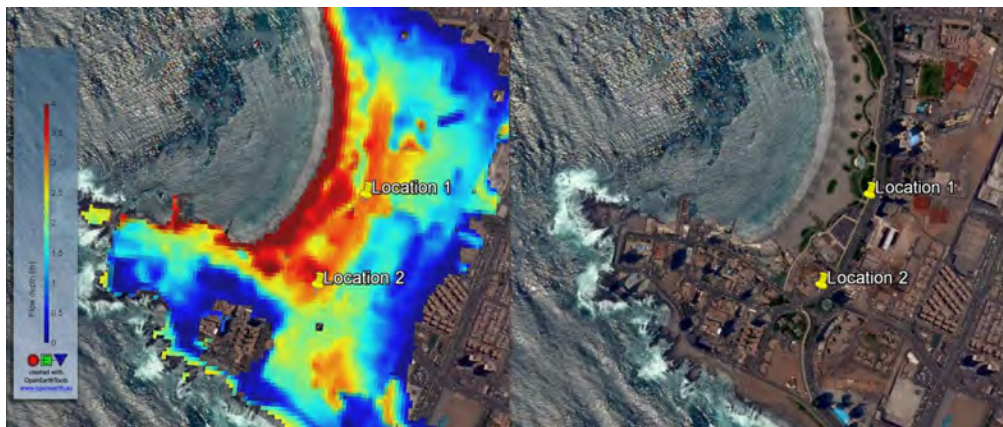


Figure J.1: Locations which are used to estimate the inflowing discharge.

Since this is the area that is most affected it will give an conservative estimation of the inflow discharge. For the flow depth over the wall the flow depth at the particular location is taken and the height of the wall (1,2 meters) is subtracted. This is a rough estimation since the sea wall will influence the flow depth at that point.

For the flow velocity the value at the particular location is taken without consideration of the wall. Both values are plotted for the 19th till the 45th minute since this is the period both locations will be inundated due to the tsunami. Figure J.2 gives an overview of the flow depths over the wall varying in time and figure J.3 gives the same overview for the flow velocities. The maximum flow depth over the wall found is 2,46 m and the maximum flow velocity is 3,58 m/s. By multiplying the flow depth with the flow velocity at both locations the discharge per meter width over the wall can be estimated, this is plotted for both locations in figure J.4. The maximum inflow discharge found with this approach is 6,8 m³/s/m.

The available capacity is related to the dimensions of the caissons. The proposed design divides the section in a wider area along the beach and a smaller area. The width is based on the available space in the city to integrate the channels best as possible. To give a first estimation of the extra time due to the storing capacity the available capacity can be compared with the required capacity. By integrating the inflowing discharge of figure J.4 over the time the cumulative capacity within a certain period can be found. This amount can be compared with the available capacity to get the extra time. The results can be found in table J.1. From this result can be concluded that the extra available evacuation time is in the order of 2,5 minutes. However this does not take the outflow capacity of the channels into account.

Table J.1: Extra evacuation time due to integrated flow channel

Location	Available capacity [m ³]	Max. discharge [m ³ /s]	Extra evacuation time [sec]
Location 1	212.400	6,0	154
Location 2	212.400	6,8	148

CONSTRUCTION METHOD

The concept of caissons is proposed because of its easy construction method. The caissons can be pre-fabricated which makes it an rather cheap solution. The construction process can be briefly explained in three steps. First the retaining walls can be installed at both sides of the road. Next the space in between can be excavated and the pre-fabricated can be installed. After installing and connecting the caissons to each other, the shafts between the retaining wall and the caisson can be filled with concrete to create the entrance for the water. By using mainly pre-fabricated elements the structure is relative easy to construct. Attention should be paid to the connection of the elements to avoid leakage or scour problems.

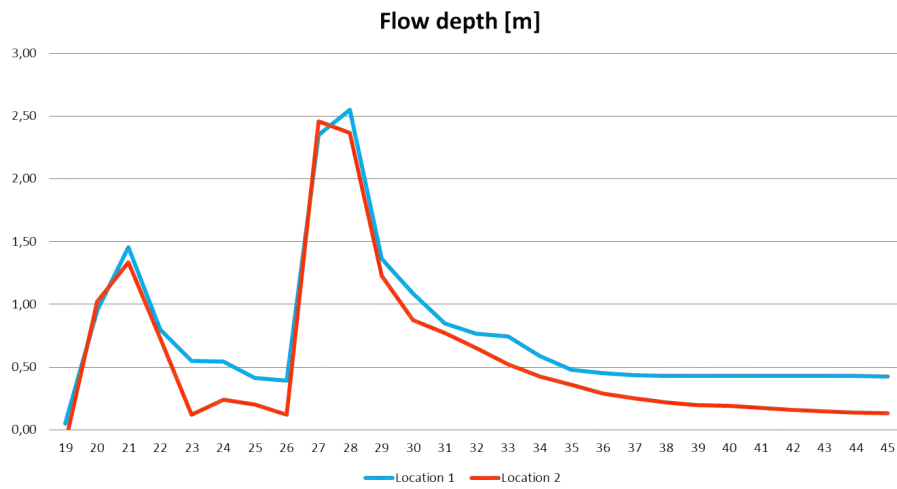


Figure J.2: Flow depth over the sea wall of 1.2 m for the worst case scenario (NCS) at two locations along the tracing.

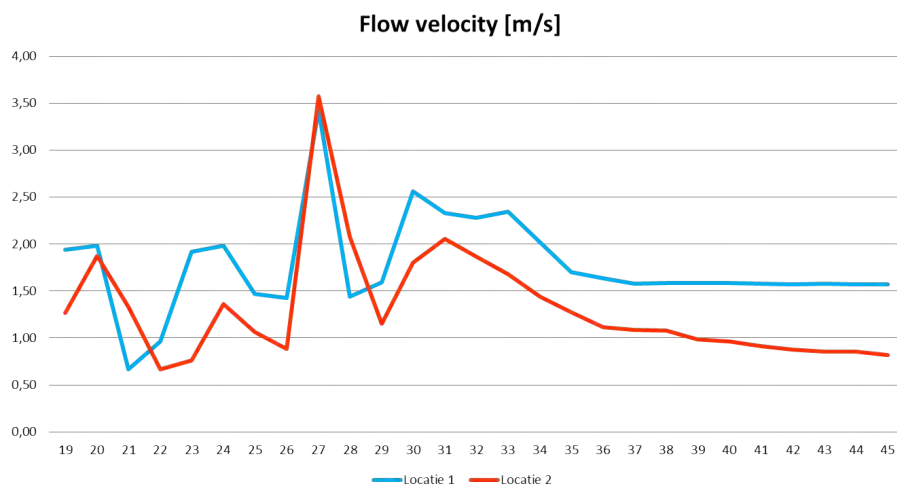


Figure J.3: Flow velocity over the sea wall of 1.2 m for the worst case scenario (NCS) at two locations along the tracing.

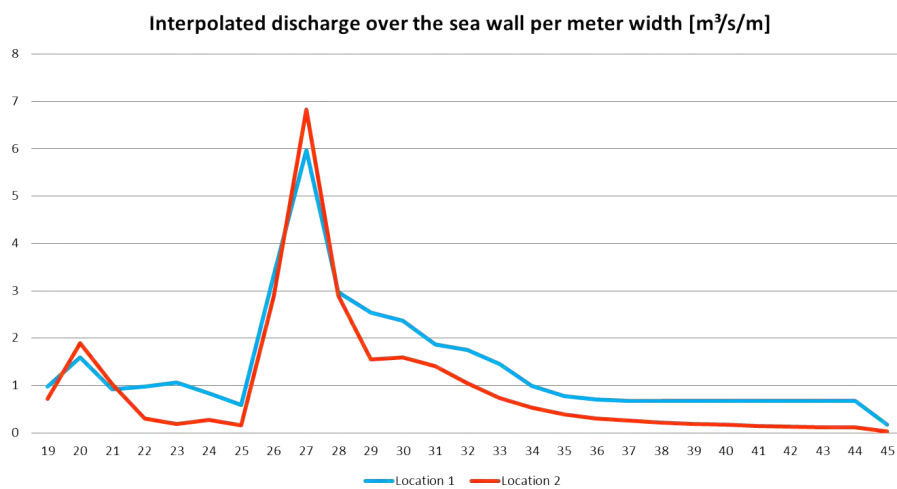


Figure J.4: Flow discharge over the sea wall of 1.2 m for the worst case scenario (NCS) at two locations along the tracing.

J.1.3. EVACUATION ROUTES FOR SYSTEM B



Figure J.5: Evacuation routes for system B

J.2. VALIDATION

In this section the methods used to validate the submerged breakwater and integrated channel are explained and elaborated.

J.2.1. SUBMERGED BREAKWATER

To validate the effectiveness of the proposed design the submerged breakwater can be modelled with NEOWAVE. By modifying the fifth grid of the NEOWAVE model, which has the highest resolution of 10m, the submerged breakwater can be implemented in the model. The bathymetry in the bay has been lifted to the required level according to the design presented in figure 3.17.

When running the model with the new bathymetry the new inundation area and arrival times can be simulated. Next the new results can be compared with the results from part 1 (without a modified grid). Based on this comparison the effectiveness can be validated. To validate the submerged breakwater this procedure has been applied for the worst case scenario (combined North, Centre, South) which is defined in part 1.

REDUCED WAVE HEIGHT

Since the aimed effect of the submerged breakwater is a reduction on the wave height in the bay, a time series of the wave height in the bay with and without the breakwater are compared in figure J.6. It can be observed that the wave height in the bay is reduced in the case of the submerged breakwater. Based on table J.2 the averaged reduction on the first 5 waves is 35%. Here the waves are defined by means of the downward-zero-crossings. Also the period of the waves in the case with the breakwater are in the same phase as without the breakwater. This gives reason to believe that it is allowed to compare the modelled results to each other.

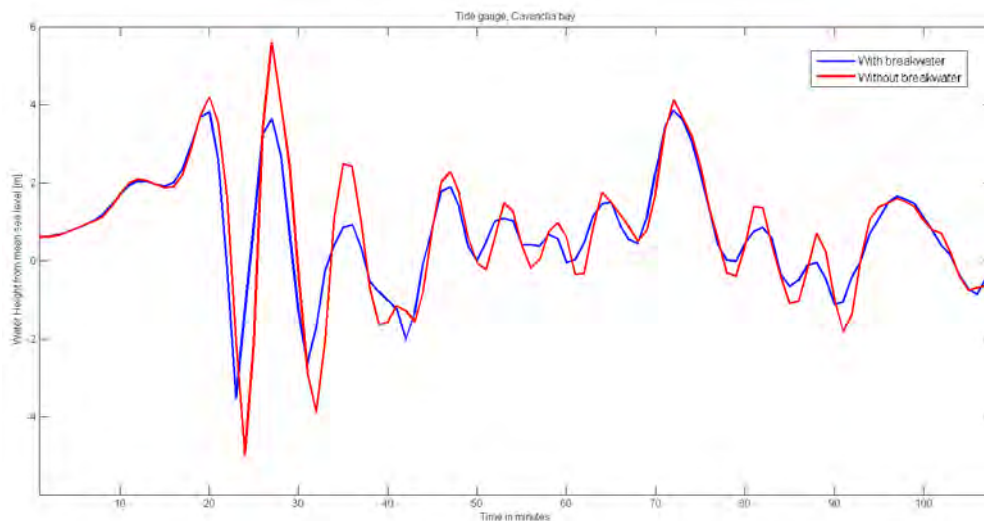


Figure J.6: Comparison of the time-series in the bay of Cavanca with and without the submerged breakwater

Table J.2: Reduction in the case with the submerged breakwater

Situation	1st wave [m]	2nd wave [m]	3th wave [m]	4th wave [m]	5th wave [m]
Without breakwater	4,2	10,6	6,4	2,4	1,7
With breakwater	3,8	7,1	3,3	1,9	0,6
Reduction	10%	33%	48%	21%	65%

From the plot and the table it can be concluded that the waves in the first 50 minutes are reduced by the breakwater. The third large wave, around the 75th minute, is now the largest wave in the time series. This has probably to due with the reflection (edge waves) and possible resonance in the bay. Because the size of the has been changed the natural period has changed as well. This could lead to a resonance effect however the effect can not be concluded from this time series.

REDUCED INUNDATION AREA

Next to the time series also the inundation area of the cavancha peninsula can be compared to the situation without the breakwater. This has been done in figure J.7. It can be observed that the reduction of the wave height, as shown in figure J.6 also has (as expected) a reducing effect on the inundation area in the city. The area covered by the water is smaller and less deep. Both at the peninsula and directly behind the playa cavancha the flow depths are reduced by approximately 1 meter. Based on the NEOWAVE results the maximum runup found in the Cavancha area is reduced from 6,8 meters to 5,7 meters when implementing the submerged breakwater.



Figure J.7: Comparison of the inundation area in the case with and without submerged breakwater.

Based on figure J.7 also a few negative side effects can be addressed. When taking a look at the inundation area north of the Cavancha peninsula a large inundation at the rocks can be observed. Also at the playa Brava higher inundation depths can be observed. The breakwater steers the water to other places along the coast.

IMPACT ON WAVE CLIMATE

As mentioned during the design phase the submerged breakwater will influence the normal wave climate since this is what submerged breakwater are mainly used for. In this experiment the submerged breakwater is used to only interfere with a particular wave, the tsunami wave. The reduction on the tsunami wave has been validated with figure J.6, however this does not give any information on the influence of the normal wave climate since that is not contained in the NEOWAVE model.

The effect on the wave climate will be a reduction of the transmitted wave heights in the bay. This will influence the surf climate which is one of the main tourist activities at the Cavancha beach. Also the sediment transport in the bay will be influenced by the reduced wave height which could lead to changes in the topography of the beach. The wave height of the transmitted waves are calculated using the transmission coefficient K_t .

$$K_t = H_t / H_i \quad (J.2)$$

Here H_t is the transmitted wave and H_i is the incident wave. To get an idea of the effect of the breakwater on the normal wave climate the transmission coefficient K_t for the proposed design can be calculated.

There has been a lot of research to the value of this coefficient and the equations are mainly empirical. Based on Makris and Memos [44] the main factor controlling the wave transmission is the relative freeboard F/H_i where H_i is the incoming wave height and F is the distance between the crest level and the water level. Other parameters which play a role in shaping the final value of K_t include the relative crest width B/H_i , the roughness parameter F/D_{n50} as well as an "internal flow parameter" B^2/LD_{n50} where the local wavelength is also taken into account. To give an estimation of the wave transmission coefficient three different equations based on three different authors are used. Below the authors and equations are presented.

Seabrook and Hall [45] used results from physical model tests with submerged breakwaters. Various values of freeboard, crest width and water depth has been applied.

$$K_t = 1 - \exp(-0.65F/H_i - 1.09H_i/B) + 0.047BF/LD_{n50} - 0.067H_iF/BD_{n50} \quad (J.3)$$

Siladharma and Hall [46] give an estimation based on statistical analysis methods applied on experimental results of wave transmission of 3-D submerged breakwaters.

$$K_t = -0.869\exp(-F/H_i) + 1.049\exp(-0.003B/H_i) - 0.026FH_i/BD_{n50} - 0.005B^2/LD_{n50} \quad (J.4)$$

Friebel and Harris [43] developed a best fit empirical model based on 5 different data sets. Their study confirmed that the transmission coefficient is highly dependent on the non-dimensional freeboard.

$$K_t = -0.4969\exp(-F/H_i) - 0.0292B/H_t - 0.4257h'/h_t - 0.0696\ln(B/L) - 0.1359F/B + 1.0905 \quad (J.5)$$

The results of the different formulas used to calculate the K_t value in figure J.8. The parameters which has been used are $B = 6m$, $D_{n50} = 3,2m$, $F = 2m$ (compared to MSL), $H_s i = 1,7m$ and $T = 12sec$. The results are plotted for different depths along the contour of the tracing.

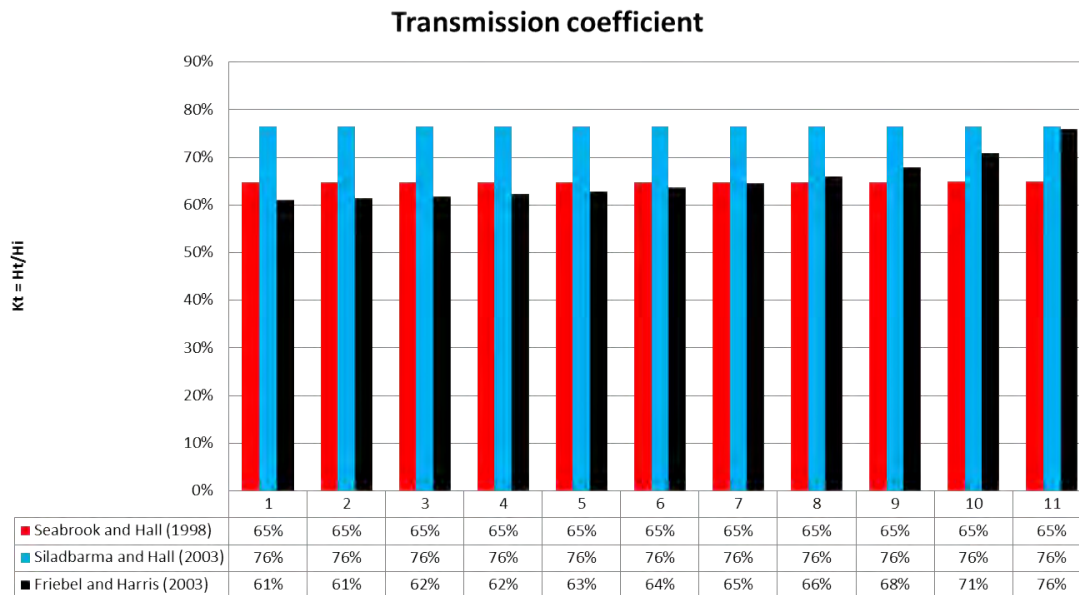


Figure J.8: Different values for the transmission coefficient based for the proposed design of the breakwater.

The different value of the transmission coefficient are varying between the 61% and 76%. For the proposed design the reduction on the wave climate is varying between 39% and 24%, this reduces the incoming swell waves with a significant wave height of 1,7 meters to minimal 1,05 meters. This could also influence the sediment transport in the bay which could lead to changes in the topography of the beach. An important side note is that the calculation of the transmission coefficient has been done for a freeboard of 2 meters. During low tide the freeboard will be 0,5 meters lower which decreases the transmission coefficient. The different values for low and high tide are given in table J.3.

Table J.3: Different values for the transmission coefficient depending on the tide.

Method	MLWS	MSL	MHWS
Water level compared to MSL	-0.5 [m]	0 [m]	+0.8m [m]
Friebel and Harris (2003)	55%	61%	68%
Seabrook and Hall (1998)	58%	65%	73%
Siladbarma and Hall (2003)	67%	76%	86%

J.2.2. INTEGRATED FLOW CHANNELS

In this section the process of validation of the proposed design of the integrated flow channels is explained and elaborated.

METHOD

To validate the integrated flow channels an advanced numerical models can be used. However, for a first estimation of the capacity it is also possible to apply a simple equation based on the principle of change in storage (S), see equation J.6.

$$\frac{dS}{dt} = Q_{in} - Q_{out} \quad (J.6)$$

The change in storage can be estimated by computing the differences in the inflow and outflow discharge. The required storage capacity can be calculated by integrating equation J.6 over the required period. In this case the period could be the duration of the tsunami event. By comparing the cumulative required storage capacity and subtracting the available storage capacity the cumulative overflow of the channel can be estimated. When the cumulative overflow is positive the channels are flooded, till this moment the water can be captured within the channel. This gives an estimation of the extra time that is available for evacuation.

TRANSACT TO VALIDATE

The transact that is subject of validation is the area along the playa Cavanha, playa Casino and a part of the North peninsula. The length of this section is 1,18 km and according to the design this area has a width of 30 meters and is 6 meters deep. This give a total capacity of 212.400 m^3 . The section is plotted in figure J.9.



Figure J.9: Section of integrated flow channels for validation.

INFLOW DISCHARGE

The inflow discharge is based on the incoming tsunami wave. First the wave has to flow over the integrated sea wall with a height of 1,2 meters. For a first estimation the inflow discharge is computed per meter width by multiplying the flow depth with the flow velocity. Both values are based on the results of the NEOWAVE model. The scenario to validate the effectiveness is the worst case scenario as described in part 1. The effectiveness has been modelled for two locations along the proposed tracing, these locations are the same as used for the validation of the breakwater, see figure J.9.

To simulate that the water has to flow over the wall before entering the channel the flow depth used is the value of NEOWAVE results minus the height of the wall (1,2 meter). The flow velocity has not been modified. Both value will be influenced by the presence of the sea wall but for a first estimation these values used without implementation of the small wall.

OUTFLOW DISCHARGE

The outflow discharge is based on the size of the outflow cross-sections and the flow velocity inside the channel. For both an assumption has been made. The total outflow cross-section is depending on the amount of outflow sections, the width of each section and the height of the water inside the caisson. The amount of outflow cross-sections is based on the design and depends on the amount of roads which are connected to the section that has to discharge the water. In the case of the chosen transact this are 6 outflow cross-sections. The width of the section that is subject of validation is 30 meters. The height of the water inside the channel is depending on the amount of water that is inside the caisson and can be calculated by dividing the total volume by the area of the channel. The maximum value is equal to the height of the channel which is 6 meters.

The flow velocity inside the channel is the largest uncertainty in this model because it is depending on local acceleration, advection, a pressure gradient, the slope and the roughness of the channel. To make an accurate estimation this should be modelled with a numerical model. For this model it is assumed that the velocity will be lower inside the channel than the incoming velocity due to dissipation at the entrance and turbulence inside the channel. In this first conservative attempt the velocity inside the channel is assumed to be 50% of the incoming velocity.

CUMULATIVE OVERFLOW

With the inflow and outflow discharge the change in storage can be computed for each time step. Since the model gives the data per minute, the change in required storage will be computed per minute. By adding the change in storage of the total period the total required capacity can be computed. When subtracting the available capacity and ignore the negative values the cumulative overflow remains. When the cumulative overflow is positive the channel is flooded. When it is negative the channels manages to discharge the incoming tsunami wave. This assumes that the outflow cross-sections have a infinite storage volume which is in practice not the case. The results of this calculation are plotted in figure J.10 and figure J.11 for location 1 and 2 respectively.

The results show three lines for each location. The first is in the case no channels are implemented and only the wall is used, this scenario uses the assumption of no outflow discharge. The second is in the case with the channels implemented. The third one also takes reducing effect of the breakwater into account this will be treated in the next section. The results are only plotted for the minutes with the first highest waves during the entire event. The first waves enters the transact at the 19th minute.

Based on the results a few things can be mentioned with respect to the overflow and the effect of the integrated channels. The channel has a significant effect on the cumulative overflow for both locations. The reduction on the maximum values are presented in table J.4. Here the reduction is defined as the ratio of the maximum values in the time series. The cumulative overflow can be related to the total inundated area since the area decreases when the volume of the water decreases. It can be concluded that the area behind the transact is reduced by at least 59% when only implementing the integrated flow channels. Besides there are 7 extra minutes before the channels get filled up and start to flood the street, this means 7 extra minutes to evacuate. The difference between location 1 and 2 is mainly due to the higher flow depth and flow velocity at location 1. This location has more open space and is situated a bit lower which makes it plausible to have a higher discharge, this results in a higher cumulative overflow. Both locations will still inundate the area after 7 minutes but the storing and diverting purpose of the channels is full-filled.

IMPLEMENT SUBMERGED BREAKWATER

Interesting is to compare the reduction due to the submerged breakwater to the reduction due to the integrated flow channels. By taking the flow velocities and flow depths of the NEOWAVE simulation with the submerged breakwater the cumulative overflow can also be calculated for this system. The value of the flow depths are taken at the same location and the cumulative flow depth is calculated with the same method. When adding the submerged breakwater instead of the integrated channels the reduction is less, see table J.4. In the case of location 1 this is (only) 23%. An even better reduction can be obtained when combining the submerged breakwater with the integrated low channels and the sea wall to one system. Based on the results in table J.4 and figures J.10 and J.11 it can be observed that the reduction is at least 72%. In the case of the second location this results in an extra evacuation time of another 2 minutes compared to the situation without the channels.

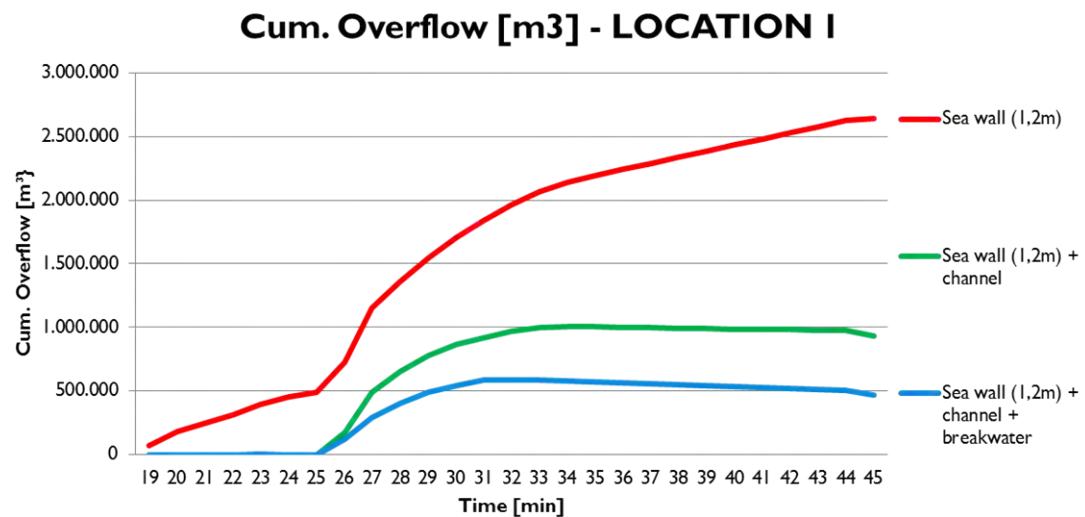


Figure J.10: Cumulative overflow at location 1

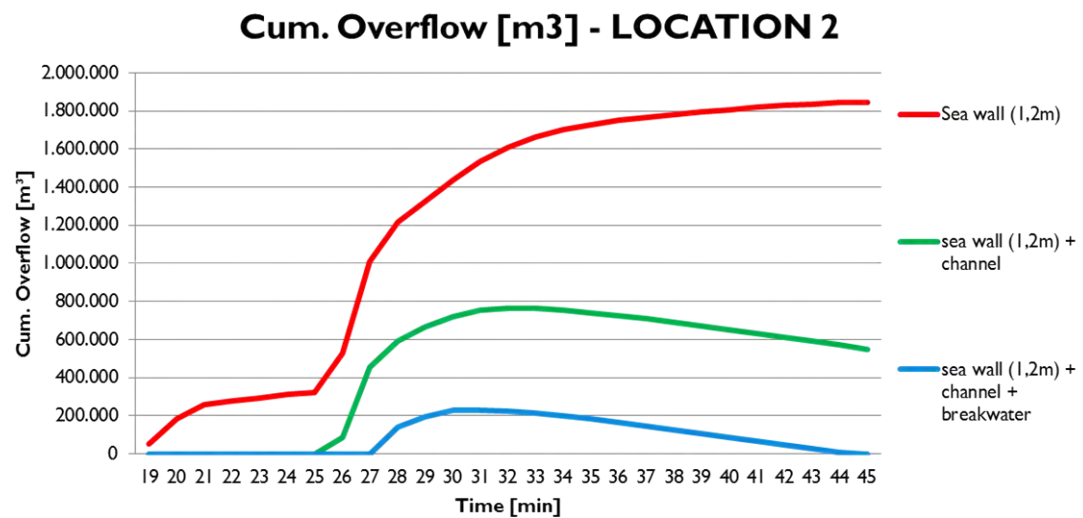


Figure J.11: Cumulative overflow at location 2

Table J.4: Reduction of the cumulative overflow between two different combination of measures for two locations. The reduction is defined as the ratio of the maximal values of both time series.

Situation	Location 1	Location 2
1. Sea wall + integrated channel; compared to only a sea wall	68%	59%
3. Sea wall + breakwater; compared to only a sea wall	23%	39%
2. Sea wall + integrated channel + breakwater; compared to only a sea wall	72%	88%

K

SYSTEM C

In the report the concluding remarks of this Appendix are used as design criteria for vertical and horizontal evacuation.

K.1. BASIC NUMBERS

In this section basic numbers used to design the evacuation routes in a safe and effective way are described.

K.1.1. EVACUATION SPEED

The median values for normal situations are 1.3 m/s (adults), 1.5 m/s (children) (Rinne *et al.* [47]). Taking into account that after an earthquake routes will be damaged and using the slowest evacuation since families will often evacuate together, the authors use an average evacuation speed of 1,0 m/s. This is affirmed by the FEMA guidelines, where an evacuation speed of approximately 1 m/s is mentioned.

K.1.2. START OF EVACUATION

The plots and time contour lines have a start point at the beginning of the earthquake. Since evacuation will not start at the start of the earthquake a delay of 8 minutes is assumed, this takes into account the earthquake time and the time it takes to gather family members and belongings.

K.1.3. FLOOR SPACE IN SAFE ZONE

Floor space per person is estimated at 0.5 m² (Oberhagemann [48]). In the FEMA guidelines is mentioned that this can be doubled, resulting in 0.25 m² per person. However, in the same article it is mentioned that the effective floor space is 85%. To simplify calculations 0.5 m² per person is used.

K.2. HORIZONTAL EVACUATION

When regarding the 30 minute line as the first safe line it can be back calculated what the maximum distance to a 30 minute contour is. With the 8 min 'starting time' 22 min evacuation time is left. 22 minutes with 1,0 m/s evacuation speed gives a maximum distance to the 30 minutes contour of 1320 meter. For the 20 minute contour this is 720 meter and for the 10 minute contour this is 200 meter.

K.2.1. CAVANCHA PENINSULA

The Cavanca peninsula, as mentioned before, is cut of from mainland in 20 minutes. The evacuation route from the peninsula is 770 meter to the 20 minute contour line, this is not allowable as horizontal evacuation route. The route can be made achievable by connecting the island to the main land with a pedestrian bridge. This is described in more detail in section [K.4](#).

K.3. VERTICAL EVACUATION

Vertical evacuation is the term used to indicate evacuation that goes up and involves getting to a safe height in a safe building. In this section the basics of this concept is explained and problems in capacity will be estimated. It is assumed that when arrived in the evacuation building there is no time pressure. This because when there is time to get to higher grounds since the first inundation will be low and people can be safe in 0-1 minute after arriving in the building.

K.3.1. ALL AREAS

At this moment the education system teaches inhabitants of Iquique (D) to vertical evacuate in the building where you are present. Because of effectiveness of the evacuation and creation of extra capacity the authors propose a change. Vertical evacuation will concern everyone present in a designated 'high rise' building, they should evacuate to the fifth floor or higher.

K.3.2. CAVANCHA PENINSULA

Because of the formation of the peninsula island horizontal evacuation of this island is not possible unless a connection is added that connects the peninsula to the mainland.

In appendix E the maximum of people present in the peninsula is estimated on 8500. For the evacuation capacity a view side notes on this number are in place.

The number is estimated on the amount of apartments and houses. However, these people will only be present in this amount during night, and at that moment the majority will be in a high rise building in which they should evacuate up. This means that only the low rise buildings, mainly located in the centre of the peninsula need to go to another building. This means an extra capacity of approximately 500 people must be created.

However this is not the busiest moment of the peninsula. In the area are bars and restaurants situated that have no option for vertical evacuation. This means that approximately 1000 people extra need to evacuate, bringing the maximum to 15000 persons.

The last increase of people comes from the area near the roundabout (in Playa Casino). The area indicated in figure 3.25 consists of buildings that are too low to use for vertical evacuation. The nearest evacuation possibility is the vertical evacuation in the Cavanca area. This group of people should also be able to reach the other 30 minute contour within the allowed timespan. However it is assumed that they will flee to closest higher ground increasing the needed capacity for the vertical evacuation in Cavanca Peninsula with 250.

The maximum capacity increase needed is thereby 1750 persons.

EXTRA SURFACE AREA NEEDED FOR VERTICAL EVACUATION

Assuming 1750 people need to be evacuated and capacity per m^2 is two people approximately 875 m^2 is needed.

K.3.3. PLAYA CASINO

The Playa Casino is almost completely inundated, for the hinterland this causes no additional problems since evacuation routes can be short and can be evacuated in time. However, the beach and the casino itself are too far from the safe zone. The shortest route is over the roundabout, but since this is relatively fast inundated it is not safe. This means that another evacuation route must be taken, approximately 720 meter to the 20 minute contour. According to the maximum determined in paragraph horizontal evacuation this is very close to the maximum and thereby not preferable.

Concluded is that different solution for this area is preferred. The amount of people present in this area is estimated at 1000.

EXTRA SURFACE AREA NEEDED FOR VERTICAL EVACUATION

Assuming 1000 people need to be evacuated and capacity per m^2 is two people approximately 500 m^2 is needed.

K.4. EVALUATION PER MITIGATION MEASURE

The mitigation measures available according to the short list mentioned in appendix H are listed and evaluated for this system. The analyses done above is used to assess the viability of the different measures for this system. This section is concluded with the two options mentioned in the report.

Level 1

New vertical evacuation building - The aim is to evacuate the whole area as fast and as safe as possible. In order to do so a capacity increase of vertical evacuation possibility is desirable for the area defined as Playa Casino (see E). In the area near the casino an evacuation building can be build. This building can have several additional user functions, however these function may never interfere with the main function of evacuation.

Local logistical centres - In the aftermath of a tsunami event the area will be in need of certain basic goods such as water, blankets and food. Also physical and mental health attention should be arranged. Coordination will be simplified if the locations for this aid are pre-assigned. However it is not necessary to build a new structure for this and therefore it will be considered a level 2 measure.

Level 2

Assigned reinforced buildings for tactical vertical evacuation - Vertical evacuation will remain a important measure to evacuate with high capacity and within a limited amount of time, especially in the Cavancha Peninsula. Therefore tactical assignment of reinforced buildings for vertical evacuation is a necessary addition to achieve sufficient evacuation capacity. Another form of vertical evacuation accounts for people already in a high-rise building. Because of the time it will take to get out from a building when on the second floor or higher it is in this case advised by ONEMI to evacuate to higher floors.

Evacuation bridges - When analysing the area defined as the Cavancha Peninsula (both North and South) it is concluded that this area is cut of from the mainland and an island is formed. As mentioned in section 1 the peninsula is closed of in 21 minutes. In order to remain the possibility of horizontal evacuation and prevent a capacity issue, a pedestrian bridge can be used to retain a connection to the mainland. In figure K.1 the location of this bridge is indicated. The bridge would have to be approximately 500 meter long, this means it takes 500 seconds (8,3 minutes) to cross the bridge. It takes $6 + 8 = 14$ minutes (400 meter + activation time) to reach the bridge, this leave 6 minutes to cross the bridge. Assuming that it is not preferable but possible to be on the bridge when the water is flowing under, this can be stretched to approximately 10 minutes of safe evacuation. This leaves $10 - 8,3 = 1,7$ minutes (100 seconds). When 1750 people need to evacuate, 17,5 persons/second are able to reach the end of the bridge, with a capacity of 0,5 persons / m', the width of the bridge must be $17,5 * 0,5 = 9$ meter. For a pedestrian bridge this is very wide and long, therefore it might not be the most feasible option.

Pallafita housing - These are designed for the minimization of property and not designed as evacuation for humans. Therefore this is no option when regarding evacuation possibilities.

Raised infrastructures - This is an useful measure when the inundation does not exceed 0.5m, this because of the possibility of implementation. Because of this restriction, only in the Cavancha peninsula it is a viable option, here it can be used to create a longer timespan to reach the vertical evacuation buildings or the evacuation bridge. Since there is enough time to reach the vertical evacuation buildings, this is not necessary in this option.

Regulation for hazardous objects - When regarding hazardous objects that can obstruct the evacuation routes there should be regulation implemented, examples are regulated car-parking and underground electricity wires.

Reinforcement of existing structures - Applied when analysing structures that are used for vertical evacuation.

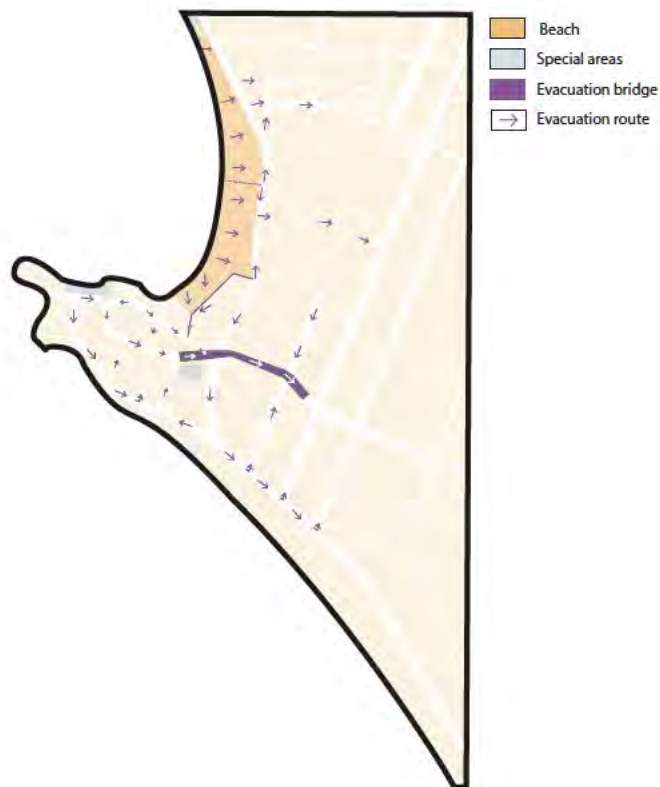


Figure K.1: System C, option 2. Evacuation plans.

Level 3

Education on tsunami risk and course of action - To be able to have an organised evacuation it is important that inhabitants know what to do when the alarms go off. Especially regarding vertical evacuation education is vital, since vertical evacuation might not be the first reaction of a person.

Implementation of crisis communication system - Firstly people need to be alarmed and triggered to evacuate. Secondly, to coordinate the tasks of the different entities a good communication system and plan is important.

Implementation of crisis team to instruct and guide - Also this measure is used to have a effective and co-ordinated evacuation. However it becomes of even more importance in the aftermath of the event. The crisis teams main task will be the occupation of the crisis centres and the coordination of aid to the harmed population.

Specific hardcopy information and signs - Hardcopy information is used to make people present in the area aware of the fact that they are in a hazardous area on the one hand and on the other hand the course of action that follows when the alarms go off, this information should be available for both locals and tourists. Signs that indicate the evacuation routes and danger/safe zone must be visible and understandable.

Design of evacuation signs As described above the design of the signs is important, in figure K.2. These signs are coupled to the evacuation routes that have specific colours, designed on the time contour lines. Red is everything within the 20 minute contour line, orange in the 30 minute contour line, yellow between the 30 minute and 20 meter contour lines and green is the indication of the safe zones, see figure K.3

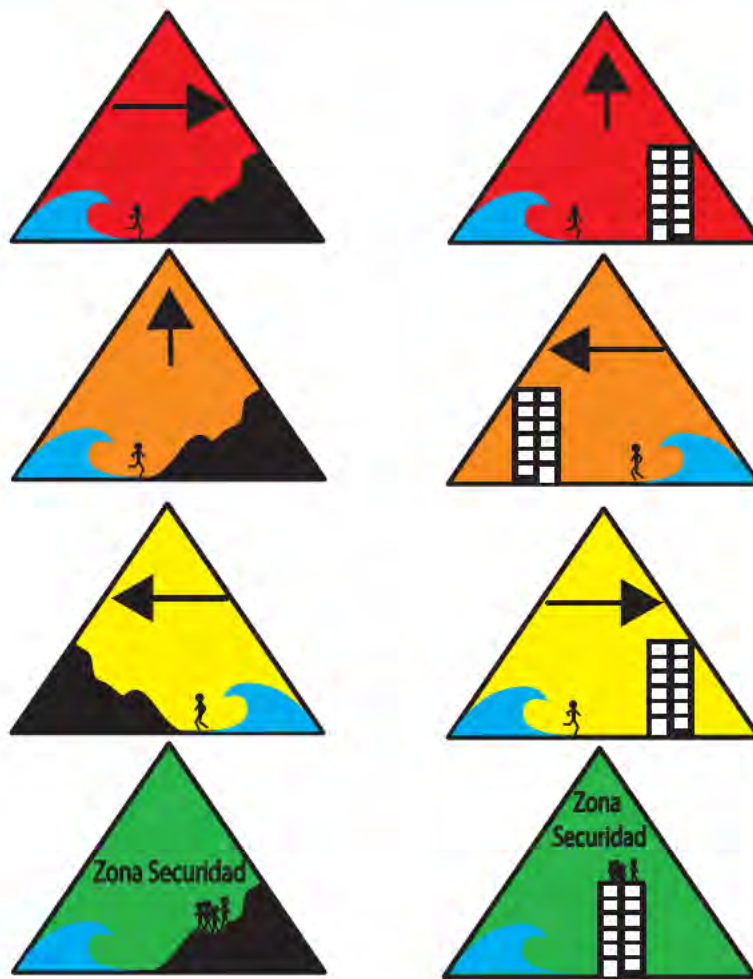


Figure K.2: Example evacuation signs

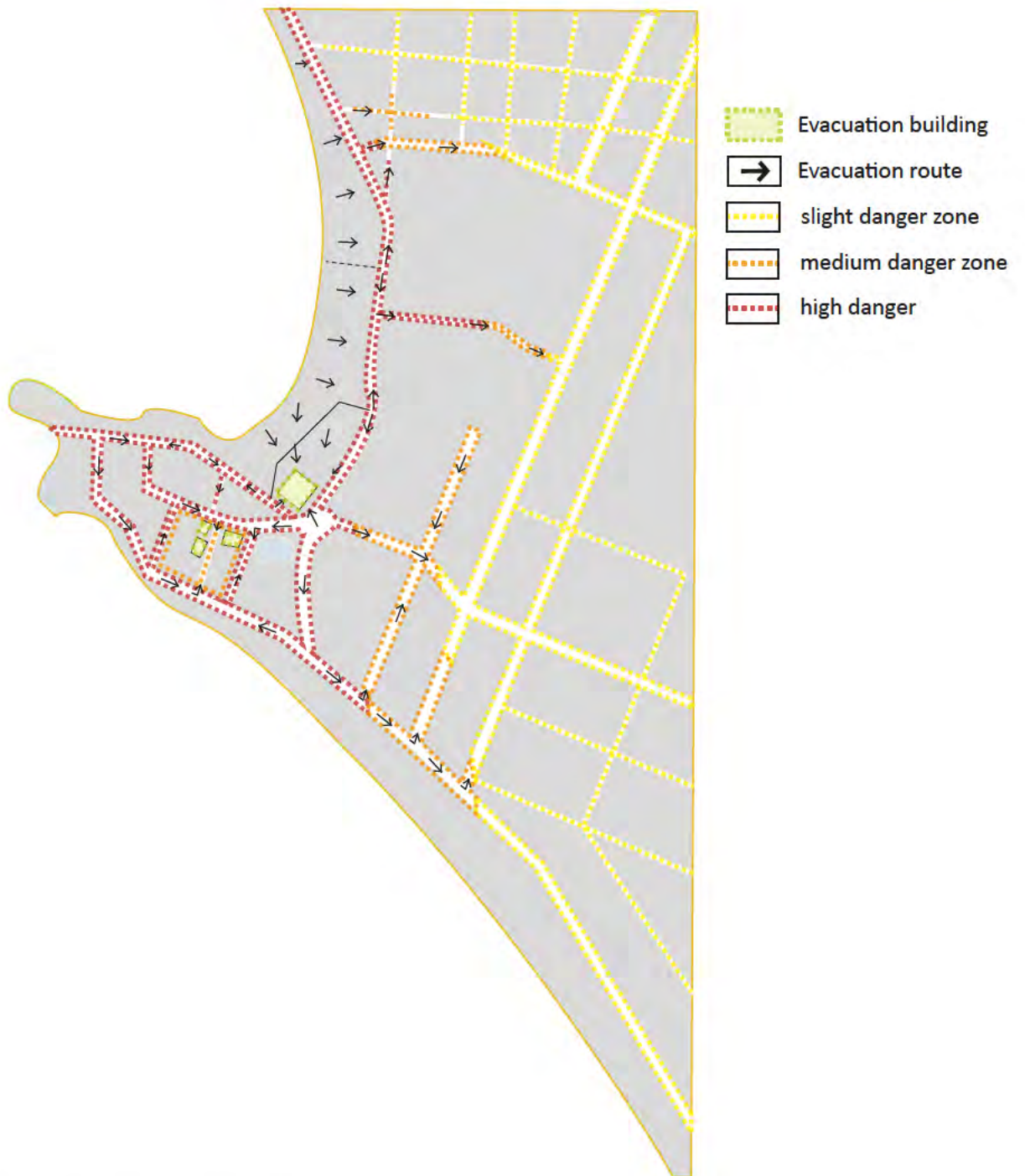


Figure K.3: Zone indication in evacuation routes.

K.4.1. CONCLUSION

From this two options can be derived, these are further discussed in section 3.6.

In order to create enough capacity to evacuate the combination of a evacuation bridge and a new evacuation building is not necessary, therefore the two options are based on using one of these mitigation measures. Raised infrastructure only adds value for the option containing the evacuation bridge, for reasons mentioned above. In neither of the options Palafita housing will be taken into account, for the reasons mentioned above. All the other mitigation measures from the short list are applicable in both options.

For the tactical evacuation buildings there is a side note. Current high rise buildings are built according to high Chilean standards concerning earthquakes, it is assumed that the buildings do not need reinforcement (see D). For this reason in the options no longer the term 'reinforced buildings for tactical vertical evacuation', but 'tactical evacuation buildings' is used.

When regarding level 3 measures ONEMI is in charge, the structure of their approach is elaborated in appendix D. Almost all the measures are mentioned in their current plan to enhance the coordination of the evacuation and aftermath.

There are two measures that should be added to their program, implementation of small crisis centres and implementation of specific hardcopy information and signs.

L

TSUNAMI LOADING ON STRUCTURES

There are several hydraulic forces on a structure like a vertical evacuation building or a vertical wall that has to be considered due to a tsunami wave. In this appendix a brief overview is given of the different hydraulic loads based on the FEMA guidelines and Yeh *et al.* [30], also the context and applicability of several equations is elaborated and summarised. The overview is given to compare different building codes and can be used for a (preliminary) design of vertical evacuation buildings or retaining sea walls and to get a general idea of the forces and dimensions that should be used.

There are a few key assumptions when talking about a tsunami wave. Generally it is assumed that a tsunami wave breaks offshore due to relative shallow water compared to the wave height. When the tsunami wave is broken it can be considered as a bore due to its long wave length. In case of tsunami loading the water is assumed to contain a mixture of sediment and salt water. Based on an assumption of vertically averaged sediment volume concentration of 10% in seawater, the fluid density of a tsunami flow is 1,2 times the normal density. That is why for $\rho_s = 1200 \text{ kg/m}^3$ is used. Furthermore there is a wide variability in wave runup due to local bathymetry, topography and the influence of large buildings. This is why for design runup (R) it is recommended to use 1.3 times the predicted runup elevation (R*) to mitigate the possible variability. The value of 1,3 is based on empirical judgement from past tsunami survey data.

1. Hydrostatic forces

The hydrostatic forces are the forces of standing or slowly moving water on a structure. The force is hydraulic pressure p_c which is linearly depending on the water depth and acts perpendicular against the structure. The hydrostatic force must always be computed in case of watertight structures. According to the FEMA guidelines the horizontal hydrostatic force can be computed with equation L.1.

$$F_h = p_c A_w = \frac{1}{2} \rho_w g B h_{max}^2 \quad (\text{L.1})$$

In this formulae h_w is the maximum water height above the base of the wall, this can be described based on the run-up R with equation L.2. In this formulae R is the design runup and R* is the maximum tsunami runup elevation taken as the estimated maximum inundation elevation based on numerical models.

$$h_{max} = 1,3R^* - z_w = R - z_w \quad (\text{L.2})$$

However the FEMA does not include the velocity head in the h_w . This is included by the City and County of Honolulu Building Code (CCH) like in equation L.3. The velocity head is not relevant to include in case of a large vertical wall where can be assumed that the water is completely retained and the flow velocities at the wall are almost zero.

$$F_h = \frac{1}{2} \rho g B \left(h + \frac{u_p^2}{2g} \right)^2 \quad (\text{L.3})$$

In the case of a retaining vertical wall the hydrostatic force could be a dominant force, especially for tsunamis that act like a rapidly rising tide, the hydrostatic forces generally become increasingly important. However the force is found to be normally relative small compared to the surge or drag forces according to Dames and Moore [49]. In the case that water is flowing around a structure the hydrostatic force is considered not to be the dominant force, unless the force act on a wide building and the hydrostatic gradient over the building is large. This could be mitigated using breakaway walls in order to let the water flow through the building and decrease the gradient over the building.

2. Buoyant forces

The buoyant force, or vertical hydrostatic force, is depending on the displaced volume of water by the structure. The force will always act vertically through the centroid of the displaced volume on the structure. The forces need to be resisted by the weight of the structure in order to resist floating. Especially basements and light structures which displace a large volume of water compared to there weight are vulnerable for the upward buoyant forces.

$$F_b = \rho_s g V \quad (\text{L.4})$$

3. Hydrodynamic forces

When water flows at a moderate to high speed around a building (or structural element) hydrodynamic loads are applied to the building. These loads are depending on the density, flow velocity and structure geometry and includes frontal impact on the upstream face, drag along the sides, and suction on the downstream side. They are usually called the drag forces, which are combination of the lateral loads caused by the impact of the moving mass of water and the friction forces as the water flows around the obstruction.

$$F_d = \frac{1}{2} \rho_s C_d B (hu^2)_{max} \quad (\text{L.5})$$

The FEMA 646 guidelines recommend to use $C_d = 2.0$ for square or rectangular piles and $C_d = 1.2$ for round piles. However the City and County of Honolulu Building Code (CCH) recommends $C_d = 1.0$ for circular piles, $C_d = 1.5$ for vertical walls and $C_d = 2.0$ for square pills. For larger obstructions the drag coefficient is mainly depending on the width over depth ratio (Yeh *et al.* [30]).

Flow velocities can be calculated with a numerical model like NEOWAVE with a gird size of 10 meter, however they can also be calculated with the analytical equation L.6. This equation is based on one-dimensional, fully non-linear shallow-water-wave theory for the condition with a uniformly sloping beach found by Shen en Meyer (1963) [FEMA 646 guidelines, 2008, p. 131].

$$u_{max} = \sqrt{2gx \tan \alpha} \quad (\text{L.6})$$

With α is the beach slope and x is the distance from the maximum runup location to the location of interest; the location of interest must be above the initial shoreline. According to Yeh *et al.* [30] the maximum fluid velocity occur at the leading runup tip, this gives the upper-limit envelope of the flow velocity for all incident tsunami forms. Because a real beach is not uniformly sloped, it is more convenient to present equation L.6 as a function of the ground elevation instead of the distance like in equation L.7 [FEMA 646 guidelines, 2008, p. 132].

$$u_{max} = \sqrt{2gR(1 - \frac{z}{R})} \quad (\text{L.7})$$

The combination $(hu^2)_{max}$ form equation L.5 represents the momentum flux per unit mass. Note that term does not equal $h_{max}u_{max}^2$ because the maximum flow depth and flow velocity do not occur at the same time. The hydro dynamic force must be based on the $(hu^2)_{max}$ which is the maximum momentum flux per unit mass. The term can be obtained running a detailed numerical model with a small grid in the runup zone to ensure adequate accuracy of the (hu^2) . It is also possible to get a rough estimation using equation L.8.

$$(hu^2)_{max} = gR^2(0.125 - 0.235\frac{z}{R} + 0.11(\frac{z}{R})^2) \quad (L.8)$$

Although the analytical solution is based on one-dimensional non-linear shallow-water theory for a uniformly sloping beach, with no lateral topographical variation and no friction, the maximum value for $(hu^2)_{max}$ obtained from L.8 can be used for: (1) preliminary design; (2) approximate design in the absence of other modelling information; and (3) to evaluate the reasonableness of numerical simulation results.

4. Impulsive forces

The impulsive forces are caused by the leading edge of a surge of water on a structure and act in a very short time. There are two main formulas known to estimate the surge forces on structures due to a tsunami one used by the FEMA guidelines and one used by the City and County of Honolulu Building Code.

Laboratory data, based on experiments by Ramsden (1993) and Arnason (2005), show no significant impact forces (impulsive forces) in dry-bed surges. However an overshoot in force is observed in bores that occur when the site is initially flooded. The maximum overshoot in this case is approximately 1.5 times the subsequent hydrodynamic force. This value is recommended to use by the FEMA guidelines as a factor for the impulsive force.

$$F_s = 1.5 * F_d \quad (L.9)$$

When the runup zone is flooded by an earlier tsunami wave the subsequent wave could impact a structure in the form of a bore instead of a dry-bed surge. Since the bore loading is greater than the dry-bed surge impact, the dry bed surge loading may not be critical. Also it should be mentioned that the impulsive force acts on members at the leading edge of the tsunami bore, while hydrodynamic forces will act on all members that have already been passed by the leading edge.

According to Yeh [50] the CCH adopted an equation from Dames and Moore [49] to determine the surge (or impulsive) force depending on the hydrostatic force, see equation L.10. The equation is derived by summing the hydrostatic force and the change in linear momentum at the impingement at the surge front on a vertical wall. The surge impingement is treated as steady using the flow velocity of $u = 2\sqrt{gh}$. This results in an equation that is 9 times the hydrostatic force per unit width.

$$F_s = 4.5\rho gh^2 \quad (L.10)$$

However the surge force computation by equation L.10 would result in excessively overestimated values if the maximum inundation depth were used for h . That is why the surge height should be used for h however this value is difficult to determine. A similar equation is used by the Building Center of Japan however with the value '3' instead of '4.5'.

5. Debris forces

The debris forces can be sub-divided into impact forces and damming forces. The impact force from water borne debris like boats, floating wood, shipping containers can be dominant however it is hard to estimate them accurately. According to the FEMA guidelines the debris forces can be estimated with equation L.11.

$$F_i = C_m u_{max} \sqrt{km} \quad (L.11)$$

It is recommended to use $C_m = 2.0$ as the added mass coefficient, furthermore are m and k the mass and effective stiffness of the debris. u_{max} is the maximum flow velocity carrying the debris. Debris should be evaluated considering the location and surrounding. For example driftwood would be expected in coastal towns with piers and small houses, whereas for larger port areas the debris could be a shipping container. Also the size of the debris has to be taken into account since large object can not float in shallow water. Using maximum flow velocities without consideration of the depth on large

objects would be unnecessarily conservative. Flow velocities can be calculated with a numerical model however it is also possible to use the analytical formula [L.7](#).

Besides the impact forces of debris also the accumulated (or damming debris) can have a severe force on the structure. This can be estimated with formulae [L.12](#) which is a modification of equation [L.5](#).

$$F_{dm} = \frac{1}{2} \rho_s C_d B_d (hu^2)_{max} \quad (L.12)$$

In this equation B_d is the so called breadth of the debris damming. According to the FEMA guidelines it is recommended to use C_d is 2.0. The value $(hu^2)_{max}$ can be obtained in the same way as described for the Hydrodynamic forces. The debris damming force should be assumed to act as a uniformly distributed load and will be resisted by a number of structural components, depending on the framing dimensions and the size of debris dam.



RELEVANT GEOTECHNICAL FAILURE MODES

In this research, various mitigation measures are considered and a preliminary design is proposed. Potential structural measures influence and are influenced by the subsoil. An additional consideration is that such structures are designed to function in the case of a large seismic event. Finally, these measures are meant to deal with an incoming tsunami c.q. large water forces. This also suggests the construction is either offshore or close to the coastline, adding the risk of other water induced failure modes. In this section a few relevant geotechnical failure modes are elaborated. Which ones specifically apply per measure will be addressed in Part Two of the research, in the system design (3).

liquefaction

Loose sand has a tendency to contract to a smaller volume. A very loose assembly of sand particles tends to collapse when sheared, resulting in a decrease of volume. Sudden volume changes can be dangerous when the soil is saturated with water. The tendency for volume decrease then may lead to a large increase in the pore water pressures. The strength in the soil then decreases in comparison with the pore pressures and the particles start to 'float' in the water. This is called liquefaction. This may occur when loosely packed sandformations offshore are suddenly shook up by a strong earthquake. In an extreme case, this may cause a locally founded structure to fail. (Verruijt [51])

circular slip surface

The stability of a slope may be found by determining the critical circular slip surface (with the lowest factor of safety). The failure mode occurs when the equilibrium of forces working on an assumed wedge is off. Examples could be the excavation of too steep a slope, but also when (suddenly) an extra force is applied (e.g. an earthquake could be seen as an additional horizontal force) or taken away (e.g. the strength of the soil is reduced).

Scour

Scour is the erosion of the subsoil from the surface down. Causes may be high flow velocities and tidal currents.

pipng

Groundwater flow or other sources of water seeping through soil with an relatively high hydraulic conductivity such as sand may cause erosion, especially when high flow velocities occur. Local erosion then will attract more water and this may lead to further erosion. The 'pipe' that is formed gives the name to the phenomenon. When piping occurs close to or underneath a structure, this may compromise its stability.

Heave

If the effective stresses in a soil are low (or suddenly reduced), occurring pore pressures may cause a foundation or layer of impermeable soil to be pushed up.

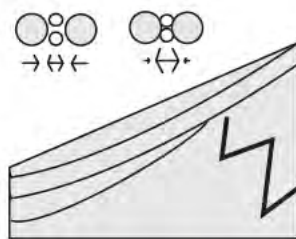
Earth pressure failure

In the case of an excavation, often a retaining structure is applied. Active and passive earth pressures play a role in obtaining an equilibrium for such a construction. When due to changing conditions, this equilibrium is compromised, a construction, such as a retaining wall may fail.

Settlement

Settlement occurs when the stress on soil is larger than the effective stress. In a undrained case, consolidation may take place. In the case of sand, seismic activity may change the stress distribution, causing the soil (and potential structures) to fail.

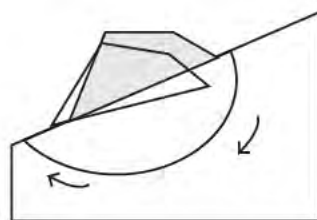
Liquefaction



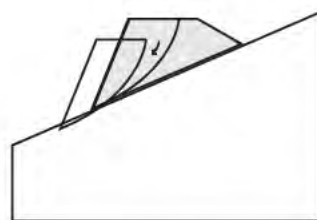
a. failure of subsoil: slope failure

Figure M.1: Liquefaction

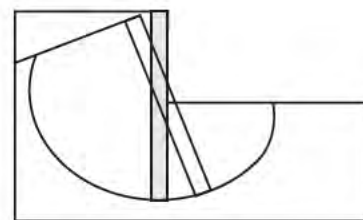
Circular slip surface



a. failure of subsoil: slope failure



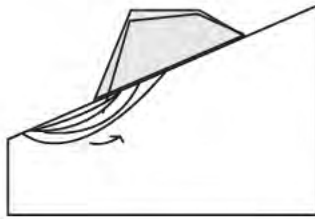
b. failure of structure: slip surface inside structure (rubble mound breakwater)



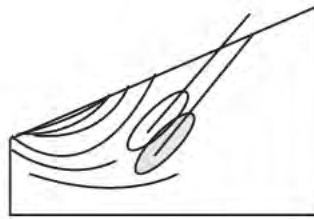
c. soil-structure interaction: slip surface (deep) excavation and insufficient retainment

Figure M.2: Circular slip surface

Scour

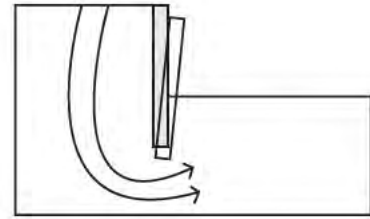


a. Offshore erosion of soil (around a structure) from the surface



b. Erosion of beach (around a structure) from the surface

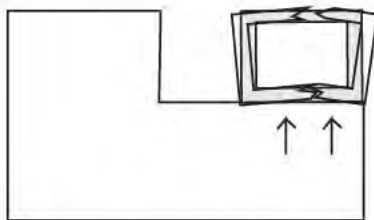
Piping



Erosion in subsoil due to flowing water

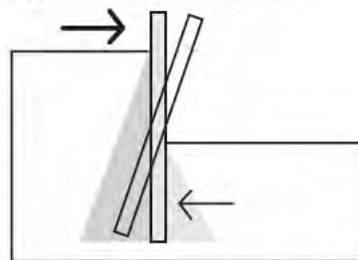
Figure M.3: failure modes

Heave



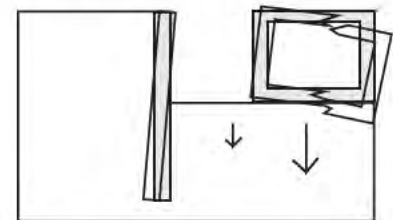
Pushing up of a structure / subsoil due to upward pore pressure

Earth pressure failure



The equilibrium of lateral forces may fail in case of high water and debris force

Settlement/ cracking



(Due to seismic activity) the subsoil may settle unevenly (e.g. causing cracking)

Figure M.4: failure modes

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