TU Delft

Final Report

A Multidisciplinary approach to Tsunami Risk Management: A proposal for a framework based on a case study of Iquique

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Summary

In this multidisciplinary project a proposal for a framework for tsunami risk management in Chile, has been developed. This was done using Iquique in the north of Chile as a case study. In the future such a framework could be a guide for both decision-makers and specialists in what to do to prevent victims and minimise economic damage due to tsunami flooding.

Solutions for improvement of current practice have been searched within specific activity areas of hazard management: prediction, mitigation and response. Prediction concerns the available intelligence on the chance of occurrence and the related force of the tsunami event. For this, earthquake (and resulting tsunami) scenarios have been defined and modeled with NeoWave in order to establish probable boundary conditions for the rest of the research. A scenario based on the conditions described by [Chlieh et al., 2011b], with a Mw. 8.8, turned out to have the worst results (runup of 12m max, inundation of almost 10m max, and arrival time less than 12 min). Based on these results estimations have been made of the number of people at risk and economic damage. The number of people at risk was derived from zonal data from [SINTIA, 2010] and resulted in at least 12,500 people living in inundated areas. Direct economic damage was derived using fragility curves [Mas et al., 2012b] and building value estimations [Blong, 2001], and resulted in 14.90M damage in an Iquique downtown area and 142M damage in the Zofri shopping mall area.

For mitigation of tsunami effects, prevention of the tsunami event (e.g. by means of breakwaters) has not been taken into account. Focus has been on city evacuation, possible slope failures of infrastructure, and possibilities of vertical evacuation. For city evacuation remarkable differences between inundation maps from SHOA, ONEMI, the Municipality of Iquique, and our model results were indicated, from which the cause is not clear. An optimistic calculation on evacuation possibilities of the Zofri shopping mall has shown that only 6,000 people (from 10,000 people present during peak hour) could escape. A slope failure analysis of the main exit from the Zofri area and the highway A16 has indicated that both slopes are instable. Additional geo analyses pointed out that safety zones in higher grounds are stable, that there's a lack of knowledge on liquefaction of quaywalls (which could be troublesome for port evacuation routes), and that scouring of sidewalks is likely (however it will not occur during evacuation). An initial analysis on high buildings in Iquique resulted in 56 buildings that have been examined for vertical evacuation and two areas that lack any possibilities for vertical evacuation (Zofri and the port). An hydraulic load analysis has been done, based on both NeoWave model results and analytical approach. After a comparative stability analysis with available criteria

for seismic loads, 21 buildings in Iquique were marked as suitable for vertical evacuation.

For response activities a setup for evacuation modeling was made, in order to assess differences between mitigation plans made in advance and actual evacuation after or during a tsunami event. The Agent Based Modelling (ABM) approach was found appropriate for evacuation modeling because of its applicability to evacuation flows of pedestrians. In ABM, behaviour of individuals (agents), based on simple rules, can be combined with behaviour on macro-level (showing congestion, spillback, etc.). Three scenarios, based on factors from all involved disciplines, have been indicated that should be simulated in future, but a literature scan on people's behaviour has shown that first several research choices should be made on especially psychological influences.

Besides the focus on the prediction, mitigation, and response, to create a successful tsunami hazard management plan, this framework should be complemented by several tools. Therefore a causal system diagram with all involved factors was made to point out all interrelations of disciplines, an actor analysis has pointed out the wishes of all involved parties, and criteria have been developed to evaluate the tsunami hazard management plan. Finally, for all weaknesses in current practice that could not to be solved, knowledge gaps were defined in order give recommendations on future research for both improvement of the framework and Iquique's tsunami risk management plan.

Acknowledgements

Even though we haven't been the first team from the TU Delft that sets foot on a multidisciplinary voyage abroad, it is impossible to see where the first steps of arranging such a trip lead to. We starting with shaving of time boundaries and countries of 'been-before', and eventually ended up with completing a team fit for integral tsunami risk assessment. Even then we had no clue on what to expect from this part of the world that's so far away from our country, but yet (as we've discovered) so similar. Who could have predicted that conditions on working in Chile would be so fine, so pleasant?

Along the way, we had to deal with our differences in language, reasoning, and prioritizing. Even though the five of us all are MSc. students of the University of Technology of Delft, we've already created ways of thinking that could easily block out other very interesting mindsets and ideas. Besides that, we discovered that risk management not only is essential for society threatening natural hazards, but also for integrating three months of work of five people. In this respect, the use of Latex can be recommended, but, without good coordination and backups this still could lead to hazardous events. Besides its challenges, we can only conclude that working multidisciplinary is both essential and enriching.

It's time to thank the people that helped performing this project. For inviting us and leading the way (even before we've seen his face on Skype), our gratitude goes to Rodrigo Cienfuegos Carrasco. Besides his diplomatic role in the overall process, we thank him for the support all hydraulic parts of the research.
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Santiago de Chile,
25th of October

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Abbreviations

Abbreviation	Meaning
ABM	Agent Based Modelling
AoF	Angle of Frictions
CIGIDEN	Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales
CRR	Cyclic Resistance Ratio
CSR	Cyclic Stress Ratio
IOC	Intergovernmental Oceanographic Commission
MSF	Magnitude Scaling Factor
ONEMI	Oficina Nacional de Emergencia del Ministerio del Interior
PGA	Peak Ground Acceleration
SAF	Servicio Aerofotogramétrico
SECTRA	La Secretaría de Planificación de Transporte
SHOA	Servicio Hidrográfico y Oceanográfico de la Armada de Chile
SINTIA	El Sistema de Información de Transporte Accesible por Internet
TIL	Transport Infrastructures and Logistics
VE	Vertical Evacuation

Concept Definitions

Glossary of terms	Definition
City Evacuation	The immediate and rapid movement of people in urban areas, away from the hazard (tsunami eventinundation), towards safety zones.
Extreme Event Scenario	A scenario with maximum impact, often less probable.
Flood line	Distance from shore line to the tsunami inundation limit.
Higher ground(s) Safety Zone	A type of safety zone where safety is ensured by the natural elevation of the location above mean sea level
Inundation depth	Height of tsunami water level with respect to the local surface level at a certain point of interest.
Inundation height	Height of tsunami water level with respect to the MSL at a certain point of interest.
Moment Magnitude	Measure of earthquake magnitude based on the seismic moment which is a function of fault size, displacement, and earth rigidity.
Runup elevation	The elevation above MSL at the tsunami inundation limit.
Safety Zone	Area where people are safe from direct impact of tsunami inundation.

Tsunami Risk	The probability and consequence associated with a tsunami hazard.
Tsunami Risk Management	Scientific field that aims to manage risks associated with tsunami hazard.
Vertical (Evacuation) Shelter or Refuge	Building that has been marked (possibly) safe from tsunami flooding.
Vertical Evacuation zone	A type of safety zone where safety is ensured by man-made structures, sufficiently high above the expected inundation level.

Symbols

Symbol	Units	Description
ϕ	deg	Angle of Friction
c	MPa	Cohesion
CRR	-	Cyclic Resistance Ratio
CSR	-	Cyclic Stress Ratio
r_d	-	Depth Correction
k_s	-	Dynamic seismic coefficient
F_s	-	Factor of Safety
α	deg	Fault slope angle
F_c	%	Fines content
l	m	Flood line
d_0	m	Initial inundation depth
h_0	m	Initial inundation height
d	m	Inundation depth
h	m	Inundation height
F_k	-	Kinematic factor of safety
P_l	-	Liquefaction Potential
MSF	-	Magnitude Scaling Factor
μ	-	Mean
M_w	-	Moment magnitude
PGA	-	Peak Ground Acceleration

β	-	Reliability Index for CRR
R	m	Runup elevation
A	m^2	Rupture area
d	m	Rupture depth
L	m	Rupture length
W	m	Rupture width
k	-	Seismic coefficient
M_0	Nm	Seismic moment
μ	Pa	Shear modulus
D	m	Slip
β	deg	Slope angle
H	m	Slope height
N_60	-	SPT Blows
σ	-	Standard deviation
D_v	m	Vertical deformation of the seabed
σ_v	MPa	Vertical overburden pressure

Chapter 1

Introduction

1.1 Relevance of tsunami hazard research in Chile

1.1.1 Tsunami history

Chile has faced many earthquakes and devastating tsunamis. The table A.1 in the appendix shows the main documented tsunami events in Chile's past. The main three events in Chile's history not only illustrate the significance of tsunami risk management, but they also introduce the main events that are relevant for the following research.

The last tsunami event formed a trigger for Chile's renewed effort to manage the tsunami risk. This happened in 2012 just south of Santiago, the epicenter 150km from Concepcion. The earthquake occurred at 03:34 a.m. [Tercera] in combination with the following tsunami caused about 575 lives [USGS].

The largest earthquake ever recorded, happened only fifty years earlier in 1960. An earthquake with a magnitude of $9.6M_w$ occurred near Temuco at 13:11 p.m. in the afternoon. The event took approximately 1,655 lives in Chile and most damage was observed in Valdivia [USGS].

Also in the north of Chile large tsunami events have been recorded. In 1877 [USGS] an earthquake with magnitude 8.8 [Chlieh et al., 2011b] hit the north of Chile in the afternoon at 06:59 p.m. The resulting tsunami had a runup height of 21 meters [SHOA].

It has been stated that regarding these historic events a similar future event is likely to occur. The port city of Iquique in northern Chile is considered to be highly sensitive for the effects of a tsunami. This city has a large number of inhabitants at risk, a port that is vital for its economy and areas that are difficult to evacuate. These characteristics make Iquique as a case study both essential and interesting for tsunami risk management.

1.1.2 Characteristics of Iquique

Iquique is located in a dry, coastal region. The city is enclosed by the Atlantic Ocean in the East and the Andes mountains in the West, it has for this reason north-south oriented. The city is characterised by it's port, a large tax free shopping area in the North, some commercial area in downtown and further mainly residential areas. The street pattern of Iquique is based on a simple grid, where different types of buildings can be found.

Zoning of the city of Iquique

For evacuation practice, the municipality of Iquique has identified five zones, all at risk:

- Zone 1, contains the area with the tax free shopping mall Zofri (daily av. Visitors 15.000) and the surrounding not publicly accessible warehouses;
- Zone 2, city center and port (approx. 600 workers), includes Playa Bellavista;
- Zone 3, residential area, includes Playa Cavancha;
- Zone 4, residential area, includes Playa Brava;
- Zone 5, residential area

These zones are used in the course of this research.

1.2 Research boundaries

In this section, the boundaries of the research are given by means of the focus of the customer, the problem definition, the project scope and limitations, the goals, and the solution scope. It results in the formulation of the main question and some subquestions.

1.2.1 Problem definition and demarcation

Focus as stated by the customer

The focus of the research, as stated by the customer, the CIGIDEN research center from la Pontificia Universidad Catolica de Chile: "The work you will conduct will contribute to the advancement of the Extreme Event Scenario case study in the city of Iquique, in view of improving the preparedness and response of critical infrastructure and communities confronted with a potential mega thrust earthquake and tsunami."

Problem definition

The city and port of Iquique should be prepared for the risk of an eventual tsunami.

Research project scope and limitations

For the case study Iquique, will the project team research tsunami flooding, and its relation to local soil conditions, infrastructure and built environment. The project team will research current activities in tsunami risk management in Chile.The project team will research international examples of measures, only if these are within the solution scope and if these are both complimentary and beneficial to Chilean practices. The research will not elaborate on financial aspects, due to a lack of information on local financial environments.

Solution scope

As a solution to the problem defined in the problem definition, measures are searched within the mentioned activity areas (prediction, mitigation and response). These measures should have a (well underpinned and) reasonable chance of success and their implementation should not be risky due to huge investment costs. The measures should lead to (in order of priority):

1. Prevention of casualties;
2. Minimization of economic damage;
3. Return to normal operational status (which is not taken into account because of the demarcated project scope.

Goals of the research

1. Identify and prioritise weaknesses in current tsunami risk management in Iquique, Chile
2. Provide options to overcome weaknesses and recognize knowledge gaps
3. Provide options to overcome knowledge gaps
4. Combine the provided options in order to establish tsunami hazard management plans in Iquique, Chile
5. Generalize research steps for a proposal of an integrated multidisciplinary framework for tsunami risk assessment

Goal of the eventual multidisciplinary framework would be to provide methods to establish an integral tsunami contingency plan. In the future such a framework needs to be delivered by the CIGIDEN research center to any (local) government.

Goal of the eventual tsunami hazard management plans would be to prevent victims and minimize economic damage in Iquique. In the future these plans need to be delivered by the (local) government to its people.

1.2.2 Research questions

The main research question is: How can victims and economic damage due to tsunami flooding be minimized in the port and city of Iquique, Chile?

The research sub questions that will answered during the project:

1. What are the weaknesses of current evacuation plans?
2. What are the hydraulic boundary conditions for flood risk?
3. To what extent do geo-technical conditions influence the possibilities of evacuation?
4. To what extent can the built environment improve the possibilities of evacuation?
5. Which evacuation processes are organized in case of an expected tsunami flooding?

1.2.3 Current tsunami risk management in Chile

This subsection on current tsunami risk management, focus is on current practices in Chile concerning tsunami prediction, mitigation and response.

Activity areas in natural hazard management

Risk management concerns the broadest way of dealing with tsunamis, ranging from origin till effects. In order to end up with a plan for prevention of victims and minimization of economic damage, focus could be put on the hazardous event, that lies on the basis of the risk. For this research, the hazard is formed by a tsunami. In tsunami hazard management, all activities can or should be found to practically deal with the event (in order to become resilient). Several activity areas can be distinguished, that can be put in a timeframe in which the occurrence of the tsunami forms the central event, as shown in figure 1.1. Activity areas prediction and mitigation can be found in advance of the (tsunami) hazard. Response and recovery activities always take place after the hazard event. Because of time constraints recovery activities are not taking into account in this research. Of course this activity area is a very important topic, critical for resilience of the system.

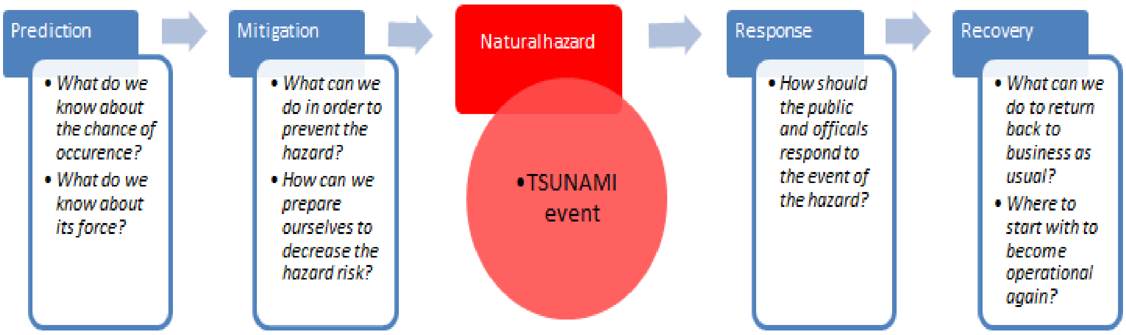


FIGURE 1.1: Activity Areas for tsunami hazard management [Tal].

Current tsunami prediction

A tsunami is a natural hazard with a low probability of occurrence but it can hold incredibly severe consequences, especially for urban coastal zones. In the above explained activity areas of hazard risk management the current situation in Chile on tsunami risk management is analysed. The first layer of safety considered is prediction.

Iquique lies on a subduction zone where the oceanic Nazca plate moves below the South

American Cratonic plate. As local history has proven that the area is very susceptible to earthquakes and even tsunamis (section 1.1.1).

This however, does not automatically justify the fear of incoming tsunamis in the future. To get an idea on the probability of tsunamis in the area both the state of the subduction fault needs to be considered and the potential for significant earthquakes. This can be investigated using GPS measurements of horizontal and vertical deformations of land across Northern Chile to quantify building up strain that might cause significant earthquakes. The use of GPS has been done before in Chile to predict the risk of earthquakes of the coast of Concepcíon near the Bio Bio river (600 km south of Santiago). An investigation of 2008 stated that in the coming decades an earthquake of magnitude $> 8.0Mw$ would occur [Ruegga et al., 2012]. In this event too, strain was building due to the locking between the oceanic and continental plates. In 2010 the predicted earthquake occurred along the expected location of the fault and a Tsunami devastated the coast of Concepcíon.

With the use of the interseismic coupling ratio (ISC) which is the ratio of slip deficit rate and the long-term slip rate, the potential moment (potential energy) at locations along the subduction zone can be approximated. The long-term slip rate at the latitude of Iquique is about 56mm/year [Metois et al., 2012], if the plates creeped over each other without seismics, ICS would be zero, and the local slip rate would also be 56mm/year. This however is not the case, the slip rate in the north of Chile is at some locations even close to zero [Chlieh et al., 2011b] which means that a large moment is being built up. Since then moment has only been building up, and only a handful of large earthquakes have released less than 7% of the moment that was released in 1877 [Chlieh et al., 2011b].

Using similar theories, assumptions, and models done by Ruegga et al. [2012], it can be concluded that the danger in the North is very real and justifies the effort to improve Iquique's ability to respond to Tsunamis.

Current tsunami flood mitigation

Various official parties are involved in the mitigation of exposed risk, which in Chile is restricted to evacuation plans. Prevention of tsunami flood by means of hydraulic structures is not practiced in Iquique and beyond the scope of this research. Basically two ways are known for evacuation: evacuation to higher ground and vertical evacuation (in buildings). Procedures for evacuation to safety zones are worked out by the government. Evacuation routes have been determined by ONEMI, while the municipality is responsible for the disposition of evacuation signs. During the last decade, the various involved stakeholders have proved not very unanimous in their implementations of evacuation policies. Over the years various evacuation maps, with various safety lines have circulated and the 2010 tsunami still is subject to debate about responsibilities. Nevertheless, there appears to exist a rough consensus on where to go in case of emergency; people will run up the hill, past the safety zone signs and preferably even further.

Vertical evacuation is more complicated and is currently not implemented in official policies made by the (local) government. Besides the preference of people to evacuate out of large buildings rather than in them, this is complicated by a lack of certification. Currently, there are no building codes available that give guidelines for tsunami based engineering, but structures are built according to earthquake building codes.

Current tsunami flood response

Current evacuation protocols are set up both by ONEMI and the municipality. ONEMI provides the evacuation paths and the municipality provides the evacuation signs.

- Communication between operating officials (and organisations) is been poorly executed during emergencies
- Responsible officials might have sent wrong information to the public (trials going on about this...)
- Coordination between the different organisations is not clearly distinguished

1.3 Report outline

The report has five chapters, which contain the following research steps:

1. In the introduction the research topic and the case study are introduced, and research questions are stated.
2. A proposal for a multidisciplinairy framework is given together with criteria to evaluate it.

3. The case study is worked out for all disciplines.

4. The framework is evaluated for the case study, by means of the criteria established; recommendations are given on the use of the proposed framework.

5. Conclusion on the research are given and discussion on the framework-versus-case study methodology is elaborated on.

Chapter 2

Proposal for a framework

2.1 Introduction to the framework

In this section a proposal for a framework is given, together with a framework system analysis of tsunami hazard management. As the framework entails a proposal, it must not be considered applicable in a complete form.

2.1.1 Framework goal and design

Goal of the framework

As indicated in section 1.2, a multidisciplinary framework should provide methods from all involved disciplines related to tsunami hazard management. This framework should be a guide for both decision makers and specialists.
In order to design a framework, the city of Iquique has been used as a case study. Basically, this means that while studying on the situation in Iquique, the followed reasoning has been extracted into a general approach.

Framework aspects

In order to be successful, the framework should contain both textual and visual aspects, strengthening each other. A few criteria for the design are that it should be easily modifiable, should emphasize on priorities, should be written in English, should use unified and accepted standards, and should integrate the subjects of all different disciplines. Furthermore, the visual parts of the framework should be easy to understand and consistent with the text. When needed, the visual part should make direct use by the client possible.

2.1.2 Framework system analysis

In this subsection the system that covers the tsunami event and all possible measures (in all activity areas) has been pictured and analyzed. For a detailed description of the case study system analysis, see figure 3.5.1.

The need for system analysis

For a multidisciplinary assessment of tsunami risks, an endless amount of factors can be chosen, to take into account. In order to reach agreement on which factors should be included and which factors not, the study environment should and has been defined as a system. The analysis that preceeds this definition has some negativities, such as a strong dependence on analyst' perception and its time restrictions. Nevertheless, the system analysis has structured the large, complex problem that's attached to tsunami risk.

Results from system analysis

The main result of the system analysis has been presented in a Causal Relation Diagram shown in figure B.7. In this diagram all factors have been identified, as well as their interrelations. The colors in the diagram indicate to which discipline the factors are related. Even though psychology has not been part of research team, factors from this discipline have been add, stressing the need for further involvement of this scientific field. These factors are especially of significance for factors of TIL.

Different types of factors can be found in the diagram. A **factor of means** depicts possible means that are available for the problem owner to influence the system. For example, the municipality of Iquique could increase the *available vertical evacuation areas* by building new ones. A **factor of performance** depicts objectives of the problem owner or is a criterion for success of evacuation. For example, the amount of vertical evacuation areas could increase the total safety zone area. An **external factor** is a factor that does influence the system, but cannot be influenced by the problem owner. It often has an unpredictable character. For example, the *experienced moment magnitude* can't be influenced, but it does have influence the *available vertical evacuation areas.*

Even though it could be done the other way, it is advised to read the diagram starting at a performance factor and ending at an external factor. This way it can be found how desired improvements can be achieved, and by what external factors these are influenced.

FIGURE 2.1: Causal Relation Diagram

In appendix B the derivation of the diagram can be found.

2.2 Criteria for evaluation (RAMS)

To be able to successfully design a framework that can be used to improve tsunami risk management to reduce life-loss and economic damage it needs to include an evaluation of the product. By considering the plan as a technical system, it can be evaluated for *reliability, availability, maintainability, and safety* (RAMS). In this section, these four criteria are defined and related to tsunami risk management.

Reliability

"Reliability denotes a product or system's ability to perform a specific function and may be given as design reliability or operational reliability" [Norweigian.University.of.Science.and.Technology] The main function of the contingency plan is to reduce loss of life and economic loss during tsunami inundation. To be able test this, acceptable life-loss and economic damage

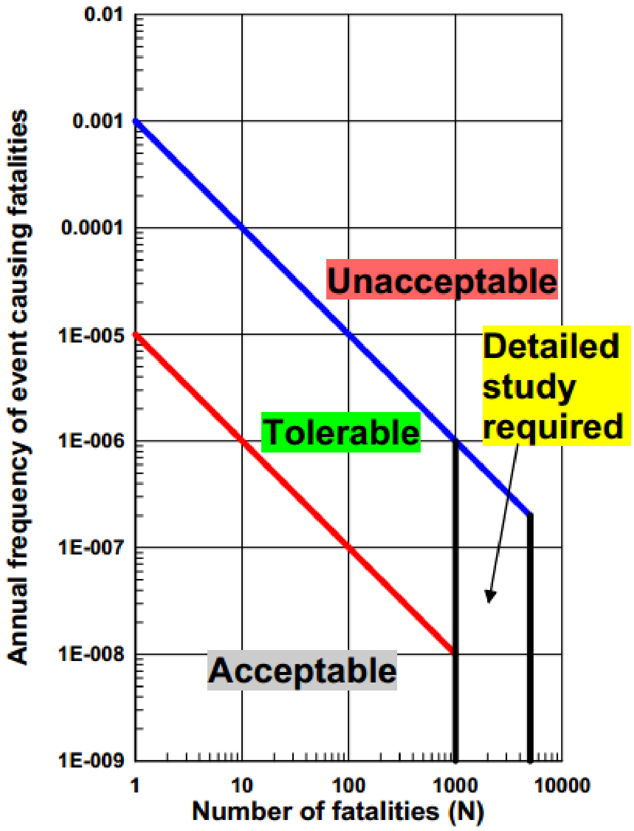


FIGURE 2.2: Level of acceptable life-loss according to the Hong Kong Geo-technical Engineering Office. [Farrohk, 2006]

needs to be determined. Such studies are beyond the scope of this report and no literature was found dealing particularly with Chilean acceptance of risk. It is however very useful for any organisation to be able to test their own product, to determine if extra funding, research, etc. is necessary. International examples can be used, for example the level of fatalities taken from the Hong Kong Geo-technical Engineering Office [Farrohk, 2006] as shown in figure 2.2. Testing the reliability involves comparing the acceptable losses to the projected losses which can be done with various models mentioned in this report. These however remain models, and true evaluation of the reliability can only be done in the case of a tsunami event.

Availability

"Availability denotes the ability of a system to be kept in a functioning state" [Norweigian.University.of.Science.and.Technology]. To rate the availability of the application of the contingency plan, the ease of implementation needs to be investigated. This includes the ease with which plans can be applied to the location taking into account

cultural, geo-technical, and hydraulic issues. Furthermore feasibility for the target areas to apply the plan, keeping in mind budgetary issues, is relevant for availability.

Maintainability

"Maintainability is determined by the ease at which the product or system can be repaired or maintained" [Norweigian.University.of.Science.and.Technology]. Tsunami risk management is inherently a long-term project. The occurrence of the hazard is very difficult to predict, where predictions can vary from years to centuries. Therefore the framework has a very long life time, which means it will have to be well maintained. This includes maintenance of evacuation routes, safety structures, alarm systems, education programs, policy, etc..

Safety

"Safety denotes what risk it is for harming people, the environment, or any other assets during a system's life cycle" [Norweigian.University.of.Science.and.Technology]. Rating the safety of the contingency plan is not related to the risks associated with tsunamis but the risks associated with implementing the plan. For example, it might create unnecessary panic or building mitigation structures could cause environmental damage. A successful plan will be implemented and used with a minimum of added risks to any parties involved.

Using the criteria in RAMS to evaluate the plan, further improvements can be developed or important weaknesses identified.

2.3 Hydraulic analyses

In this section the hydraulic conditions are considered in relation to tsunami risk management. The description of the generation, propagation and arrival of tsunami waves shapes the boundary conditions for the risk. Probabilistic assessment of possible scenario's results in information on for example wave arrival times, inundation depths, and flow velocities. In the context of the previously described activity areas the hydraulic issues will be part of the prediction in case of looking at tsunami risk.

2.3.1 Tsunami generation

A tsunami can be generated by different causes, of which in this report only an earthquake located at sea will be addressed. This report is also limited to locally generated tsunamis since in Chile these are governing for the covered topics.

Possible scenarios for earthquakes inducing tsunamis can be found by investigation of plate tectonics and local seismic history. Often such research is based on GPS measurements, historical eye-witness reports and fault modelling. These subduction zones are almost always located up to hundreds of kilometers below the ocean floor, which in itself can be inaccesible from above already. For this reason any predictions made regarding possible future earthquakes always contain a high uncertainty.

The deformation of the ocean bottom is translated to a surface water elevation. The degree to which this elevation follows the bottom deformation can be determined using methods proposed by [Hammack]. Considering a deformation area with a much larger length than width, this surface elevation propagates mainly in two opposite directions; perpendicular to the length axis of the fault, with both propagating waves having half the amplitude of the initial surface elevation. In reality the rupture of the seismic area is a process that takes time, so multiple waves could be generated.

Dependent on the location and size of the rupture zone also subsidence of the land may play an important role. Especially when looking at tsunamis with a high level of risk, which are often generated by high magnitude earthquakes, subsidence can be considerable. If subsidence occurs at the coastal zone that is being invistigated this will lead to an increase of the risk.

2.3.2 Propagation of tsunami waves

The propagating wave has a wavelength which is much larger than the depth of the ocean and a waveheight which is much smaller than the depth of the ocean. For this reason tsunami waves propagating in oceanic waters can be described using hydrostatic, shallow water equations.

As the tsunami waves approach the coast, the water depth decreases and regular phenomena like shoaling and refraction start acting. Using the shallow water wave celerity and Green's law, a relation between the wave height on the ocean and the nearshore can be established:

$$\frac{h}{h_0} = \left(\frac{d_0}{d}\right)^{1/4} \tag{2.1}$$

Futhermore there are a lot of other phenomena on local scale that play an important role regarding wave characteristics. Depending on bathymetry and coastline geometry these can be for example: focussing of wave energy on headlands, spreading of wave energy at convex coastlines, resonance and reflection at embayments, wave trapping at ridges, etc.

2.3.3 Arrival of tsunami waves

When the tsunami waves approach the coast they will break at a certain point. Due to the high amount of energy that the waves carry the water flow however keeps moving inland for a large distance. Depending on the tsunami characteristics, local topography, and possible preventive measures serious floodings are often a direct consequence of tsunamis. Although wave heights can be considerable, it is mainly the run up that determines the amount of inundation and potential damage. The runup is dependent on the beach slope and wave steepness and due to the very small steepness of tsunami waves the run up can be considerable. For a clarification of definitions see figure 4.1. Due to the slope of the land water will often also retreat again, so receding waves develop. As described above there are a lot of phenomena that play a role on local scale. Therefore considering a set location, a series of incoming and receding waves could develop causing varying inundation levels and flow velocities in time. Furthermore regarding the extend of flooding the tidal elevation can be an important factor. Because the exact time of rupture is nearly impossible to predict it is difficult to make a probabilistic assessment of the tidal elevation at time of tsunami occurence. For tsunami risk management this means that for a worst case scenario regarding flooding, high tide is governing.

2.3.4 Tsunami modelling

Taking into account the above mentioned issues, it becomes very difficult to make a simple assessment of the risks. Even though estimates can be made of tsunami characteristics in oceanic waters, given that a potential earthquake scenario is available, local effects make it almost impossible to transpose these characteristics to the coastline in a simple manner. To be able to make a decent assessment on the risks it becomes a necessity to use numerical simulation methods. Drawbacks of numerical modelling however are that for an accurate result, high resolution data on topography and bathymetry is needed. On top of that setting up these models and running them requires skilled specialists and is time consuming and therefore often involves considerable costs.

Different numerical models exist for computing initial deformations, wave propagation, and inundation. Depending on time and budget constraints and availability an assessment should be made on which models are used. These models can give approximations of wave arrival times, inundation depths, and flow velocities. Models on generation and propagation are fairly advanced, but especially models regarding inundation are still under constant development. Most limiting in inundation models is including the built environment in the calculations. For a sound calculation on actual local inundation and flow velocities full 3D models using very high resolution data would be necesarry.

Results from the modellig can be used to assess time available for evacuation,determining safety zones, inundation depths to estimate economic damage and flow velocities to determine loads on structures. However, as described above the modelling results do contain some uncertainties that should be accounted for.

2.4 Geo-technical analyses

In this section the geo-technical conditions are considered in relation to tsunami risk management. A successful understanding of ground conditions and geo-technical risks is a real benefit to a multidisciplinary approach to tsunami risk management. The situation in the subsurface will play a significant role on evacuation capabilities since it dictates the magnitude and type of damage on evacuation routes, safety zones, and important infrastructure to the evacuation effort. Understanding of potential slope failures, liquefaction, etc. will help decision makers design proper evacuation routes and safety zones. It is also very important to include geo-technical aspects when using man-made structures in the evacuation plan, for example the stability of foundations for vertical evacuation. In addition, knowledge from other disciplines will improve the understanding of the geo-technical conditions. By knowing what the best evacuation routes could be, necessary geo-technical evaluations can be identified such that not all risks are necessary to evaluate. Furthermore information on inundation heights and water flow velocities are required to successfully analyse risks associated with water induced strength loss or scouring.

2.4.1 Risk of slope failure for evacuation

Due to the cyclic loading on the ground due to the preceding earthquake and the tsunami itself the stability of slopes change. It is important to identify the probability of landslides and the impact on evacuation during Tsunamis. This includes the stability of slopes before and during evacuation and the stability of slopes during inundation.

Analyis of slope stability during earthquakes, the screening process

Due to time and budget constraints it is not always possible to analyse each slope in the area extensively for landslide risk. Therefore a screening process can be used to determine if further analysis is needed. This involves a look at both probability and consequence of a landslide for all slopes in the area.

Consequence: The first question to be answered is the matter of consequence. If a landslide were to occur, to what extend will it affect the management of the tsunami risk? The following aspects should be investigated with the aid of road maps, evacuation plans, inundation heights, population distribution, and geological information.

- Will a potential landslide hinder the evacuation of pedestrians and/or vehicles?
- Will a potential landslide cause damage to evacuation routes or routes needed for first response like medical aid for survivors?
- Will a potential landslide cause damage to city life lines like water and electricity, either above or under ground?

Probability: The second matter is that of probability. Even if there is a direct or indirect consequence of a landslide for tsunami risk management, the probability of the landslide occurring could be too low to be of importance. To determine if a slope might fail during an earthquake, different failure mechanisms need to be considered. This could be circular failure from the top of the slope through the toe, superficial flows, or discrete failures like toppling. Each mode of failure will call for different analysis methods and is dictated by the nature of the slope and the ground it is made of. Due to the complexity of the mechanics during earthquakes the combination of empirical and analytical methods are used in the form of slope stability charts and limit equilibrium methods (LE). Using data from back analysis done at sites hit by earthquakes, magnitudes and subsurface properties can be compared to the probability of landslides.

Loose soil slope failure: For soil slopes where bedrock is expected to be deep and not interfere with the slip surface, Taylor stability charts can be used in combination with pseudo static theory [Baker et al., 2006]. Here the angle of the slope, cohesion (c), internal friction angle (ϕ), slope height (H), and the seismic coefficient (k) can be used to determine the load safety of factor (F_k). k is dependent on the maximum horizontal acceleration caused by the earthquake and can often be found in the buildings codes of the local area since it is used for designing buildings in seismic areas. If these are not available there are some rules of thumb relating expected earthquake magnitude to k [Baker et al., 2006]. The limit seismic coefficient (k_c) can be used to find F_k using equation 2.2 [Baker et al., 2006].

$$F_k = k_c/k \tag{2.2}$$

This method makes one very important assumption, that the ground mass does not change strength characteristics. This implies that phenomena like liquefaction do not occur. Liquefaction will be considered later in the chapter.

Rock slope failure: In many cases the slope will be made of rock rather than soil. The method that can be used for rock failure depends on whether the slope can be considered as a continuum (either very fractured or not at all) or as discrete (clear planes of failure and weakness). If the rock is considered a continuum a pseudo static method and Hoek & Brown theory can be used to analyse slope stability [Li et al., 2008]. Here it is important to use material properties that are determined in cyclic conditions. If the rock is not continuous, the analysis should be done along expected failure surfaces like bedding planes or fracture surfaces. In this case the fractures need to be investigated for friction angle, fill, water conditions, etc. Potential failure planes can be identified using kinematic analysis of fracture orientations and slope angles. Then to determine if the rock mass will indeed fail during a seismic event a pseudo static analysis can be done using k and mass strength properties.

Superficial slope failure: The third type of slope failure considered in this report is superficial slope failure. Many slopes are made of multiple layers of ground with varying strength properties. Therefore during earthquakes, superficial flows are very likely. This could be either soft soil laying on top of stronger rock or loose rock overlying either soil or rock layers. To analyse superficial flow, the potential failure surfaces need to be identified. This could be layers of loose sand, saturated clay, boulders, etc. Then, similarly to analysing moderately fractured rock slopes, the potential for failure can be investigated kinematically. Finally the slope failure can be analysed with strength and seismic properties.

Further Analysis

The methods mentioned above are all relatively simple, as that they do not need an extensive soil investigation. Therefore, the screening process only gives an idea of stability and due to its conservative nature it is suggested that if a slope is found to be instable further investigation should be done as the next step. This is best done with the aid of numerical models like the method of slices that analyses a slope in separate slices. More extensive models are only useful if more soil mechanics data is available, so in-situ tests and lab testing of samples will be needed. In addition, if the strength of the soil is expected to change this should be accounted for which will need the help of numerical simulations. Finally they will allow the use of a probabilistic approach rather than the deterministic one used in the screening process. This will show an improved analysis of failure probability and an idea of the extent of possible landslides.

Analyis of slope stability during tsunami inundation

Methods for mitigation

Besides simply avoiding the slopes as a whole, there are available methods to reduce the risk of landslides. The method to use depends on the ground conditions, ground water conditions, and available budget. Examples of mitigation methods are; complete avoidance of consequences of a landslide by moving any important structures away from the slope, soil improvement (e.g cementation), rock bolting, support walls, and many more.

2.4.2 Risk of liquefaction for evacuation

Liquefaction is the complete reduction of soil strength due to increase in pore water pressure as a result of loading (static or cyclic) if the water is not allowed to escape sufficiently fast. Liquefaction can occur in loosely packed saturated sands and can lead to failures of surrounding buildings, roads, pathways, slopes, etc. Due to the cyclic loads on the soil during earthquakes, liquefaction is a necessary risk to investigate. In addition, the tsunami can dramatically change loading and water conditions in the sand which could also lead to liquefaction.

Analysis of liquefaction potential during earthquakes

Similarly to slope stability, analysis of liquefaction induced by earthquakes can be based on empirical and analytical methods. With the use of Cone Penetration Test (CPT) analysis in earthquake zones and degree of liquefaction some rules of thumb have been developed for preliminary judgment of liquefaction risk [Yuan et al., 2003] In Chile it is more common to use Standard Penetration Tests (SPT's), especially in the north since the subsurface is mostly sand and rock rather than soft soils. Empirical relations for SPT's and liquefaction have also been developed [Martin and Lew, 1999], [Hwang et al., 2004] and are elaborated in appendix B.

Analysis of liquefaction potential during tsunamis

During the tsunami inundation liquefaction can also occur. The increase in weight on the subsurface from the water could lead to liquefaction, if the soil has not already liquefied due to the earthquake [Yeh et al., 2012]. Besides the load, the water could infiltrate into the soil and change the ground conditions such that previously non-liquefiable soils become liquefiable. Before analysing the risk of this happening, it is important to determine the important locations for which the consequence of this risk is highest, for example foundations of vertical evacuation buildings or safety zones. Furthermore, due to the fast movement of water, the chance of soils becoming saturated is very small but if the water remains in places where normally there is none the long term effect could indeed be ground failure since the water has time to infiltrate.

Reducing risk associated with liquefaction

Besides predicting liquefaction probability, it is possible to reduce the risk. This includes ground improvement like densification, altering building practice, or complete avoidance of danger zones.

2.4.3 Other geo-technical risks

Besides the two geo-technical risks elaborated in this chapter, there are a few more that should be considered. These include ground shaking, scouring, and water related strength reduction.

Ground shaking: An obvious effect from the earthquake is ground shaking. Depending on the magnitude and amplification due to soil conditions, structures can be damaged by

Soil type A	$V_s > 1500m/sec$	Includes unweathered intrusive igneous rock. Occurs infrequently in the bay area. We consider it with type B (both A and B are represented by the color blue on the map). Soil types A and B do not contribute greatly to shaking amplification.
Soil type B	$1500m/sec > V_s > 750m/sec$	Includes volcanics, most Mesozoic bedrock, and some Franciscan bedrock. (Mesozoic rocks are between 245 and 64 million years old. The Franciscan Complex is a Mesozoic unit that is common in the Bay Area.)
Soil type C	$750m/sec > V_s > 350m/sec$	Includes some Quaternary (less than 1.8 million years old) sands, sandstones and mud stones, some Upper Tertiary (1.8 to 24 million years old) sandstones, mud stones and limestone, some Lower Tertiary (24 to 64 million years old) mud stones and sandstones, and Franciscan melange and serpentine.
Soil type D	$350m/sec > V_s > 200m/sec$	Includes some Quaternary muds, sands, gravels, silts and mud. Significant amplification of shaking by these soils is generally expected.
Soil type E	$200m/sec > V_s$	Includes water-saturated mud and artificial fill. The strongest amplification of shaking due is expected for this soil type.

TABLE 2.1: Shear wave speeds for different soil types and corresponding amplification.

ground shaking. In areas close to subduction zones like Chile, buildings are constructed according to seismic codes that make them more resistant to ground shaking. Small damages however can still affect the response effort. For example a very common result of ground shaking is jamming of doors and windows due to small deformation and settlements. Although this will not directly harm anyone it will block evacuation out of or into the building. Another risk is the damage of pipelines or electricity poles that will leave the evacuation routes and safety zones without water and electricity. To analyse this risk the amplification of the seismic can be found. This is determined by classifying the soil as given in the table 2.1 taken from the USGS(United States Geological Survey) which shows the speed of shear waves for different soil types.

Scouring: During inundation and recession high water velocity could lead to scouring of loose sand. Another form of scouring is through dissolving, if soils are soluble in water like salt rich sands they too will wash away. This could lead to undercutting of infrastructure and ultimately failures, the structures that can suffer are roads, bridges, foundations, and walk ways.

Loss of soil strength: During inundation and water infiltration, liquefaction is an extreme event. Even if liquefaction does not occur, the soil could lose strength and lead to ground failure. Changes in hydrological conditions could lead to loss of soil strength when the weight of the overlying water recedes. This will mainly cause damages during and after inundation.

Mitigation of remaining geo-technical risks

Ground shaking: As mentioned, design codes in Chile account for seismic activity. Therefore extra mitigation of this risk is not very necessary. It is however important to realise that even though buildings might stay standing, the jamming of doors and windows needs to be addressed. A possibility would be to make sure that all households include a tool to force any doors or windows open, like an axe.

Scouring: The main damage caused by scouring will be on roads, pathways, bridges, shallow foundations, and over topped hydraulic structures and walls [Yeh et al., 2012]. To make sure that scouring does not cause further damage on such infrastructure, founding on loose soil should be avoided.

Loss of soil strength: The final risk is the loss of soil strength as a result of the change in load and hydraulic environment. Mitigation of further damage during inundation could include avoidance of loose soils, especially for safety zones. Another option is densification or cementation of soils, although these could be expensive options and will demand extra tests to determine if the soils is sufficiently improved.

2.5 Analyses of the built environment

2.5.1 Focus points for the built environment

Regarding the built environment there are several areas that can be focused on. Two of the areas that are covered in this report are assessing economic damage due to the tsunami event and secondly investigating the possibility of using the built environment for evacuation of people. For assessing the economic damage a lot of factors have to be taken into account, wherefore any estimates on this will contain large uncertainties. Nevertheless a first approach on this will be made. For the evacuation several mitigation methods can be applied and one option is to aim on the current built environment. Therefore the question arises, to what extend can the built environment improve the possibilities of evacuation? The evacuation of people in buildings is indicated by the CIGIDEN center as a viable solution. However, there is no current reliable knowledge about this solution. The building will be exerted to certain forces and flood level. The magnitude of the tsunami wave and the properties of the building will determine if a structure can be used for the evacuation of people. Literature study will provide a theoretical background to broaden knowledge, which results in a proposal to check if a structure is suitable for evacuation.

Assessing economic damage

Estimating the extent of economic damage on any town is a very complicated process. From only looking at physical damages to buildings, a long list of expenses appear. Besides the immediate cost of physical damage to the building, other costs could be damages to objects within the buildings, clean-up, relocation of victims, down-time of business, sentimental value, and many more. Because quantifying these costs is so difficult, in this report the analysis is limited to the immediate physical damage of structures and the resulting monetary loss. Assessing physical damage to structures can be done with the help of fragility curves [Mas et al., 2012b] shown in figure 2.3. These curves reflect empirically collected data from sites that experienced tsunami events in the recent past. Satellite data and inspection surveys have been used to investigate damaged towns and the local building culture. In addition, numerical models have been used to model the tsunami inundation to classify inundation depths, flow velocities, etc. Combining these three investigations, a relation can be made between building types and their fragility in tsunami events; the fragility curves. In addition to the graphical representation, it is possible to express the relationship with equation 2.3 which gives the probability of damage ($P(x)$) as a fitted log normal distribution function of inundation height (x), and the mean (μ') and standard deviation (σ') of $ln(x)$. These values are also given in figure 2.3 for the different fragility curves.

$$P(x) = log_{normal}(\frac{ln(x) - \mu'}{\sigma'}) \tag{2.3}$$

The curve made for Chile in figure 2.3(d) is based on the damage experienced by Dichato during the 2010 tsunami. Its use is limited to determine fragility for similar towns and buildings. Since Chile is very big with a high variety of natural resources, it has varying building cultures. Therefore, when analysing cities along the coast of Chile, it important to use the most suitable curve. A way in which this can be done is also using the other five curves in combination with the Chilean curve and account for the different building materials used locally.

To be able to put a monetary value to the immediate damage of the tsunami, the expected damage to the buildings needs to be valued. This can be done by using an analysis done in Australia, where values are given to different building types that can be found in any town [Blong, 2001]. The analysis is however based on values in Sydney so the data might not be perfectly relevant to Chile. It does nonetheless give an estimate that could be further improved with locally applicable values when these become available. The values for buildings are given in appendix B. Finally the economic damage can be expressed by multiplying the probability of damage from the fragility curves with the value of a specific structure. Assessment of the structure type for its value and the construction material for determining which fragility curve to use can be done best by doing a field visit, but a preliminary assessment can also be made by using Google street view.

Current tsunami risk management

Foreign tsunami events form the foundation for an overview of recommendations and some examples can be given. The important factors concerning the tsunami forces are described and an estimation is given for the resistance of a building. Structures in Chile are nowadays built according to the earthquake building code, which forms a governing load for the construction and is defined via a load-frequency spectrum [NCh433, 2009]. However, a lot of research is preformed concerning tsunami based engineering and researchers are starting to tackle this knowledge gap. As mentioned, no Chilean building codes are available these days, that give standards for tsunami based engineering. However, Chile published a new proposal for their building code. The 'Chilean Standard Project' (NCh). There are two codes available, the American Society of Civil Engineering Standard 7 (ASCE 7), and the City and County of Honolulu Building Code (CCH).

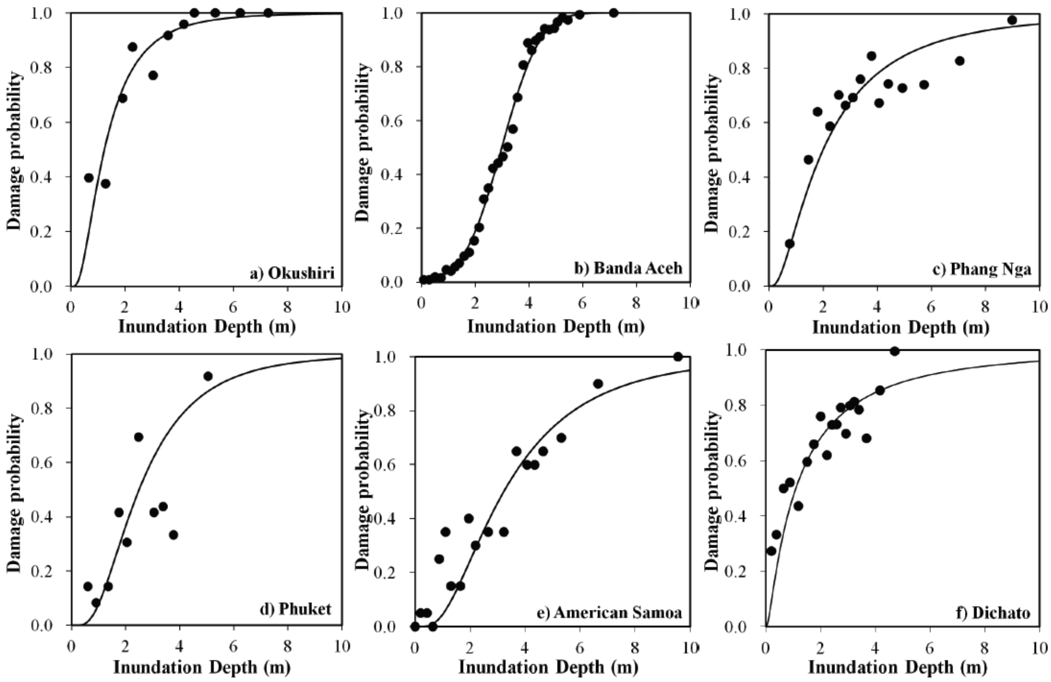


Figure 2.3: Fragility curves for structures effected by tsunami inundation developed for multiple locations in the world. (a) Japan; (b) Indonesia; (c),(d) Thailand; (e) American Samoa; (f) Chile. [Mas et al., 2012b]

There is also an important guideline, namely the Coastal Construction Manual of the Federal Emergency Management Agency (FEMA), where the Chilean Standard Project is based on.

Figure 2.4: An existing building in Japan designated as suitable for vertical evacuation within the high-risk zone and high-density population. The tsunami evacuation signboard is put on the building. [Fraser et al., 2011, p. 14]

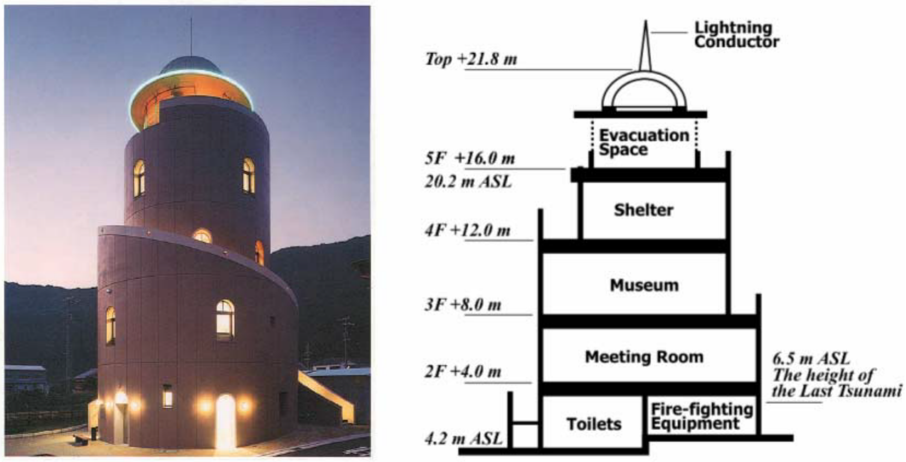


FIGURE 2.5: VE at Nishiki, Mie Prefecture – the Nishiki Tower consists of five levels and a circular plan shape to reduce lateral tsunami forces. [Fraser et al., 2011, p. 16]

International examples

It is shown that evacuation of people in structures has let to success in the past. In March 11, 2011 a devastating tsunami stroke a coastline in Japan, where the evacuation structures provide a safe refuge with success for thousands of survivors [Fraser, Leonard, Evans, Prasetya, Saunders, Pearse, and et al., 2011]. Examples of such structures are illustrated in figures 2.4 and 2.5. For the success of this, special considerations are to be taken. First of all should the elevation and height of the refuge be sufficient to provide safe evacuation. The second demand is that the building should be able to resist all effects of the maximum considered tsunami. Because of the required height, it is common to speak of Vertical Evacuation (VE).

Vertical Evacuation refuge

The ASCE 7 is not explicitly concerning tsunami based engineering. Therefore in the ASCE 7 recently work is being done on a new chapter: Tsunami Loads and Effects for the 2016 edition of the ASCE 7 Standard [Chock, 2013]. In this standard the necessity for structural safety is set by Risk Categories. These categories describe the importance or criticality of the facility and are dependent on e.g. the level of occupancy or the function. For example, a range is given for taller Risk Category two buildings. A minimum height of 20 meter is defined as sufficient for both reliable life safety and reasonable economics. Chock [2013, p. 3] links this type of taller risk category buildings to the type of building that is suitable for vertical evacuation and gives a clear definition: *'Vertical Evacuation Refuge Structures is a special classification of buildings and structures within* *the tsunami evacuation zone designated as a means of alternative evacuation in communities where sufficiently high ground does not exist or where the time available after the tsunami warning is not deemed to be adequate for full evacuation prior to tsunami arrival.'* Besides indicating the required safety levels of buildings it is of major importance to clarify the tsunami event to make an estimation of the forces that the water brings to the structures.

2.5.2 Tsunami Event

All codes illustrate and define the tsunami event and associated equations in a similar way, but there is no coherence in labeling the different parameters. For simplicity is an uniform description given for the labeling, which will be used in this report. The tsunami event is illustrated in figure 2.6 and the different parameters are listed in the appendix in table B.1.

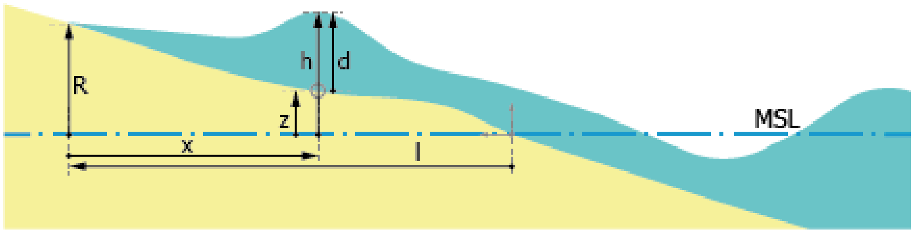


FIGURE 2.6: Illustrated tsunami terminologies

The inundation depth (d) is the height of tsunami water level with respect to the local surface level at a certain point of interest. The runup elevation (R) is the elevation above Mean Sea Level (MSL) at the tsunami inundation limit. The wave determines the magnitude of the associated hydraulic forces. Two important wave parameters are the flow velocity (u_p) and the momentum flux (du^2). These can be estimated using a numerical simulation model, which can provide a complete time history analysis of the parameters at the point of interest [Yeh, Robertson, and Preuss, 2005]. However, such models are not easily available and results may not be significantly accurate. Most codes offer, for this reason, analytical solutions that can be used as guidelines.

2.5.3 Vertical Evacuation design aspects

To ensure sufficient elevation height the conservative approach formulated by the ASCE 7 can be used, which is illustrated in figure 2.7: $h \geq 1.3R + 3m$. Here, the minimum elevation (h) has to be taken with the maximum possible flooding event. This is to prevent overtopping by the waves, which can cause overturning of some structures. There are several basic considerations for vertical evacuation structures regarding the location, several building characteristics, and the minimum expected performances. A diversity of reports prescribe rules and guidelines, which are used to indicate the desired properties that a certain structure should have to be suitable for VE.

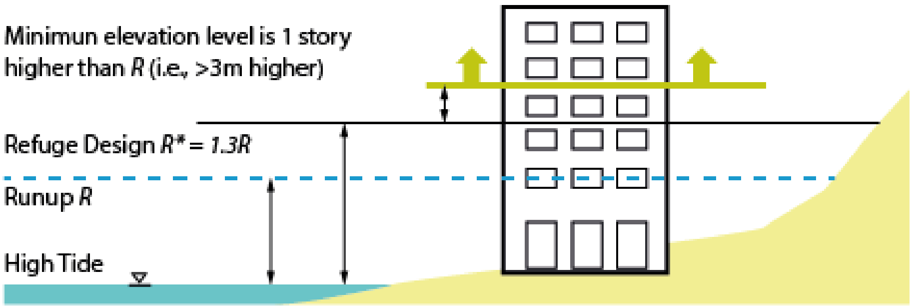


FIGURE 2.7: Minimum Refuge Elevation [Chock, 2013, p. 9]

Location

Vertical evacuation buildings should not be located next to the coastline, to avoid a direct impact and in order to consider the natural and learned behaviors of refugees. The location and distribution of VE structures should take into account the travel distance and speed and also the warning time from the tsunami alert. Time required to access the target floor and possible obstructions or other consequences from the previous earthquake are also very important [FEMAP646, 2012]. A second influence factor for the location is the distance to the shoreline. There is no specific guideline for this factor, but foreign examples of the past give an indication. Fraser et al. [2011] describe that in Thailand the majority of reinforced concrete buildings, except those very close to the shoreline, survived the 2004 tsunami with minor structural damage. These buildings where not specifically designed for tsunami or earthquakes. Also observed is that well-built buildings such as churches, which were located close to the shore, provided a protective function to buildings behind them during the 2009 South Pacific tsunami in Samoa. Site hazards form the last important factor concerning suitable locations for VE structures. According to FEMAP646 [2012] there are two hazards that can be particular to a location, debris or breaking waves. In case of structures that have to be built near ports, they must be designed as to withstand the impact forces from boats and other buoyant objects. On shore, breaking waves are very rare, but also very dangerous.

Recommended VE buildings are usually located inland, so that it does not become a real threat.

Structural aspects

The first floor configuration is determining the water to flow through. Minimum resistance will reduce the impact on the building. In order to achieve such requirements breakaway wall may be used. These walls are designed to collapse under certain forces, without damaging the structure or wearing down its resisting capacity. Fraser et al. [2011, p. 13] also mention that shear wall orientation should be parallel to the anticipated direction of the expected tsunami as to reduce the hydrodynamic load. Shear walls are structural walls and essential for the load carrying system of the building. Nonetheless, empirical data suggest that such factors do not have a significant impact on the performance of the structure. Another aspect to be aware of is the potential fire hazard. Either the earthquake or the tsunami can produce fires, by cutting power lines, which can ignite waterborne debris or floating oil. Reinforced Concrete (RC) behaves in most cases well in fire, but for steel structures additional measures should be taken [Fraser et al., 2011, p.211]. Besides that, the FEMAP646 [2012] noted that prestressed concrete floor systems can form a significant threat. They should be calculated to resist eventual buoyancy and hydrodynamic uplifts. The roof and floor systems should also be checked if they are able to resist the live load from the refugees. Foundations must consider the effects of scour and liquefaction, as they are amongst the main sources of collapse. The foundational and geo-technical analysis should also consider the effect of the uplift force due to the buoyant and other anti-gravitational forces. The design of large pile foundations should also consider additional lateral forces and the down drag due to the scour in the surface. Special scour recommendations can be found in the FEMAP646 [2012] code.

Capacity

The buildings should allow a large number of people in a short time above the inundation height. Fraser et al. [2011] even concerns the situation after the event. Access routes must remain operational and the building functional. The capacity of a building is not only dependent on the available space, but also on the type and duration of the occupancy. Depending on the duration additional services may be required. According to ICC-500 [2008] on the Design and Construction of Storm Shelters the required space per person during an evacuation is 10 square feet (0.93 m^2). The FEMAP646 mentions that the priority of VE structures is the accommodation of a large number of people, and should be designed with this objective in mind. Parking garages could be useful, but the height will be limiting. Hotels, however, could have large rooms above safe height in order to be used as evacuation sites [FEMAP646, 2012].

2.5.4 Criteria for structural analysis

A list of criteria can be used to evaluate the suitability of a building for vertical evacuation. The main criteria are the sufficient height and resiliency against all loads. The resistance of the building is a property that will require some amount information and knowledge for an useful analysis. The height, for example, is more easy to measure. For this reason it is advisable to preform the analysis of the built environment in steps. These steps will include a certain level of accuracy and eventually result in a first judgment.

1. **Location and height:** The location of the building is essential for the usability of a building for vertical evacuation. This location should be between the shore- and the flood line. The distance to shore is an important factor which influences the suitability of the location. As noted before, buildings that are located inland are favorable. People will prefer to run uphill, the wave force will be less inland and the ground elevation will probably be higher. The flood line can be determined according to the inundation map. If this map is not available it is advised to use the "safety evacuation area", which most cities already have.

   The building height is an important parameter. Sufficient height is necessary for a safe evacuation refuge. The height can easily be measured, even behind the desk by counting stories in Google Street View. Inundation maps are needed to determine the safe evacuation level. However, it is questionable if an inundation map is readily available. For this reason the indication of the ASCE 7, that 20 meters will be sufficient for reliable life safety, is used. This will be equal to a minimum amount of seven stories.

2. **Strength, stability, and stiffness:** The building should resist all loads. These are the earthquake-, hydraulic-, live- and dead loads. The knowledge and methodology to perform this step is presented in the following sections.

3. **Capacity and accessibility:** The available capacity should be equal or larger than the required capacity and is determined by the building size. The capacity can be estimated using the product of the height above safety level, the width, and the depth. This however is an upper boundary and should be evaluated if more information is available. The width and depth can be measured in Google Earth. The selected buildings have a certain accessibility, that is fixed by the product of the walking speed and the amount of evacuation time. To select the right vertical evacuation refuges the accessibility should be checked to ensure that every evacuee is able to arrive in time. It is important to include the time to enter the building and to get to the safety level.The amount of evacuees should be able to enter the building within the available evacuation time. The smallest passage is governing for the maximum flow of people.

4. **Foundation:** The foundation should withstand the earthquake and tsunami load. Therefore it has to be checked for liquefaction and scour. This step is discussed in section 2.4.

A certain amount of input data is required to check the criteria formulated in the different steps. To perform step 3 and 4 field work is required. A checklist can be helpful to collect the correct data. A checklist with the points of attention is added in appendix B.3. During the field work, it is important to validate the data retrieved via Google Earth and Street view. This report will not elaborate on these steps. The forces and resistance have to be defined, to perform step 2. The inundation depth, flow velocities and momentum fluxes have to be taken into account. The following sections will elaborate on this.

2.5.5 Considered tsunami characteristics

As discussed before, the analytical solution can be used to determine flood velocities (u) and the momentum fluxes (du^2) at a point of interest. The methods and equations to determine these values are further elaborated on in appendix . These values can be used as guidelines and to check results from numerical simulation model. Yeh et al. [2005] has developed some of these solutions, which are used and fine-tuned in the FEMAP646 [2012] standard. This analytical approach can also be found in the Chilean Project Standard, which gives rough estimations. Hence, it is interesting to compare the outcomes of the different standards with the results of the numerical simulation model.

2.5.6 Hydraulic loads analysis

As described earlier, structures in Chile are not designed to resist tsunami loads, but mainly to resist earthquake loads. The hydraulic loads have to be defined to be able to give a judgment about the suitability of a certain building for VE. Different tsunami forces are exerted on a structure. Not only the type and form of tsunami influence the force of the impact, but also the building layout, construction material, the surrounding area and many other factors. All standards provide equations and sometimes definitions to determine the different types of forces. These forces, hydrostatic, hydrodynamic, impact, and other forces are defined according to studies of Yeh et al. [2005]. Definitions of each force are given in appendix B.3.2.

The different standards give a variety of equations to determine the hydraulic loads. The parameters in these equations are dependent of the tsunami wave event, the location and the dimensions of the structural object. An overview of the different equations is presented in table B.2. At last loading combinations need to be considered. The types of forces, as described before, can occur at the same time on structural elements or on whole structures. The standards describe different load combinations. The impact forces F_i are not included in this analysis, and therefore it is appropriate to use a conservative approach and take all hydraulic forces into account.

2.5.7 Assessment of building resistance

Now the hydraulic loads (Q_{hyd}) are known, the question remains what a certain building can resist. A way to estimate the resistance of the building is to use the seismic design load (Q_{seis}). Nowadays the most governing load in the Chilean construction world is the earthquake load, given in the Chilean Standard [NCh433, 2009]. It is assumed that all buildings are designed and constructed conform this standard. Using this assumption, the seismic load can be used as in indication for the biggest load that a building can resist. The method to determine this load is further described in appendix B.4. The most important parameters can be separated in input data and classifications.

Input data:

- Number of stories: n
- Seismic weight of the building: $W = 1.0DL + 0.5LL$
- Reduction factor: R_0

Classification:

- Seismic zone: 1, 2 or 3
- Soil type: 1, 2, 3 or 4
- Building category: 1, 2, 3 or 4

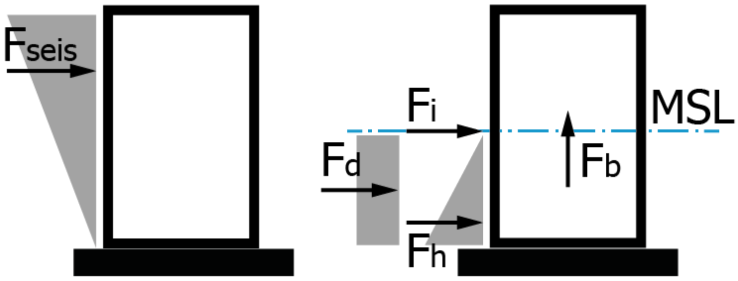


FIGURE 2.8: The seismic load (left) and the hydraulic loads (right) exerted on the building

2.5.8 Stability check

With the hydraulic forces determined and a threshold value for the resistance, the stability can be checked. Figure 2.8 gives an overview of the involved forces. An unity check is used to check in a quick matter if the building is stable. Uplift, sliding and overturning are the failure modes that have to be verified, as illustrated in figure 2.9. This results in three criteria regarding the stability of the building.

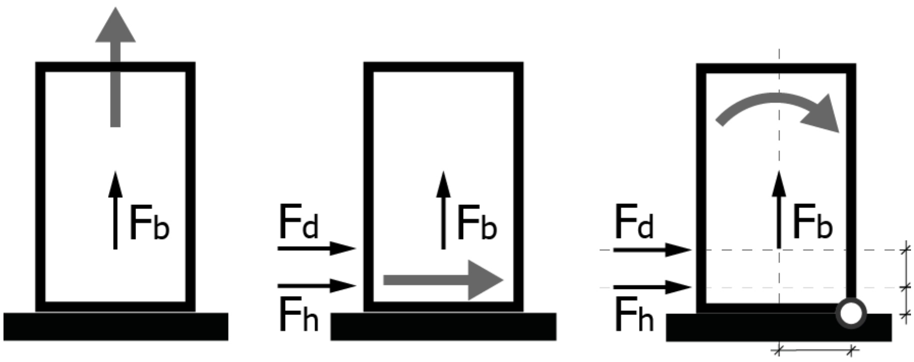


FIGURE 2.9: Possible failure modes: uplift (left), sliding (middle) and overturning (right)

$$\begin{aligned} \frac{F_b}{G} &\leq 1 \\ \frac{F_{hyd}}{F_{seis}} &\leq 1 \\ \frac{M_{hyd}}{M_{seis}} &\leq 1 \end{aligned} \tag{2.4}$$

- **Uplift:**

$$\begin{aligned} \frac{F_b}{G} &= \frac{\rho_s g A d}{n A G_n} \\ &= \frac{\rho_s g d}{n G_n} \quad \leq 1 \end{aligned} \tag{2.5}$$

Where G is the weight of the building in kN and n the number of stories. This forms a first criteria regarding the stability of the structure due to the hydraulic loads.

$$\Rightarrow \quad d \leq \frac{n G_n}{\rho_s g} \tag{2.6}$$

- **Sliding:**

$$\frac{F_{hyd}}{F_{seis}} = \frac{F_s + F_d + F_h}{F_{seis}} \leq 1 \tag{2.7}$$

This forms a second criteria regarding the stability of the structure due to the hydraulic loads.

$$\Rightarrow \quad F_s + F_d + F_h \leq F_{seis} \tag{2.8}$$

- **Overturning:**

$$\begin{aligned} \frac{M_{hyd}}{M_{seis}} &= \frac{\frac{1}{3} d F_h + d F_s + \frac{1}{2} d F_d}{\frac{2}{3} h F_{seis}} \\ &= \left(\frac{3}{2}\frac{d}{h}\right)\left(\frac{\frac{1}{3}F_h + F_s + \frac{1}{2}F_d}{F_{seis}}\right) \quad \leq 1 \end{aligned} \tag{2.9}$$

This is satisfied if $\frac{3}{2}\frac{d}{h} \leq 1$ and $\frac{1}{3}F_h + F_s + \frac{1}{2}F_d \leq F_{seis}$. If the building fulfills the requirement for uplift and sliding, than only the first condition has to be checked.

$$\Rightarrow \quad d \leq \frac{2}{3} h \tag{2.10}$$

2.6 Evacuation process analyses

2.6.1 Introduction to the evacuation process

Following the tsunami event, a response from both authorities and public can (and should) be expected. In order to seek safety, the public will search for places to wait for the tsunami to pass by. In order to provide safety for its people (it is assumed that, the authorities will start evacuation procedures. In this section, the entire evacuation process is taken into consideration. The procedures that are followed as a response, could be part of mitigation plans, made in advance of the event, but they could also be part of improvisation. Therefore, it could be stated that for evacuation processes, the line between mitigation and response activities is rather thin. At the same time, however, evacuation plans never turn out to be the same as evacuation practice.

In this section, a method has been made to analyse all evacuation processes, both organized in advance, and revealed. Therefore, the following steps are taken:

1. Main evacuation processes must be identified and important actors must be recognized;
2. Infrastructure that is used for evacuation procedures must be analysed;
3. A model approach must be chosen and a following model setup must be given, for comparison of intended results and practice;
4. Literature must be used to underpin model input;
5. Additional model input, especially for local information, must be acquired (by means of a survey).

These steps can be found in the following subsections.

2.6.2 Identification of important processes and actors

In this subsection first the stakeholders of tsunami hazard management are recognized and, secondly, the evacuation processes described.

Need for actor analysis

A framework is worthless if it is not applicable to the real world. In the real world all kind of actors (in different degree) contribute to tsunami hazard management. Actor analysis can provide insight in who's involved, and to what extent. This insight can help the client to derive the strategy to overcome opposing arguments among actors. The different perceptions, decisions, and actions that emerge from the different desires and goals, also have a big influence on evacuation processes.

Results from framework actor analysis

Various ways exist to start searching for involved actors. Brainstorm sessions, literature scans, internet based sources, historic news papers (on past tsunami events). More difficult is how to sort found actors. In the research two examples have been worked out, which can be found in appendix B. The first is a power vs. interest grid. In this grid for each found actor it can be determined how influential the actor is, and how interested. By uniting actors close to each other in the grid, the way of dealing with the actors can be found.

The results of the initial derived list of actors can be used as input for a actor chat. In such a chart, relations between actors can be identified, or questioned. The power vs. interest grid can be used to bring some hierarchal order in the chart, with then later should be varified by all the links that can be found. An initial actor chart can be found in appendix B.

Preparations for evacuation by the government and the people

After identification of the most relevant actors, the link with evacuation processes should be made. A tsunami hazard management plan, made by any responsible government, should provide the means to make people escape from the tsunami hazard. Such plans should be made well in advance of the hazard, because implementation of the plan is both essential and time-consuming. Sometimes these plans and related considerations are publicly accessible, because they are published. Therefore, the first step to acquire knowledge on mitigation plans, is to search on the internet. Secondly, for additional knowledge, interviews or specific investigations should be made, in collaboration with those responsible. In case the government does not see the need for tsunami hazard management, or denies it, both steps can be rather difficult.

Local inhabitants do not have any kind of official responsibility to publish their organized plans, and besides that, their number is likely lead to a huge variety of mitigation plans. Therefore, assessing how people prepare themselves is a huge job. Steps that could be considered are the use of surveying, or any other kind of door-to-door investigations. These steps mainly lead to stated preference knowledge, and is hard to compare or verify with revealed preferences. Another option is to assess the use of evacuation maps, provided by the government, but used by the people. Then again, the knowledge would be mainly based on stated preferences.

Use of flowchart

All acquired knowledge could be structured by means of a flowchart, in which the different activities, decisions, and events could be put in a timeframe. From the resulting flowchart, four different phases have been defined for the evacuation of a city. The first is the detection of the hazard, which for the tsunami event results from an occurring earthquake. The second is the evacuation phase, from which the evacuation of people is (gradually) started. Third phase concerns guarding of evacuation process, during which responsible authorities decide on how to instruct the public on evacuation proceedings. The final, fourth phase is the closure of evacuation, which concerns the decision of the authorities to end the evacuation.

The derived flowchart, which can be found in appendix C, indicates that most evacuation decisions and actions are government related, that the public however has a huge, but uncertain, influence on the evacuation process, and that many phases are hard to quantify. When more specified time units could be added to the flowchart, the effects of evacuation plans could be indicated better (than for example counting evacuees, or victims after a tsunami event).

2.6.3 Analysis of evacuation routes

In order to see how suitable evacuation routes and meeting points in safety zones are for made mitigation plans, the area of interest must be scanned. Besides for determining infrastructure' suitability, this information could be used for focusing at the most critical areas, and for development of evacuation simulations. The analysis concerns the following prioritized objectives:

1. Identify dangerous zones and specific dense cumulations of people, in order to see where improvement of mitigation plans should be done first;
2. Identify evacuation routes in dense cumulations, in order to see if successful evacuation of very dense areas (e.g. shopping mall) is possible;
3. Identify road infrastructure characteristics and suitability for evacuation, in order to see if general evacuation of the city is possible and to recognize possible bottlenecks;
4. Identify suitability of meeting points in higher grounds, in order to see if people arrived at the safety zones are actually safe;
5. Identify suitability of vertical shelters, in order to see if any alternative shelters exist for people in remote places;

In appendix B the stated objectives have been specified in questions.

To reach the objectives, use can be made of information from the internet (e.g. GoogleStreetview or GoogleEarth), field observations, and architectural and structural plans of buildings. The results should be compared with existing evacuation policies, to see if responsible authorities are missing possibilities for improvement of their mitigation plans.

2.6.4 Evacuation model choices

Need of evacuation modelling

Even though mitigation plans for evacuation can be established based on knowledge from prediction activities, actual evacuation processes might turn out to be completely different. Evacuation modelling could be used to see which effects mitigation measures could have (under various circumstances). After comparing modelling results to desired results, mitigation measures could be adapted, and (circle wise) be checked. Results from a simulation could for instance be: the number of estimated victims, the number of saved evacuees, the latest moment at which people need to depart for a successful evacuation, places where demand exceeds capacity (bottlenecks), and to what extent demand exceeds capacity.

The choice for the Agent Based Modelling approach

In the field of evacuation modelling various model approaches exist. In this research, the Agent Based Modelling (ABM) approach has been chosen for use in simulation. In current evacuation simulation modelling, this approach is used by many researchers [Mas et al., 2012b]. Pedestrian evacuation has been assumed predominant, because evacuation distances are relatively short (within approximately 25 minutes walking distance), and because use of cars during evacuation has been prohibited by the government. Even though modelling at micro-level is not strictly necessary for pedestrian simulation, simulation at micro-level gains the advantage that focus is on individuals (that e.g. have prior experience with tsunamis). In the ABM approach this behaviour of individuals (agents) can be modeled by means of relatively simple rules. Starting with very basic rules for agent behaviour (for instance simple shortest-path algorithm for route choice), rules on behaviour can be extended stepwise. Moreover, the use of many individuals (over 100,000 agents could be simulated concurrently), with varying behavioural rules, could reveal the connection between behaviour on micro-level and macro-level patterns that emerge from their agents' interactions [Mas et al., 2012a].

The proposed choice for NetLogo

For simulation of ABM scenarios, use of the NetLogo software is proposed. NetLogo is world-wide known multi-agent programming software [Northwestern.edu, 2013]. In NetLogo simulation, numerical simulation of tsunami flooding can be incorporated. This combination could lead to answering how evacuation practice will really proceed and what predominant evacuation mechanisms are.

In section 2.10 the concept for simulation with NetLogo is given.

Desired model scenarios for simulation

In the introduction to the framework, section 2.1, factors have been indicated that influence pedestrian evacuation. By studying the effects of different (values of these) factors, strategic scenarios can be defined, in which both policies and the environment of the system can vary.

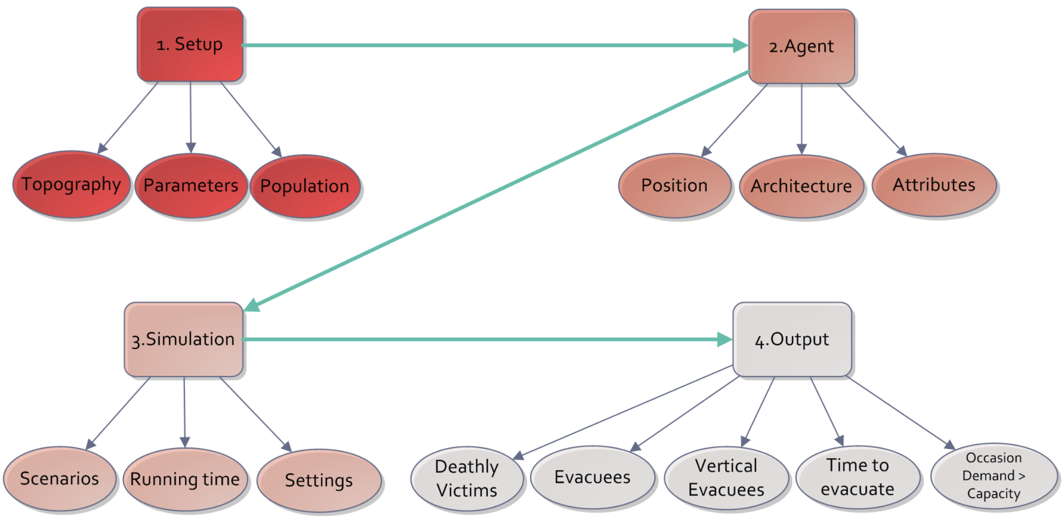


FIGURE 2.10: Concept for simulation with NetLogo

In order to enable quantitative simulation the derived factors need to be made operational, i.e. made appropriate for adding an unit. In the following table all factors of influence on pedestrian evacuation flows have been indicated (where possible with their units). To be precise, only factors that were either extern, means, or unsure are mentioned here. Three scenarios have been indicated, with inclusion of all factors for each scenario. Factor values range from 1 (least influential) till 5 (most influential).

Model validation

In order to check on the validity of derived models, calibration data could be used, or literature studies could be assessed. Difficulties here are that data on past (revealed) evacuations is not present, drill simulations (another type of revealed preference) are not reckoned to be very realistic because people don't take these drills very serious [CIGIDEN research center, 2013], and that stated preferences and revealed preferences are likely to vary largely. The use of literature might solve problems in doing the right assumptions for simulation.

2.6.5 Literature check on psycho-behavioural aspects

The table of scenarios (table 2.2) has pointed out that specific knowledge is required on people's behaviour and predominant evacuation phenomena. Therefore, a literature scan has been performed over 23 sources. The actual results of the scan can be found in Appendix B.

Factor	**Unit**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Extern	-	**Worst case**	**Regular case**	**Minimal case**
High tide	-	5	3	1
Wave height	[m]	5	3	1
Water depth	[m]	5	3	1
Speed of wave	[m/s]	5	3	1
Inundation level	[m]	5	3	1
Stability of the slope	[-]	1	3	5
Distance blocked per street	[m]	5	3	1
Daytime	[-]	5	5	1
Nighttime	[-]	1	1	5
Means	-	-	-	-
Amount of people in unsafe area	[no of persons]	5	3	1
Number of Vertical Evacuation buildings	[no of buildings]	1	3	5
Time difference of earthquake and siren ringing	[minutes]	5	3	1
Amount of people per vertical evacuation building	[no of persons/building]	1	3	5
Unsure factors	-	-	-	-
Level of knowledge on safety zone	[-]	1	3	5
Level of knowledge on evacuation routes	[-]	1	3	5
Moment of Magnitude experienced	[-]	1	3	5

Table 2.2: Table of Scenarios

Agent behaviour points of interest

The literature scan has revealed that there exist agreements or clear assumptions on:

- What speed agent could have concerning age and health
- When do agents die concerning water levels (approx. 1m)

The literature scan has revealed lack of knowledge or discussions on:

- Influence of road capacity on agents' speeds
- Agent's route choice and re-routing capabilities
- Time of departure, panic behaviour and risk perception (all hugely influenced by psychological factors)

Evacuation phenomena points of interest

The literature scan has revealed that there's little knowledge on occurrence of congestion, and dedication of people to evacuation plans. Helbing et al. [2000] indicates that "panicking individuals will block up an exit that they could pass through safely at normal walking speed. They also show that a widening in a corridor actually slows down the movement of pedestrians".

2.6.6 Setup for survey on stated preference

Besides gaining information from literature, information on local psycho-behavioural factors is still needed to make a reliable simulation possible. B.7.3 it was concluded that several factors still need to be researched on. This could be done by means of a survey. The setup for a survey on psycho-behavioural factors is given here; in section Section 3.5.1 results on the survey performed in Iquique can be found.

Derivation of survey questions

First, it should be determined what level of knowledge is needed from the survey. If qualitative preferences are sufficient, a rather easy survey can be conducted with nominal or ordinal scale variables. This allows closed questions ('yes' or 'no'). If more detailed information is needed quantitative analyses are necessary, which require a scale. Secondly, formulation of questions should without any preference for a certain answer, clear, as short as possible, and ordered logically. If specific knowledge is necessary, it should be provided with the question, but it is likely to make the survey more complicated and less attractive to respond to.

The kind of question necessary to ask should cover the topic of interest. As evacuation preferences are asked, the questions should cover the following subjects:

- Stated preference on timing to evacuate (e.g. right after earthquake or wait for a signal)
- Stated preference on which mode to evacuate with
- Stated preference on how to prepare for a tsunami event
- Stated preference on which information to choose for preparation and respons activities

Conducting and evaluation of the survey

The survey should be conducted on the streets or from door-to-door, within institutes, digital or handwritten. As the survey for evacuation is most relevant on the inhabitants in the city of subject, the street surveys or door-to-door are most valuable. With these surveys more work is necessary to perform the survey. Within institutions the survey can be provided via email, meaning less work.

Another time-consuming job is the evaluation of the survey results. Different statistic tests should be performed to define differences between population categories (e.g. age, or sex), and to find a general conclusions, i.e. a well reflected stated preference for the population.

Chapter 3

Application of framework to Iquique

3.1 Introduction to case study

In the case study the proposal for the framework to assess the tsunami hazard plan of Iquique has been applied. For each related discipline the main findings are presented in the following sections. The order of those disciplines addressed, is logically equal to the activity areas of the tsunami hazard plan starting with prediction, followed by mitigation and closing with response. Every subsection contains a summary of these findings.

3.2 Application of hydraulic aspects

In this section all related aspects regarding hydraulics, applied to the case study of Iquique, will be covered. Because of the importance of geotechnical issues in the modelling, first the seismic scenario's will be determined. All topics covered are part of the activity area prediction, in which an assessment of the actual tsunami hazard in Iquique is made.

3.2.1 Tsunami generation and seismic scenarios

Due to the unpredictability of the potential tsunami and preceding earthquake, multiple scenarios that are plausible for the case of Iquique are tested. These scenarios are based on hypotheses formed by different scientists. The scenarios all differ in fault location, moment magnitude (M_w), and length (L). To simplify the comparison, rupture width (W), rigidity (μ), locking depth (d), dip angle, and rake angle are kept constant. Their corresponding values are given in table 3.1.

TABLE 3.1: Constant variables for all scenarios.

Constants		
W	125000	m
Dip angle	0.33	rad
Rake angle	1.75	rad
d	40696	m
μ	3.00E+10	Pa

The remaining details of each scenario are the rupture area (A), the earthquake moment (M_0), the slip distance (D), the vertical deformation of the seabed (D_v), and the projected area of the rupture area on the earth's surface (A_p). M_0 can be found using equation 3.1 [Hanks, 1979] and D can be found using equation 3.2. The remaining variable can simply be found using geometric relations and is used as input for the model. These values are given in table 3.2.

$$M_w = \frac{2}{3}log(M_0) - 6 \tag{3.1}$$

$$M_0 = \mu AD \tag{3.2}$$

The Loa fault rupture: The first scenario is based on research done by Metois et al. [2012], who proposed the existence of three segments in the subduction fault between the Nazca Plate and the South American Plate. These segments are locations of similar seismic slip and are bounded by sections of either extreme locking or aseismic slip. These sections were found by analysing recent ruptures in the subduction zone. Magnitudes of earthquakes and deformations of land have shown that ruptures were stopped at these parts. This would mean that they are extremely well locked and the initial friction was not overcome. Another possibility is that these parts are not at all locked and absorbed all energy such that the rupture did not continue. The locations of these boundary sections and the segments are given in figure 3.1. A likely rupture to occur in the near future is *Loa*. According to Metois et al. [2012], the most likely magnitude to result from the rupture of this segment is 8.3 and the following rupture details are given in table 3.2.

Three segment rupture: Another possibility is that all three segments rupture simultaneously. This could occur if the bordering sections transfer the energy to the next segments. As a result there will be three different rupture faults: Paranal (M_w=8.1), Loa (M_w=8.3), and Camarones (M_w=8.1), which can be considered as an extreme scenario since the total rupture length is more than 760km. In addition, Camarones is expected to have a shallower rupture depth (30km).

The 1877 earthquake from Antofogasta to Arica: The third scenario is based on research done by Chlieh et al. [2011a] and Aranguiz and Belmonte [2012] and historical data from Kausel [1992]. The most likely scenario, occurred in 1877, was a rupture of a fault ranging from Antofogasta up to Arica with a magnitude of M_w=8.8. This rupture length would be 420 km [Aranguiz and Belmonte, 2012] with the hypocenter below Iquique, also shown in figure 3.1. Since this happened before, it is a likely scenerio to repeat itself. The length however is based on historical data of 1877 and are likely to be questionable; the South American population was small in that era.

The Loa fault rupture 1877: According to Metois et al. [2012] could the 1877 earthquake have been generated by the small segment from Mejillones to Iquique, illustated as Loa in the figure 3.1. This is based on observations of the 2011 earthquake near Japan, that had a magnitude over 9.0 and was originated from a rupture zone with a similar length. Therefore the North of Chile needs to consider the rupture of the Loa segment, which is about 200 km long.

3.2.2 Tsunami modelling for Iquique

The NeoWave model is used for modelling the hydraulic aspects involved with tsunami risk management in Iquique. NeoWave is a depth-integrated, non-hydrostatic wave model with grid nesting for tsunami generation, propagation, and inundation. The model is developed by University of Hawaii [Yamazaki et al., 2010]. It includes features for static and dynamic sea floor deformation using either uniform or finite fault models as

Table 3.2: Details of the involved ruptures zones for the considered scenarios for tsunami generation.

	Loa (8.3)	**Camarones**	**Paranel**	**Antofogasta to Arica**	**Loa (8,8)**	
$\mathbf{M}_w$	8.3	8.1	8.1	8.8	8.8	-
L	188700	210900	133200	420000	188700	m
A	2.36E+10	1.94E+10	1.66E+10	5.25E+10	2.36E+10	m^2
$\mathbf{M}_0$	2.82E+21	1.41E+21	1.41E+21	1.58E+22	1.58E+22	Nm
D	3.98	2.42	2.83	10.06	22.40	m
d	1.30	0.79	0.92	3.28	7.29	m
$\mathbf{A}_p$	2.23E+10	1.84E+10	1.57E+10	4.96E+10	2.23E+10	m^2

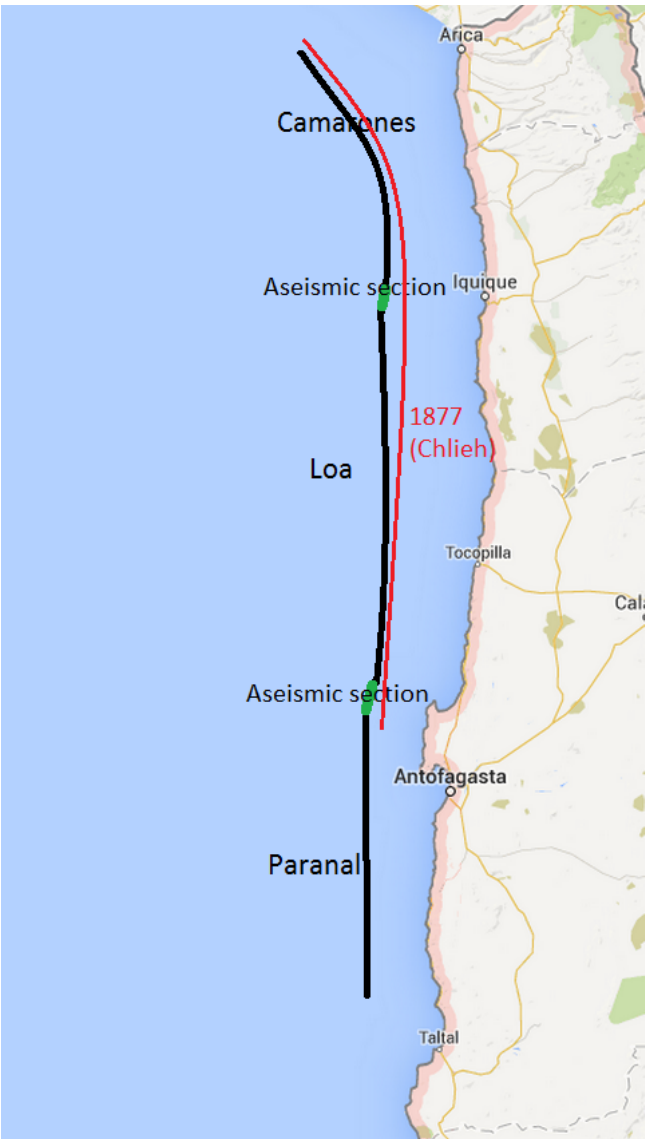


Figure 3.1: Possible scenarios for rupture zones. The line to the left represents the three faults segments according to Metois et al. [2012] and the line to the right is the fault that ruptured in 1877 according to Chlieh et al. [2011a].

input. It has the ability to include wave dispersion, wave breaking, and bore propagation. The model is verified and validated using a series of laboratory tests and test studies of the 1993 Hokkaido tsunami and the 2009 Samoa earthquake and tsunami. For these reasons the package is very suitable for application to the Iquique case study.

Input

To be able to model the hydraulic aspects, a lot of input data is required. In this case bathymetric data were obtained from General Bathymetric Chart of the Oceans (GEBCO), which is a global 30 arc-second grid containing quality-controlled ship depth soundings and land data from the Shuttle Radar Topography Mission elevation model. Additionally in the nearshore zone of the study area higher resolution bathymetric data are used, which is provided by ship soundings from SHOA (only between latitudes 20.17° S and 20.24° S). Also for the topography higher resolution data are available, in the form of 5 meter interval contour lines, extracted from data gathered by SAF.

The data gathered are put together and interpolated using linear triangular interpolation for four nested grids with resolutions of 2 minutes, 30 seconds, 6 seconds, and 1 second. For more information see appendix C.1. NeoWave uses the methods established by Okada [1985] to calculate initial bottom deformations and ocean surface elevations. For this study only uniform faults with an instant rupture are used. The input needed for these calculations are slip, local depth, fault length, fault width, strike angle, dip angle, rake angle, and the coordinates of the deformed area. These parameters are calculated for the scenarios summarized in table 3.2. As an example in figure 3.2 the initial sea surface elevation is calculated with this model. In this figure it is clearly illustrated that there is some land subsidence in Iquique as a consequence of the rupture. This is an additional negative effect with regard to inundation levels.

Results

The NeoWave model had run for the four scenarios as described in the previous section, of which the results are shown in table 3.3. It can be seen that the most negative consequences are caused by the 'Chlieh' scenario. Since all scenarios still have a high uncertainty the results from the Chlieh scenario are used as input for the other involved disciplines. A more detailed comparison of the results is shown in appendix C.1. More

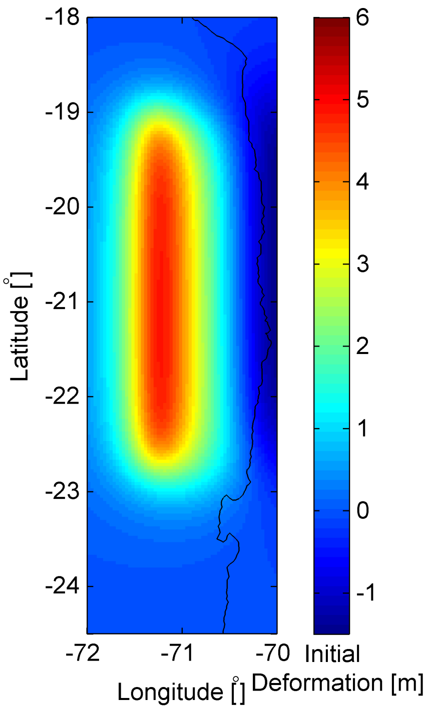


FIGURE 3.2: Initial deformations as calculated with NeoWave and Okada model based on Chlieh scenario.

detailed information on other parameters and settings used for running the model can be found in C.1.

	Chlieh	**Metois - Loa**	**Metois - 3 faults**	**Loa historical**	
Maximum-runup	11.99	2.50	3.48	9.84	m
μ-runup	10.46	1.54	2.88	7.56	m
σ-runup	0.71	0.15	0.37	0.85	m
Maximum inundation	9.84	1.75	3.43	8.14	m
Arrival time	11	15	18	13	∼min

TABLE 3.3: Results of tsunami modelling founded on different scenarios, where the comparison is made based on results between latitudes 20.240335° S and 20.183667° S

Results on the inundation are illustrated in figure 3.3 and results on arrival times are illustrated in figure 3.4. The results on inundation levels and flow velocities were mainly used to determine the suitability of vertical evacuation structures, which can be found in sections 2.5 and 3.4. The results on arrival times were mainly interesting to evaluate evacuation routes, see sections 2.6 and 3.5. For the buildings the option of NeoWave to output 10-second interval data on inundation depth and both horizontal velocities for

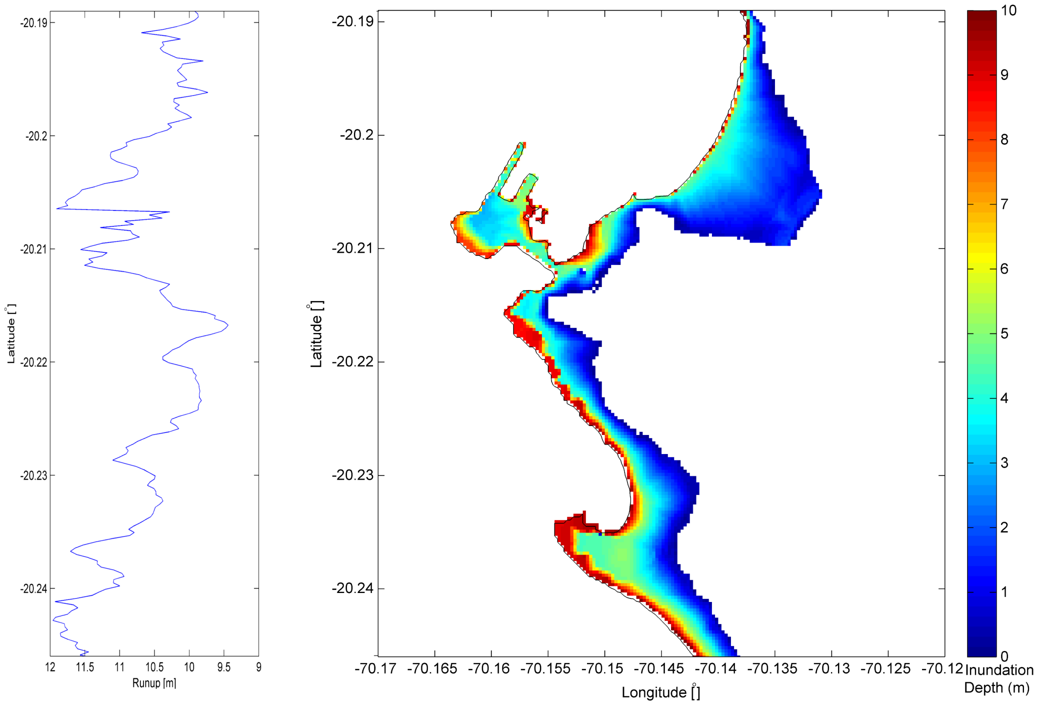


FIGURE 3.3: Inundation

specific coordinates are being used. Arrival times are determined by checking at what time instant the inundation depth of every grid cell becomes larger than zero.

For assessing the suitability of vertical evacuation structures information on the runup is needed, this is illustrated in figure 3.3.

The results on the arrival times seem to be very negative for some areas close to the coast. There are places, for which the arrival time is less than 8 minutes. However, the reliability of this result is not certain. Due to the grid sizing of approximately 30 meters and linear interpolation of the bathymetric and topographic data, this could become an unreal reproduction of the actual situation. Additionally, the calculations are made with the assumption of high tide and the area being subject to subsidence. This might contribute to these uncertainties.

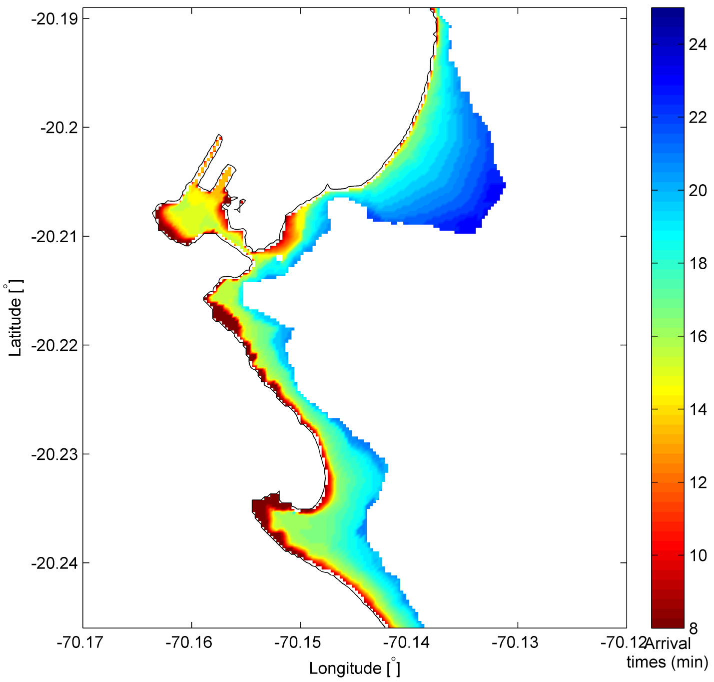


FIGURE 3.4: Arrival times

3.2.3 Concluding remarks on hydraulic aspects

Weaknesses

- Tsunami models are complex; based on their outcomes, it is hard to say which models are the most reliable;
- Input for tsunami models, especially high resolution bathymetric and topographic data, is hard to get;
- Tsunami model results are strongly dependent on seismic aspects;
- Tsunami modelling is a labour and cost-intensive

Knowledge gap

The main knowledge gap in tsunami modelling now, is that there's no agreement on how to implement data for more sophisticated models, especially for inundation. Detailed information of e.g. roads, buildings, obstacles could be used.

3.3 Application of geo-technical aspects

Part of the framework is the use of the geo-technical discipline to improve tsunami risk management. In this section this is applied to Iquique. Different geo-technical risks are identified and analysed that are relevant to mitigation and response.

3.3.1 Stability of slopes in Iquique

As mentioned in section 2.4 it is not necessary to evaluate all slopes in the city to successfully determine and quantify the risk of slope failure. A screening process is used to determine the consequence of particular failures and whether these are probable. The first step is to identify important slopes in the proximity of evacuation routes, access roads, life lines, etc. The second is to conclude the possible consequence of such slopes failing and the third is to evaluate the stability of the slope using simplified methods to determine if failure is probable.

Identifying slopes of interest

Iquique is situated between the coast and a high range of hills rising up to 600m at an average angle of around 30°. At the North and South the hills reach the coast serving as a natural boundary to the city. There are two main roads in and out of Iquique, one is highway one (A1) that is situated at the coast and runs from north to south. The other is the road up the hill to Alto Hospicio, the A16. Furthermore most evacuation routes start at the coast and follow perpendicular to the coast directly upland towards the hills. Others are more complicated, like the ones out of Zofri where the route is very steep and winding. Finally most safety zones are on gentle slopes (smaller than 5°).

For this case-study two slopes were studied, one along an important evacuation route out of Zofri, *Puerto 10* and one along the A16 to Alto Hospicio. The A1 runs along very steep slopes at the north and south ends of the city which might be interesting to investigate for slope stability, yet the value of this investigation is lower since it is not an evacuation route nor an access road during inundation since it is isolated from the safety zones.

FIGURE 3.5: A picture of the slope along the evacuation route out of Zofri through *Puerto 10*.

Identifying possible consequence of slope failure

To determine if further investigation of the two slopes is necessary the possible consequences of slope failure need to be identified.

Puerto 10: When considering the evacuation of people, the slopes along the evacuation routes out of Zofri are possibly critical. The route out of *Puerto 10* crosses *Las Cabras* and goes into *El Colorado* via a narrow walkway that climbs a short but steep slope (dip angle averages 36°) as shown in figure 3.5. During evacuations from the tsunami this path should be accessible. So after the earthquake, the path should not be too damaged and the path should be free from rocks, rubbish, and other items. If this slope were to fail it will definitely obstruct the evacuation effort.

A16: Besides evacuation, access in and out of the city's safety areas is important for rescue workers to help survivors when necessary. If the A16 were to be inaccessible, this would be obstructed. Therefore the consequence of failure could be very high.

Determining if the slope might fail.

The final step of the screening process is to calculate if the slope can potentially fail.

Puerto 10: The slope was characterised by a quick walk over survey; identifying slope angle, rock type, and potential instabilities. The slope is mainly highly fractured sand stone and covered by dry sand, gravel, trash, and boulders. The maximum height of the slope above the walkway is about 10m. From a primary investigation the most likely form of slope failure will be superficial. The slope is not extremely steep and due to the

Average Slope Angle	Friction Angle	Maximum Boulder Size	Rock Type	Rock Density	Conservative k	Likely k
37°	40°	$0.1m^3$	Sand stone	$2000kg/m^3$	0.4	0.3

TABLE 3.4: Slope characteristics *Puerto 10* [Stanford.edu]. The conservative k is taken from building designs used in Iquique to determine seismic loading. The likely k is taken from literature studies [Baker et al., 2006] shown in Appendix C.

Seismic Coefficient k	Factor of Safety
0.4	0.51
0.3	0.62

TABLE 3.5: Factor of Safety for the slope at *Puerto 10* in case of seismic loadings from deterministic pseudo-static Newark analysis.

absence of water, extreme slope failure is not too likely. On the other hand the slope is covered in loose sand and gravel that slides very easily. Moreover on top of the sand are a lot of loose stones and boulders with maximum size of $0.1m^3$ that can move quite easily. Hence, to analyse the stability of this slope the methods for superficial slope failure mentioned in section 2.4 are used. In table 3.4 information from the field visit is sumarised. Using Newark's Pseudo-static method equation 3.3 is derived and used to determine the factor of safety (F_s) in equation 3.4. F_h is the pseudo-static horizontal force caused by the earthquake, W is the weight of the sliding mass, β is the slope angle, and ϕ is the friction angle given in table 3.4. For this slope, the cohesion is assumed to be zero for dry sand. If F_s is found to be smaller than one, the slope is probably going to fail.

$$F_h = k * W \tag{3.3}$$

$$F_s = \frac{F_{resisting}}{F_{driving}} = \frac{(W * cos(\beta) - F_h * sin(\beta)) * tan(\phi)}{W * sin(\beta) + F_h * cos(\beta)} \tag{3.4}$$

Using equations 3.3 and 3.4 F_s was found for the two different k values, shown in table 3.5. It is clear that from this preliminary analysis that the slope along the evacuation route out of Zofri will fail. Further numerical methods can be used to determine the extent of this failure.

A16: This slope was investigated with the same methods as the one at *Puerto 10.* The total height of the slope is about 600m high and a slope angle between 26° and 36°.

Average Slope Angle	Friction Angle	Mass Type	Rock Density	Conservative k	Likely k
36.4°	40°	Sand	$1800kg/m^3$	0.4	0.3

Table 3.6: Slope characteristics *A16* [Stanford.edu].

Seismic Coefficient k	Factor of Safety
0.4	0.52
0.3	0.63

Table 3.7: Factor of Safety for the slope at *A16* in case of seismic loadings from deterministic pseudo-static Newark analysis.

It is covered by 20cm of loose dry sand and no vegetation. That there is absolutely no vegetation probably means that there is no ground water remotely close to the surface which is reinforced by results from ground investigations done in Iquique for building projects. Below the sand cover is mainly sand stone, fractured from a history of seismic activity. Furthermore the highway is cut into the slope, 4 lanes wide which artificially steepens the slope. Similarly to *Puerto10*, it seems like the most likely mode of failure will be superficial flow. Here however, there are no boulders and only the layer of sand is likely to flow downwards. Again for this slope Newark's Pseudo-static method can be used. Table 3.6 shows the information gained from the site investigation and table 3.7 shows the results of the preliminary screen analysis. Here too, the analysis shows that superficial flow is very likely in case of an earthquake. Furthermore, the road was built in an artificially cut slope which often leads to unstable conditions. Due to time and safety constraints the entire road was not investigated, and from below it was clear that the investigated area was not the most critical. Steep cuts in the slope further uphill point to possible rock slope failures and more rock falls that should be considered.

Tables 3.5 and 3.7 show the difference in stability if the k changes from 0.4 to 0.3. It is clear from the results that the stability does not change much. Therefore, although it seems like k is unknown in this evaluation, it does not seem very important when analyzing superficial failure modes.

Mitigation of slope failure

For both slopes the expected failure mode is superficial movement of sand and/or boulders. The main consequence of this is the blockage of important routes. For mitigation of this risk, there are two main possibilities; complete avoidance and containment.

Puerto 10: For this slope complete avoidance could be to relocate the evacuation route around the slope, which means that people leaving from the gate would either walk eastward along the wall of *Zofri* or westward and turn up-hill after about 200m. Both routes will significantly increase the time needed to escape and so are not acceptable solutions. Another option could be to remove any material that is expected to fall. This however includes the 5cm of sand which could be quite a lot. Also the slope will have to be kept clear, requiring periodic maintenance. Containment could be to build a wall that will protect the path from any loose sand and rock. This should be a wall that is designed to contain the expected volume of loose material. The height will be dictated by the expected bounce height of rocks [Martin and Lew, 1999]. This could be extended to include a ditch to reduce the height of the wall and reduce costs. Finally, since the path is at an angle to the dip direction, falling material can be deflected rather than completely stopped, reducing the impact on the containing wall.

A16: For the slope along the A16, avoidance is not a option. A containment design is necessary to guarantee a clear path. Due to the height of the slope, the wall will need to be larger and stronger than for *Puerto 10.*

3.3.2 Liquefaction in Iquique

The second geo-technical risk mentioned in the framework is liquefaction. This risk is especially interesting in seismic conditions due to the dynamic loading on soils. As mentioned in section 2.4, a good way to determine the potential for liquefaction (P_L) is to use CPT or SPT tests. During the field study done for this report, these resources were unavailable. Therefore a desk study has to be sufficient, where data from previously done site investigations are used to understand the ground conditions in Iquique.

Conditions for liquefaction in Iquique

In Iquique the bedrock is very shallow, but it is covered by a layer of marine sediment that is probably not very dense[Martin and Lew, 2006]. All buildings that are considered for vertical evacuation are founded on the bedrock, not on the liquefiable soils [Pizarro, 2010]. Walkways and roads however are more likely to be on the sediment layer and could be at risk. Furthermore, due to the many construction projects in the city, a lot of this sediment has been excavated and relocated. These 'man-made' fills are notriously prone to liquefaction. One such fill is used to build the quay wall at the harbour.

The water conditions in Iquique make the chance for liquefaction very small [Pizarro, 2010], [Ruz, 2009]. Eventhough there might be a lot of liquefiable soils, they are mostly dry. The only real area at risk is directly at the the quay walls at the port. The fill is probably saturated which creates a large potential for liquefaction. To determine if this will truly be a problem, field testing should be done to determine the density of the fill. If liquefaction were to occur here, evacuation of of the port will be obstructed since part of the path is built over the quay wall.

Liquefaction during tsunami inundations

As mentioned in section 2.4, the conditions change during tsunami inundation. These changes could lead to liquefaction that did not occur during the earthquake. When the water arrives at Iquique it floods the dry surface. This will preliminarily cause puddle forming since the water cannot easily penetrate dry soils. The tsunami can however take hours, which might be enough time. If the first waves saturate the top soil levels, the loads from following waves can lead to liquefaction. When considering life-loss, this phenomena is most interesting at safety areas like vertical evacuation buildings. In Iquique these are founded in bedrock, so support from below and from the side is given by the rock. If the covering soil were to liquefy, stability should remain. However, the phenomon could cause damage to roads and side-walks that are not founded on the bedrock. This will have little impact on life-loss but could be significant economic damage.

Mitigation of liquefaction issues in Iquique

It is clear that liquefaction is less significant in Iquique than in many other tsunami prone areas. There will surely be some degree of damage that seems unavoidable. Founding roads and side-walks on bedrock is an expensive undertaking and does not seem worth the profit, this can however be checked. One point that does call for attention is the quay wall. The fill from which it is made is likely prone to liquefaction, and the consequence will be obstruction of evacuation for workers on the docks and ships. A CPT or SPT should give a better indication of the liquefaction potential. If the potential is too high the fill can be densified or replaced with other materials like concrete.

3.3.3 Remaining geo-technical risks

Besides liquefaction and landslides, Iquique could be vulnerable to multiple other geo-technical risks. The first to account for is ground shaking. In Chile, all buildings are designed according to seismic building codes. This reduces the risk of damage from ground shaking during earthquakes. Also, Chileans are taught to open all doors and windows during earthquakes after initial seismic shakes to avoid jamming. This is however not always possible and residents should be aware that they might have to break through doors and windows to evacuate. Furthermore in Iquique, soil investigations have classified soils according to figure 3.6. This can be used to give an idea of amplification in Iquique when used in comparrison with table 2.1. It is clear that there is no significant amplification in Iquique.

In case of flooding, Iquique will likely experience scouring. Due to the climate the top soil is mostly dry, loose sand and gravel which is very susceptible to scouring. On top of this, the sand has a high salt content which will only increase the magnitude of scouring. This was already made clear during the field visit, where numerous signs of scouring were visible below roads and walkways. The main impact of scouring will be physical damage to infrastructure with a likely effect on the evacuation and the following economic consequences of recovery.

Finally, the loss of soil strength due to changes in water conditions will also affect Iquique. Due to the dry nature of the top soil, infiltration of the soil will be very slow or non-existent. Yet even the smallest amount of water can already reduce the strength

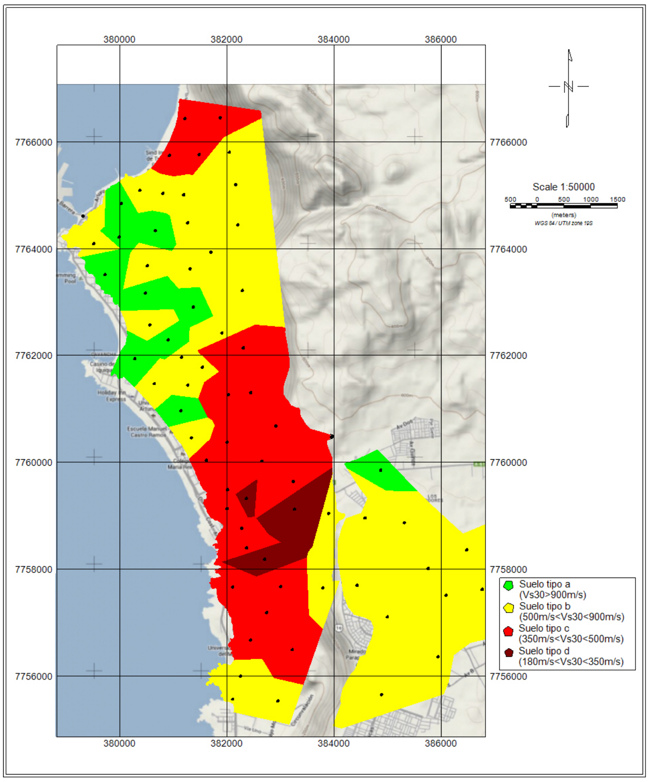


FIGURE 3.6: Soil classification of Iquique depending on shear wave velocities. [Sae].

of the loosely cemented sands. The consequence for evacuation is difficult to determine. This risk will probably arise towards the end of the tsunami event so might not effect evacuation. If this is true, people in vertical evacuation buildings will also probably be safe since these buildings are founded on bedrock. There is however the question what the effect is on utility infrastructure, these are vulnerable to changes in soil strength. Lines like water and sewage will be important during the response activities, when survivors will have to wait out the flooding. The true magnitude of this risk remains speculation and needs further investigation.

3.3.4 Concluding remarks on geo-technical aspects

From the evaluation of the case study from a geo-technical point of view multiple weaknesses could be identified. The following weaknesses should be considered when improving Iquique's contingency plan:

- Superficial failure at *Puerto 10.*
- Superficial failure at *A16* highway to Alto Hospicio.
- Failure of quay walls at the port due to liquefaction.

- Jamming of building exits due to ground shaking.
- Damage to infrastructure and utility lines.

To be able to overcome these weaknesses a few options were mentioned above, yet to be able to do this there are a few knowledge gaps to overcome:

- The extent of damage and blockage due to slope failure of *Puerto 10* and *A16*.
- Ground conditions at quay walls and critical slopes.
- Location and ground conditions of utility lines.

Overcoming these knowledge gaps with the aid of ground investigations, cooperation with local governments, and computational models will help come closer to reducing the weaknesses.

3.4 Contributions from the built environment

3.4.1 Followed steps for focus

The main goals are to estimate economic damage and to assess the suitability of a building for vertical evacuation. For the economic damage analysis two zones will be evaluated. Using results from the NeoWave model and methods further described in section 3.4.3 a quantitative assessment will be made. For the investigation on the suitability of buildings for vertical evacuation, the end product is a list of buildings which are approved or disapproved for this use. This end product can be used to mitigate on the possible tsunami hazard. However, the analysis for the suitability depends for a large part on the magnitude of the hazard, which is set in the prediction part. It should be notified that the preformed prediction concerning the tsunami event is determining for the possibilities of vertical evacuation.

The first step of the analysis consists of a quick scan of the built environment. This analysis is performed using Google Earth and Street view, which focuses on the location and the height of a certain structure. This analysis of the built environment is narrowed down to the flooded area. A flood line of SHOA is used to define this area. Besides that, it is obvious that vertical evacuation is not necessary for people whom located close to the flood line. Therefore the area is further narrowed, with 600 m. Based on the assumption that the escape time is 7 minutes and that people evacuate with an speed of 5 km/h. Next to the specification of the location a minimum height of 7 stories is considered. The result of this analysis is a list of 56 tall buildings along the shore line of Iquique, see figure 3.7. There are no tall building situated in the two important zones, the Zofri and the Port.

3.4.2 Tsunami event in Iquique

It is predicted that a large part of the built environment will be flooded, as result of a tsunami event. However, there are at the moment three predictions concerning the magnitude of this event for the city Iquique, which are illustrated in figure 4.1. The lines from the NeoWave model, SHOA and ONEMI are all rather different. Nevertheless, the data from the numerical simulation model NeoWave are used as input to determine the hydraulic forces. Also is the runup level (R) of the NeoWave model prediction used as input for the analytical solutions.

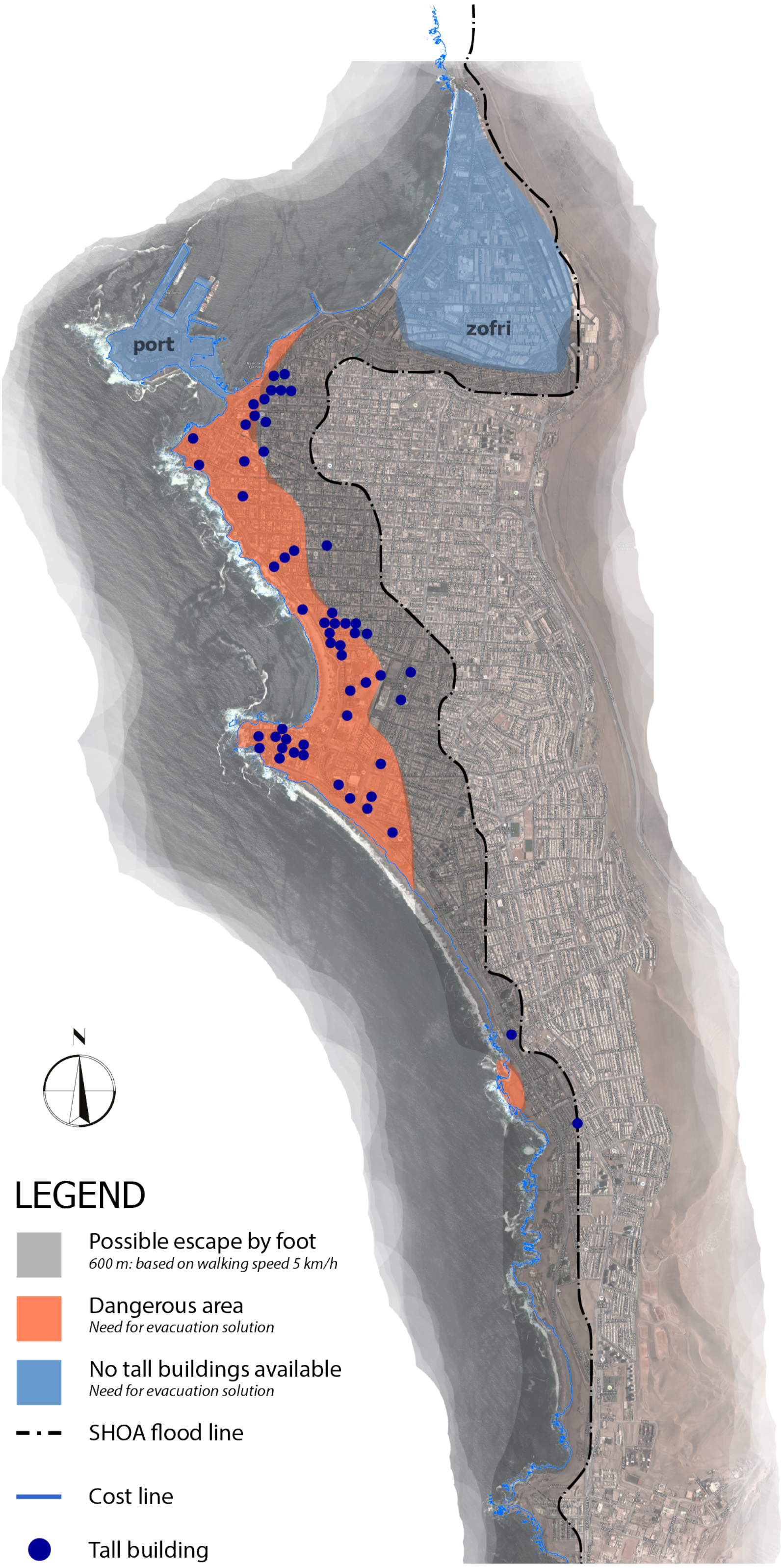
3.4.3 Economic damage analysis

As mentioned in section 2.5 it is possible to estimate the value of direct damages from the tsunami using a known inundation depth, building types, and building value. This is done with the fragility curves given in section 2.5.1. For the case study, two neighbourhoods have been investigated; the downtown area between *Grum Bolados, Anibal Pinto,* and *Esmeralda* covering approximately 500 m. by 300 m. and Zofri's warehouses. For the downtown area 480 structures were identified using Google street view, including their function, construction material, and coordinates. With the experience of the field visit a decent assessment of the construction material could be made using only this visual inspection.

The coordinates are used to locate the nearest grid cell from the NeoWave for each structure, from which the inundation depth is taken. Zofri was covered in a coarser way. For this area an average inundation depth of 2.32 m. was determined from the NeoWave model results. Secondly it was estimated that approximately 80% of the structures are made out of reinforced concrete and 20% out of steel. The results of this can be found in table 3.8.

For buildings made out of wood, masonry, or mixed masonry the fragility curve based on Chile, Dichato (figure 2.3(f)) is used while for concrete buildings the curve made for

Figure 3.7: Locations of 56 tall buildings along the shore line of Iquique



Building Function	Number of Units		Cost US$/$m^2$
	Downtown	**Zofri**	
House	347	0	759
Office	55	0	1803
Warehouse	0	2706	569
Shop	43	0	598
Church	1	0	1233
Appartment	21	0	1139
Garage	13	0	379

Table 3.8: The number of functions of the considered buildings and the corresponding values per square meter [Blong, 2001]

Thailand (figure 2.3(c)) is used. For the steel structures in Zofri the curve made for Japan, Nansei Hokkaido is used. This curve was originally developed for mostly wooden structures, however it has been noted in Japan that however collapse of steel structures doesn't occur as fast as for wood, they often suffer heavy non-structural damage [Fraser et al., 2011]. For that reason in this case it is assumed this curve is suitable to assess damages to steel warehouses.

By multiplying the $P(x)$, the total surface area of each building, and the corresponding monetary value, the total damage can be calculated. For the downtown area, the estimated damage is 14.90 million US$. For only the warehouses of the Zofri area, an estimated damage in case of 2.32m inundation depth is 142.0 million US$.

3.4.4 Vertical Evacuation design

The major part of the 56 buildings is located close to the shore line and a minor part inland. The buildings that are located inland have, for a number of reasons, a higher chance for survival. The ground elevation is there, in most cases, higher. Further on, there are buildings inland protected by other structures and the chance that a breaking wave will hit the building is assumed to be zero. Information is gathered on site from 20 of the originally 56 buildings, that where located more favorable. This is also for practical reasons, because a three day field trip is not sufficient to perform 56 site visits. During these site visits besides general observations, the properties of the buildings and its surrounding have been listed.

The first floor configuration of all buildings is the same, namely 'closed'. Here are shear walls applied in two directions. The buildings are assumed as one closed block for the calculation of the hydraulic impact, because of this configuration. All tall structures are built with reinforced concrete. Expected is that it concerns only in-situ cast concrete and that prestressed systems are not applied. The available capacity is expected to be lower, due to the fact that almost all buildings visited where residential and only one is a hotel. Residential buildings often have a lack of common space. However, in half of the buildings the roof is accessible, were a large amount of people can be accommodated. All buildings possess a basement, with a parking lot and services as generators, boilers, etc. Information on the foundation was only available for one building. However, it may be assumed that all buildings will be founded on bedrock. A last a significant threat concerning debris impact forces is expected, especially in the city center. Here are many wooden houses and in front of the city center is a large amount of containers stored in the port.

3.4.5 Application of structural criteria

Steps of Analysis

The first step, given in framework section 2.5.4, is already preformed to limit the scope of this analysis. The result is a list of 20 buildings. The next step is to determine the forces due to the tsunami event and resistance of the building. The equations and methods to do so, are given in the framework section 2.5. To illustrate these, an example of building number 6 is given in the upcoming sections. The last steps concerning the capacity and the accessibility, are not preformed due to lack of time. However, the importance for the completion of the analysis should not be underestimated.

The data needed to determine the forces on and the resistance of the buildings are summarised in the appendix in table C.3 and C.4. Here is a single example given for building 6 in table 3.9. The location and the tsunami parameters follow directly from the NeoWave model. Therefore, the coordinates of the buildings are needed. Google Earth and the Chilean standard are sufficient methods to provide the input needed considering the structure [NCh433, 2009]. The data needed for further steps are also collected, but these are not used in this case study.

TABLE 3.9: Required input for stability analysis for building example

Building	**6**		**Structure**		
	Location		**Seismic Zone**	3	
z	10.29	m	**Soil Type**	1	
l	1079.17	m	**Building Category**	2	
x	92.50	m			
			N	22	stories
	Tsunami		$\mathbf{R_0}$	9.0	-
R	14.82	m	**W**	93666	kN
$\mathbf{u}_p$	1.44	m/s			
d	1.20	m	**b**	31	m
d $\mathbf{u}^2$	29.66	m3/s2	**b'**	14	m

3.4.6 Relevant tsunami characteristics

Predictions of the magnitude of the tsunami event, and associated parameters inundation depth (d), flow velocities (u) and momentum fluxes (du^2), are estimated using two methods. In the first method, the parameters are directly retrieved from the numerical simulation model, NeoWave. The second method uses an analytical approach, based on the runup level (R) to determine these parameters. Here is R retrieved from the output of the NeoWave model, to be able to compare the differences. The R could also have been taken from historical data or any other floodmap available. The output of these different methods is given as example for one building in table 3.10. Two values for the u are given, because [Yeh, Robertson, and Preuss, 2005] describes two equations to determine the flow velocities. An overview of the direct model output is given in appendix C.3. It may be clear that the differences between the model outcome and the approximations are, for all parameters in this single example, pretty big.

TABLE 3.10: Magnitude parameters due to tsunami event for building example 6

Building 6		d [m]	u [m/s]	du^2 [m^2/s^3]
Model		1.20	1.44	29.7
	Yeh	4.5	16.3 5.0	4.5
Approx.	FEMA	9.0	13.3	112.3
	NCh	9.0	13.3	32.0

3.4.7 Hydraulic loads

The hydraulic loads are determined according to the equations provided by the different standards. An overview of these equations can be found in appendix B.2. The results are given for the three different standards with input from the NeoWave model (Model) and from the analytical approach (Approximation). The total force is given by the summation of each individual force. Two values of the total force are given, because input is used from the Model and the Approximation. The difference, in percentage, is listed per code. An overview of all total forces is given per building in the appendix C.5. A comparison is made in figure 3.8 and 3.9. Both graphs indicate that the differences, between the total forces derived from with the input from the model or the approximation, are large. In the Chilean Standard Project the differences are the least. The correlation, as illustrated in figure 3.8, is the best fitting. However, these differences vary also quite a lot and can certainly be doubted, as illustrated in figure 3.9.

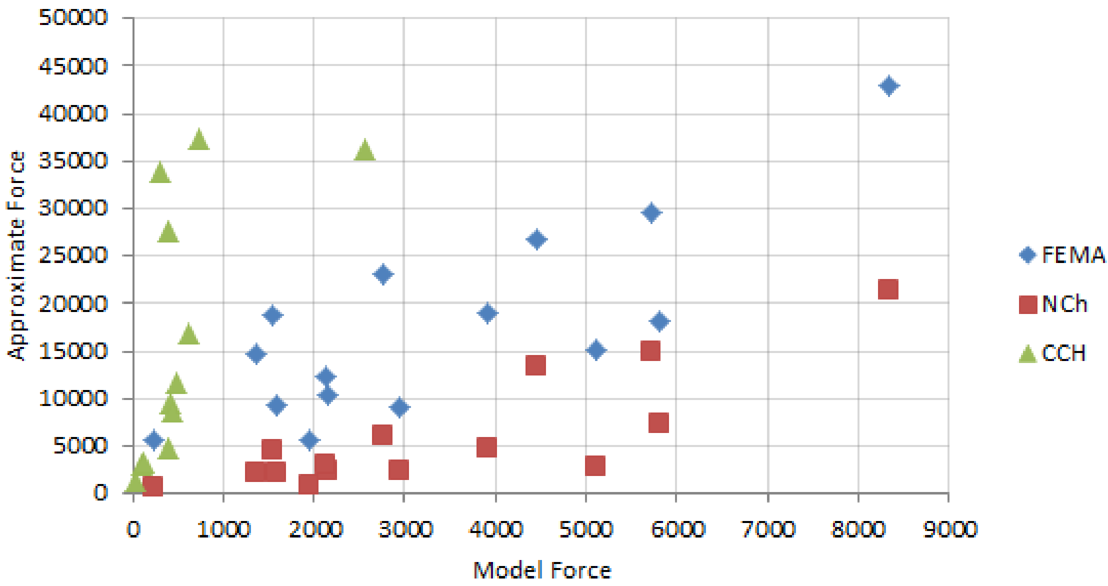


FIGURE 3.8: Comparison between total forces, for each standard, based on input from Model or Approximation

TABLE 3.11: Hydraulic tsunami forces for building example 6

		Hydrostatic	Buoyant	Drag	Surge	Total	% dif
		kN	kN	kN	kN	kN	
FEMA	Model	241.7	5629.7	1011.4	1517.1	2770	832
	Approx	13466.5	42022.5	3829.8	5744.7	23041	
NCh	Model	241.7	5629.7	1011.4	1517.1	2770	222
	Approx	3429.6	21206.9	1091.2	1636.7	6158	
CCH	Model	286.4	5629.7	64.2	70.2	421	2259
	Approx	5623.0	21206.9	2885.4	995.7	9504	

3.4.8 Resistance of the assessed buildings

The resistance of the buildings is estimated with the use of the seismic design load (Q_{seis}). The equations, classifications and input are described in the appendix B.4. This Q_{seis} is determined for each building and the input for this seismic calculation

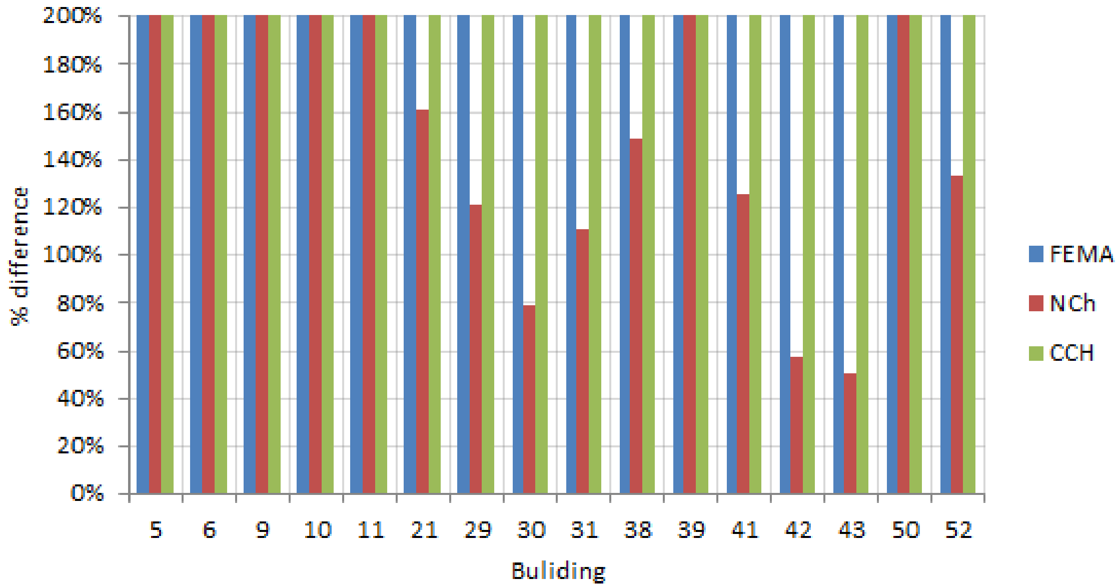


FIGURE 3.9: Differences between total forces, for each standard, for each building, based on input from Model or Approximation

given in the appendix C.4. The results of a single building example are given in table 3.12. The number of stories is here used to estimate the period (T_n). Note that, R^* is the design spectrum and α is a certain given coefficient. The other parameters that are used as input are given in table 3.9.

TABLE 3.12: Seismic calculations for building example 6

Tn	**R***	α	**Sa**	$\mathbf{C}_{min}$	$\mathbf{C}_{max}$	$\mathbf{C}_{calc}$	**C**	$\mathbf{Q}_{seis}$
(s)	(-)	(-)	(g)	(-)	(-)	(-)	(-)	(kN)
0.55	8.23	1.22275	0.58326	0.0972	0.1837	0.071	0.0972	9105.3

3.4.9 Results from stability check

The total load is used to perform a stability check. These loads are given in table 3.13 for building example 6. Here, the resistance given according to the seismic force and the hydraulic force according to the three different codes. The hydraulic loads are here determined with input from NeoWave model, see appendix C.3.

TABLE 3.13: Final Loads for building example 6

Seismic Force		
$\mathbf{Q}_{seis}$	9105	kN
$\mathbf{T}_n$	0.55	s
Hydraulic Force		
FEMA	2770	kN
NCh	2770	kN
CCH	421	kN

When the total loads are known the stability of the building can be checked. The unity checks for sliding, overturning and uplift are preformed as described in section 2.5.8. In table 3.14 this is performed for building 6 and being found accordingly, is that the building is stable. An overview of all results, regarding the stability, are given in appendix C.6. The stability checks are performed with the maximum given hydraulic force given by the standards, so for a worst case event. In this stability check some simplifications have been made. For the failure mode sliding is the friction of the building is excluded. While all buildings have a foundation and are clamped in. For the overturning failure mode is the own weight of the building neglected to be on the save side.

TABLE 3.14: Load check for building example 6

Sliding		**Ok!**
$\mathbf{V}_{sis}$	9105	kN
$\mathbf{V}_{hyd}$	2770	kN
Overturning		**Ok!**
$\mathbf{M}_{sis}$	345395	kN-m
$\mathbf{M}_{hyd}$	41937	kN-m
Uplift		**Ok!**
Weight	93666	kN
Buoyant	5630	kN

The results of the two preformed steps of analysis are shown in figure 3.10. The final criteria used, to asses suitability for vertical evacuation, are the minimum height compared to the expected inundation depth and the stability check for the building to resist the hydraulic forces. The buildings that are recommended accordingly this criteria are depicted in green, and the buildings that are disapproved are are shown in red.

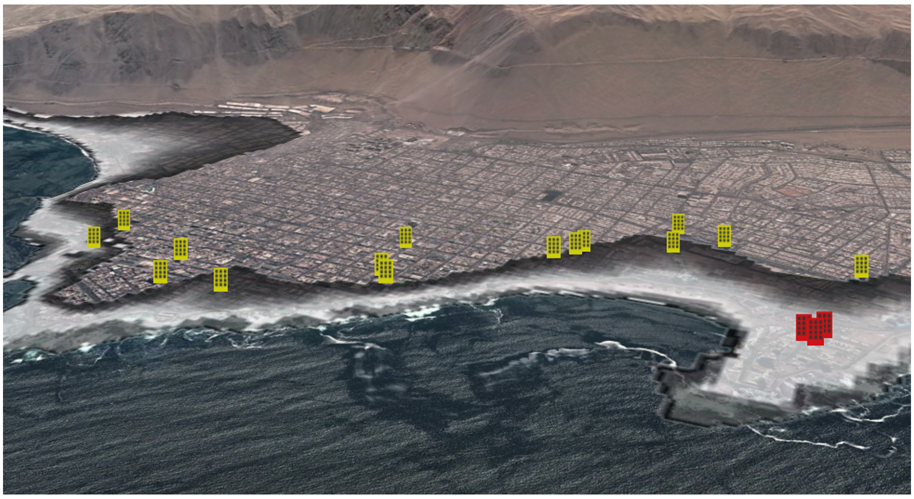


FIGURE 3.10: Recommended buildings suitable for VE

3.4.10 Concluding remarks on structural aspects

The main goal is to assess the suitability of a building for vertical evacuation. The end product is a list of buildings that are approved or disapproved, regarding the use as a vertical evacuation refuge. The means of vertical evacuation in buildings could help reduce the number of victims during a tsunami event. The height and location are the first criteria to scan the built environment for such structures. The height should be sufficient to provide a safe refuge area above the inundation level. The location of the building should be in the flooded area with a respectable offshore distance. With this analysis, 20 buildings have been selected in Iquique. The second important criteria concerns the stability of the structure. For this check the hydraulic loads (Q_{hyd}) on the building, and the resistance of the building, have been calculated with NeoWave. The inundation depth (d), flow velocities (u) and momentum fluxes (du^2) are direct output of this model. The equations to calculate the hydraulic loads are prescribed by the an American guideline (FEMA), the Honolulu Building Code (CCH) and a proposal for a new Chilean Standard for tsunami loading (NCh). The resistance of the building is estimated according to the seismic design load (Q_{seis}), which is calculated according to the current Chilean Standard. The stability check is performed for three failure modes, uplift, sliding and overturning. If the analyzed buildings also fulfill this criteria, than it is safe to recommend the structures for vertical evacuation.

Weaknesses

- Breaking wave forces are not included, because it is expected that they break offshore. Arguments for this are briefly addressed in the FEMA Standard.

- In the hydraulic load calculations are the buildings assumed as one closed block, due to the 'closed' first floor characteristics. This is a conservative approach and it would be better to model the flow of water through the building. This will result in a reduction of the resistance and therefore a more realistic estimation. Standards give some information about break-away-walls, but mention nothing about the breaking of windows and the possible flow of water through the building.

- All buildings are assumed to be designed and constructed in reinforced concrete. No checks have been performed concerning uplift forces or high live loads on floors or roofs.

- It is assumed that all buildings are founded on bedrock and that failure of the foundation, due to liquefaction and scour, will not be governing failure mechanisms. Information concerning the foundation is hard to get from the municipalities and in most cases not available.

- Impact forces due to floating debris are not taken into account in the analysis. However, this could form significant threat due the large amount of wooden houses in the city center and stack of containers in the port.

- The resistance of the building is determined according to the seismic load (Q_{seis}). It is assumed that all buildings are designed and constructed according to this code.

Knowledge gaps

- Input for equations to determine the hydraulic loads is difficult to validate. This holds for input required via the model (NeoWave), and for the approximation. The assumptions about the runup level (R) have a large influence on the differences of the outcomes of the approximations. A reason for this is the variety of assumptions concerning this R value. It is very hard to validate which assumption is correct.

- The three standards give all different equations for the hydraulic loads. The outcome of these equations show big differences, which cannot be easily explained or validated. To perform the stability check the worst case scenario is used.

- There is no official certification for vertical shelters in practive by government.

Recommendations

The model is a first tool to scan the built environment for structures that can be used as vertical evacuation refuge. The steps described in this analysis can be performed with information gathered via Google Earth and Street View. A site visit is not necessary for the use of this model. However, the outcome is solely an initial indication. Only the minimum height and failure modes regarding the stability are assessed. Therefore, further checks and research should be conducted, concerning:

- Foundation: include in strength and stability analysis.

- Strength and stiffness: expand current model with checks to judge the strength and stiffness of the building.
- Useful or not useful services: for example the danger of a gas tank in the basements.
- Impact force: add debris impact forces in the calculation of the hydraulic force.
- The capacity and the accessibility: by means of municipal information of the plans.
- Policy: way to implement vertical evacuation as a policy.

3.5 Assessment of evacuation processes

In this section the evacuation processes is defined and linked to actors. After this, the most important results of the evacuation route analysis are presented, that could be used descriptions of the case by means of road infrastructure analyses. With the total case defined both physical and conceptual, the application of the qualitative analyses in order to conduct a future pedestrian flow simulation are carried out entailing a behavioural check and a survey. Finally, weaknesses and knowledge gaps are summarized.

3.5.1 Link to system analysis

System analysis is applied to further determine how a local oriented governmental organization can get hands-on recommendations to improve their tsunami hazard plan. For this reason the so called Means-end analyses have been further specified.
In figure 3.11 the main focus objectives 'minimizing victims' and 'minimizing economical damage' are derived by subdividing the main goals of a Tsunami Hazard Plan. The following diagrams are provided starting from the pink factors contributing directly to the focus objective 'minimizing victims'; 'Decrease amount of people exposed to risk' and 'Improve evacuation efficiency'. These two means to minimize victims will play a central role in the following sections (see figures 3.12 and 3.13).

Decreasing exposed risk on population

To decrease the exposed risk on the population the local government can increase the Total Safety Zone area by providing alternative shelters, providing Vertical Evacuation shelters and providing more higher ground area. Furthermore, the local government can improve the safety in the Safety Zone area by for example diminish the exposure

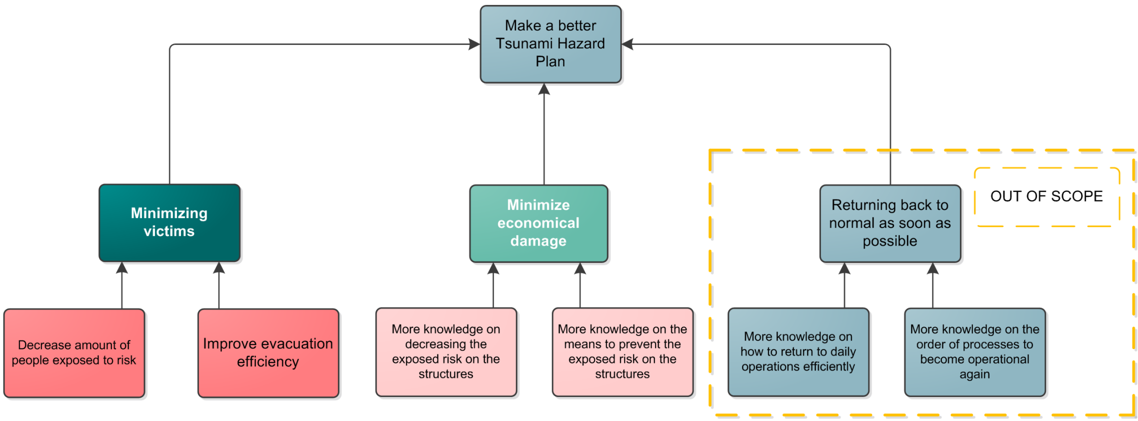


FIGURE 3.11: Main goals Tsunami Hazard Plan

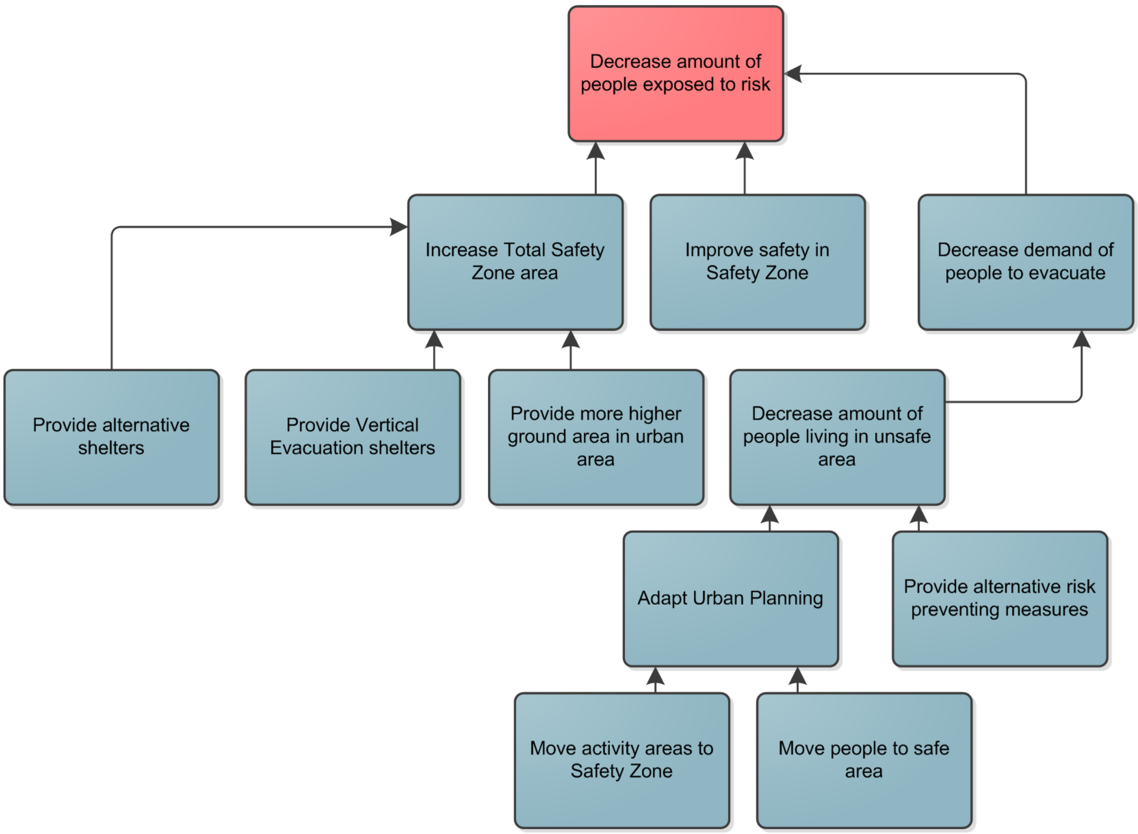


FIGURE 3.12: Means-end diagram for Iquique zoomed in upon Decreasing Amount of People Exposed to Risk

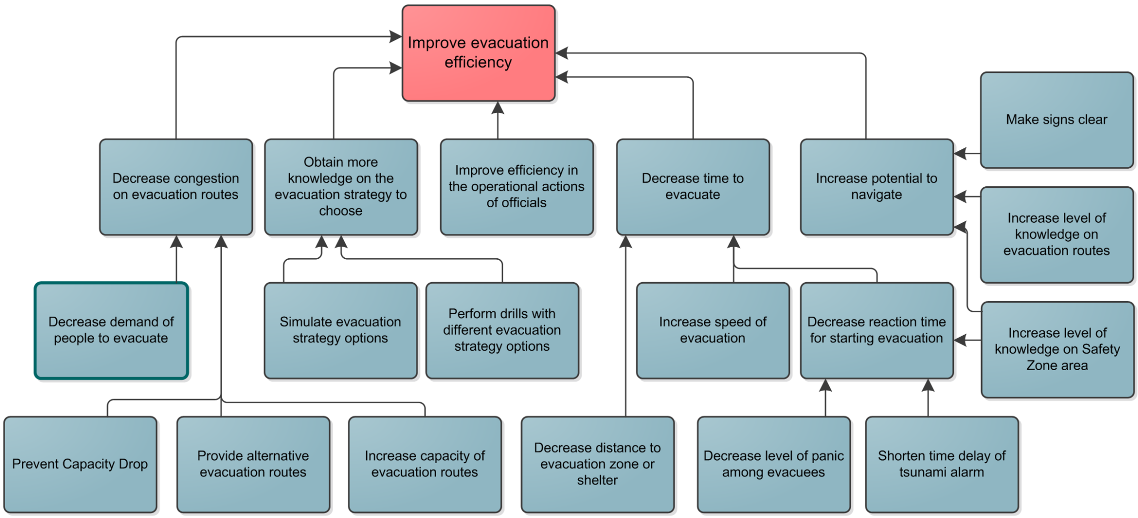


FIGURE 3.13: Means-end diagram for Iquique zoomed in upon Improving Evacuation Efficiency

to electricity and gasoline. As third measure the local government can decrease the demand of people to evacuate. This can be done my decreasing the population living in the unsafe area. A way to achieve this is adapt the Urban Planning. Because the topic is to be researched upon it is imaginable that more alternative risk preventing measures can decrease the amount of people living in unsafe areas. The decreasing demand of people to evacuate affects positively the congestion on the evacuation routes. Therefore, we will now elaborate on the next direct measure to contribute to the minimization of victims: Improve evacuation efficiency, please find figure .

Improving evacuation efficiency

With improving efficiency the congestion on the evacuation routes should decrease, there should be more knowledge on the evacuation strategy to choose, the efficiency in the operations of officials should improve, the time necessary to evacuate should decrease and the potential to navigate should increase. This is the first layer to be found in 3.13. As can be seen in the Causal Relation Diagram in section 2.6, the factors highly interrelate with eachother and therefore it is hard to seperate the topics totally. It is easy to imagine that with implementing one of these proposed means (factors), the implementation of another measure has been influenced. For this reason, the client should take into account the interference of the other factors of influence when implementing one measure and rather consider the result of the implementation as the sum of all measures of significant influence, see appendix B.

We will now elaborate further on the different measures considered in section 3.13. The congestion on evacuation routes can be decreased by decreasing the demand, prevent the capacity drop, increase the capacity of the routes or provide alternative routes. The capacity drop is a phenomenon in Traffic Flow Theory in which the state is meant after congestion occurs. The so called queue discharge rate capacity is with a rule of thumb 15 percent lower than the free flow capacity. This means that the total capacity on the road is not reaching free flow capacity anymore after congestion has occurred which leads to inefficient use of the roadway. Besides this, with providing alternative routes the flow of people is more distributed over the available network of the city. This provides an efficient use of the available network. Furthermore, it makes sense that by increasing the capacity of a route, meaning the free flow capacity, the more people can evacuate per period of time which contributes directly to a more efficient evacuation performance. As last measure in this category, the local government can manage the inflow on the evacuation routes by adapt the urban planning, which is elaborated upon in the previous section 3.5.1.

Next to decreasing congestion, more knowledge on the evacuation strategy to choose is necessary. As will follow from this research, a few knowledge gaps should be overcome. In order to do so simulation studies and drills in study subjects should be performed.
It is also not quite clear how officials act during an emergency event which is also a factor contributing to the improvement of evacuation efficiency. Because the matter of succes of the evacuation depends highly on time, the efficiency within the operations of these officials should be of prior focus for continuous improvement.

The fourth contributing measure is to shortej time to evacuate by decreasing the distance towards the Total Safety Zone area or increasing the allowed speed on the evacuation routes. Here an improvement can be found when adapting the urban planning as discussed in section 3.5.1. Theoretically spoken, the higher the speed, the more people per period can evacuate. This is of course not true when the capacity of the route is not sufficient for the evacuation demand. Therefore, this is rather simply put. The increasement of capacity on the evacuation route should always be considered together with the management of the inflow (demand).
The last submeasure to mention here is to decrease the reaction time of people before

starting to evacuate. It is assumed that with the increase of level of knowledge on the safety zone (distance to cover by a human), when panic is captured and time delay of the tsunami alarm is shortened, the reaction time will decrease. Here it is still unsure in which matter the factors contribute exactly to the delay of evacuation.

The same counts for the fifth measure of direct contribution to the improvement of evacuation efficiency; to increase the potential to navigate. It is assumed that by making clear signs which are available in all circumstances and with the increasement on knowledge among the people over the Total Safety Zone area and the evacuation routes the potential to navigate is improving. That the psychological factors do influence the efficiency during evacuation is acknowledged. However, more study is needed upon the causal effects of psychological factors like panic on the total efficiency during the evacuation.

Operational Performance Indicators

Together with these defined means, the operationalized objectives for achieving a better tsunami hazard plan have been determined in the section 2.6 which are:

- Shortage on time to evacuate
- Flow surplus of people evacuating via evacuation routes
- Flow surplus of people evacuating into the building
- Demand of people to evacuate to Higher Ground Safety Zone
- Total Safety Zone area

At this stage it is clear that the client can actually achieve a better tusnami hazard plan by taking the means into account. However, one should take into full notice that in the way the means interact with eachother will definately influence the performance on the stated indicators. This is derived from the section 2.6 where the causal relations are described, see also appendix B. is presenting all interrelations among these so called 'factors'. Furthermore, not only these interrelations are important for achieving a positive saldo on a performance indicator also the actors influencing this process will play a main role. To fully grasp the system in which these factors are being influenced stakeholder analyses have been conducted. This is done by analyzing the current organization in which these actors interact.

3.5.2 Actors in action

In this subsection the current operations on the alarming of citizens is investigated. In order to do so, one needs a more detailed description of the actors involved in emergency cases and the order of operational processes of evacuation. Firstly, the actors involved directly in the emergency operations are pictured. Secondly, the flowchart is presented which gives an overview on the current way the alarming and evacuation of citizens is organized.

Identifying emergency actors

The following figure 3.14 gives an overview of the current actors in action during evacuation. The figure pictures the hierarchy of actors and their relationship, which can be either formal or hierarchical. The hierarchical relationships are single arrowed, the formal representation relationship double arrowed. When there are relations between actors of different groups the arrows are coloured blue and red, respectively for hierarchical relations and formal representations. All actors directly involved in emergency cases are coloured and in bold.

The signal for the earthquake and tsunami arrives at the Pacific Center for Tsunami Warning in Hawaii. The system passes through the signal to SHOA, the military oceonographic research center and to ONEMI, the governmental emergency coordination agency. SHOA provides ONEMI with following-up information gathered from PTWS. ONEMI coordinates the Local Emergency Coalitions (CLE) and gives admission to the intendant of the regional government to put on the tsunami alarm system along the coastline.

The municipality is not directly involved in the emergency operations according to this diagram. The operations of the municipality are rather intern and there is no direct formal link between the municipality and ONEMI in case of emergency. It is remarkable that in emergency cases no clear relation has been found between the CLE and the municipality of Iquique. The diagram pictures that the CLE are only coordinated by ONEMI in case of emergencies, which is in contradiction with the reality. Also the regional ONEMI (OREMI) has no clear relation with the CLE or Red Cross. OREMI has as primair goal to supervise the emergency plans of the municipality in normal days, but their role specifications in emergency cases is not clear.

The municipality coordinates the Red Cross, aiming to help harmed people. Also in this case no clear relationship has been found among the CLE and the Red Cross in order to coordinate the aid to people.
Zofri and the Port Authorities are barely linked to the municipality. Zofri and the Private Port Authority have their own evacuation plans. No link has been found establishing the supervision of those evacuation plans by any governmental organization.

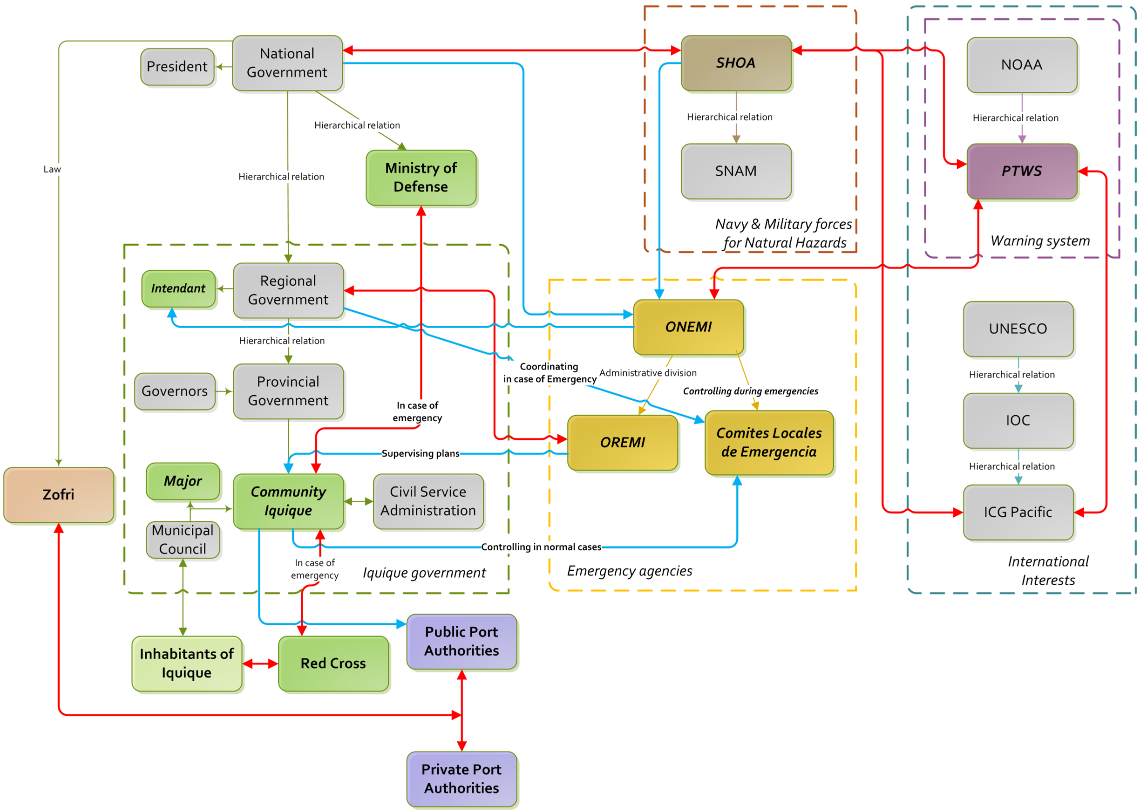


FIGURE 3.14: Actor Chart Emergency

The following figure 3.15 pictures the different actors identified with their power or interest in the topic of tsunami risk management. As one can see the majority of the actors are highly interested in the topic of tsunami risk management but lack power or means to actually change the situation. Tree key players do have the interest and power to influence the situation in Iquique, which are the local government, ONEMI and the Public Port Authority. Zofri, the private Port Authority and the National Government do have the power to influence the situation, but lack the interest to do so compared to the Key Players. The so called Subjects are the stakeholders which should be informed during the implementation of solutions to the current situation, they are rather dependent on the acts of the Key Players and Context Setters. Then as final, there is the crowd in which organizations take place with minimal effect on the situation.

With this figure in mind one can actually organize to implement solutions adequately. Meaning not to forget anyone important or to address issues wrongly to the stakeholders. This is important when there are policy measures or other solutions found to improve the situation in Iquique.

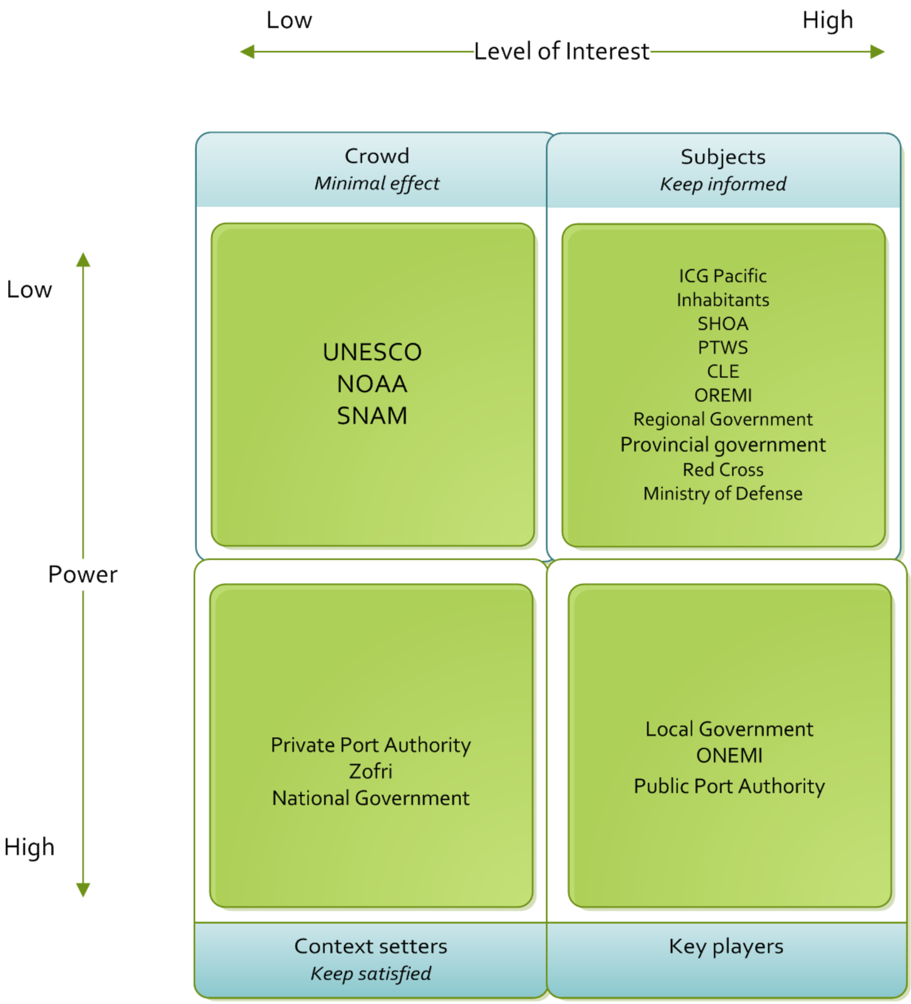


FIGURE 3.15: Level of Interest

Identifying the order of processes among emergency actors

Four phases have been distinguished: Detecting, Evacuating, Guarding and Closing. To enter the next phase, a decision of an organizaiton higher in the hierarchical emegency actorchart is necessary. It has to be noticed that as soon as the evacuation phase starts, the guarding phase starts. The guarding phase is considered after the evacuation phase in the flowchart, because of the logical order of events. However, it is likely that the anticipation and keeping track on the follow-up of the primair evacuation starts right after the order of evacuation is given to the municipality. For the flowchart see appendix C.

Communication plays a vital role, because of timing and of the hiearchy in decision making versus operationality. The timing of the different actions is in this phase of study not clear, besides there are more doubts. It is known that ONEMI alarms the CLE and the citizens via the intendant of the regional government. However, SHOA's role towards citizen alarming is unclear. SHOA should somehow play a role in the decison making to alarm citizens and is therefore included in this object, it is assumed that SHOA provides the information to ONEMI where ONEMI should decide upon. Next to this, the tsunami alarm rings approximately 2 or 3 minutes after the earthquake according to [Municipality.of.Iquique, 2013]. However, in the evacuation plan of the municipality, it is stated that 10 minutes after the earthquake the maritime alarm rings and 13 minutes after the earthquake the coastal alarm. The maritime alarm is only for the people at the port and nearby environment. The coastal alarm rings along the total coast of the city. This has implications for the success of the evacuation as a whole, as it has been stated that time to evacuate is a main performance indicator.

Next to these specific uncertainties the way the CLE works together with ONEMI and the Municipality to establish the evacuation is unclear. Following from the hierarchical relations, the flow of processes should look similar to this chart provided. However no clear actor-dependent operations and coordination decisions could been distinguished between those 3 actors. Of course this is still important to derive a flowchart of evacuation processes consistent with the current way of operating.

3.5.3 Results from evacuation route analysis

The actors together with the system of the study case have been defined, which leads us to discuss the current infrastructure characteristics. We are interested in the local infrastructure. The zonal system of the city of Iquique indicates 51 zones (68 including nearby, but irrelevant Alto Hospicio), from which information is available on residential and jobs' distributions [SINTIA, 2010]. The municipality of Iquique has indicated five aggregated zones: Zofri (1), Port and Downtown (2), 3 ,4 and 5.

Two specific dense cumulations have been found, namely the Zofri shopping mall (evacuation zone 1) and the port of Iquique (evacuation zone 2). Based on inundation levels and arrival times derived from tsunami modelling see 3.2, it has been concluded that for day time especially the commercial area of Zofri is of prior importance and for night time especially evacuation zone 2. Nevertheless, evacuation zone 3 does remain interesting for its distant peninsula and evacuation zone 4 for the large detours people must make during evacuation (due to large buildings on steep hills).This focus leaves us with a detailed description on zones 1 and 2 in the main text, for a description of the other zones see appendix C.

Unless indicated otherwise, the results below are based on the findings of a field visit to Iquique, held from September 9th til September 11th 2013. During this trip evacuation infrastructure has been investigated and vertical shelters have been examined.

In the framework objectives have been identified for analysis of (weaknesses in) evacuation processes. These findings will be enumerated per zone after a short introduction to characteristics of the zone is given. The objectives were:

1. Identify dangerous zones and specific dense cumulations of people
2. Identify evacuation routes in dense cumulations
3. Identify road infrastructure characteristics and suitability for evacuation
4. Identify suitability of meeting points in higher grounds
5. Identify suitability of vertical shelters

Introduction to evacuation zone 1 (Zofri)

Zone 1 mainly consists of the private institution Zofri. In the areas south of the commercial area live 13,859 people [SINTIA, 2010] in poor facilities. Zofri is surrounded by fences and gates to indicate the taxfree area. On a normal working day all trucks come through Zofri from gate 7 in the West side of area 2 till gate 12 in the North of area 1.

The commercial area can only be entered and exited from downtown Iquique via the west side of area 2, near gate 7. There are 6 'puertas' or gates which are 3 till 5 meters wide. At gate 10 the pedestrians of the mall should exit in case of emergency. The gates are all guarded by men. In case of emergency these guards are instructed to open the gates and/or leave them open. The malls are concentrated with two main parking slots with two exits. The amount of exits in the mall is approximately four. For those indicating signs exist. For now we take the indication of four exits out of the mall as starting point.

From the edge of the Zofri area to the safety zone in the South there exists a slope, which on average has an inclination angle of 19° steep. On the slope two concrete ramps are constructed with a width of 2.5 meters. In case of emergency the pedestrians out of area 2 should exit Zofri and continue their evacuation along these ramps through the residential area towards the main evacuation route Soto Mayor uphill. Besides, slope failure is likely to occur which will likely influence the suitability, see section 3.3.

The expected amount of people in the total Zofri area is on average 25,000 till 30,000 in peak hours with on average 10,000 people in the commercial area [ZofriSA, 2013]. A simple calculation stresses the need for attention in the commerical area of Zofri. Taking the most optimistic arrival time from the tsunami modelling of 20 min (see 3.2) and a assumed walking speed through the ramp (2.5m) from literature (0.50m/s per person) [Goto et al., 2011] an more than ideal (irrealistic) estimation can be given on the number of evacuees. In 20 min times 6,000 people could escape, leaving 4,000 killed by the water (assuming 10,000 people present in the commercial area). In this calculation the evacuees are assumed to fall in endless arrival bin and no backlogging mechanisms are taken into account, which is unrealistic considering available infrastructure.

The line of the safety zone is formed by the avenida Sotomayor. This is the avenue on which both evacuation routes out of zone 1 end. The avenue provides a lot of space (two traffic lanes plus parking lanes at both side of the streets and is on average between 10 and 12 meters wide[Lagos et al.]. The street is allowed for traffic from one direction only, towards the coast, except for the first part of the street that is headed oppositely. No signs of meeting points have been identified.

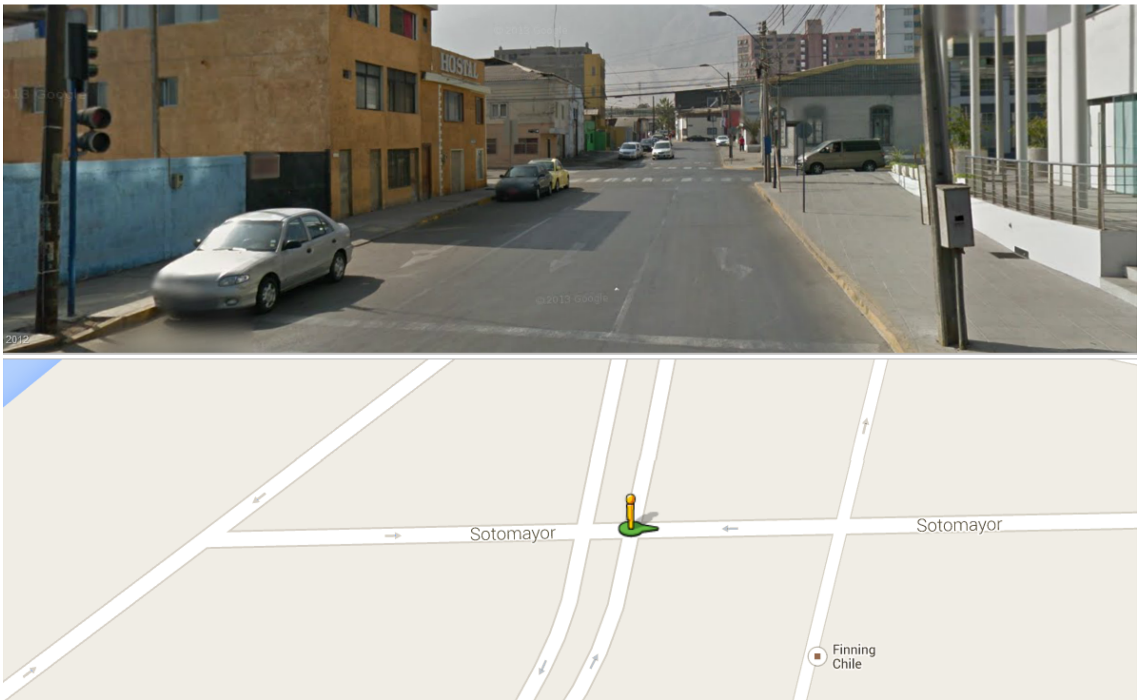


FIGURE 3.16: Sotomayor and Arturo Prat Chacon section

[GoogleStreetview, 2013]

Based on vertical shelter analysis in evacuation zone 1, see section 3.4, no suitable vertical shelters have been indicated.

Results for evacuation zone 1 (Zofri)

The following results have been derived; below is indicated to which objective the results are related.

- Large mass of population in the commercial center during the day (objective 1)
- One evacuation route out of the commercial center ending in a ramp of 2.5m wide and slope of 19° (objective 2)
- One evacuation route for industrial area (objective 2)
- Road infrastructure is not sufficient enough to evacuate all people (objective 3)
- Few signs identified at meeting points in safety zone (objective 4)
- Street for meeting point is 10 till 12 meters wide [Lagos et al.] (objective 4)
- No vertical shelters available (objective 5)

Introduction to evacuation zone 2 (port and center)

The port has approximately 600 workers, but in case all three berths are all fully used (e.g. a large vessel with 4,000 cars at pier one and two containers vessels at pier two) the expected number of people present can reach up to 4,000 [Puerto de Iquique, 2013]. For evacuation the port makes use of the sirens on the shore provided by the maritime agency located on the site [Puerto de Iquique, 2013]. The fenced core of the port (the container stock area) hardens a direct passage across the peninsula to the coast. However, three evacuation routes are available, all ending at the dam that houses the only connection road (Av. Jorge Barrera). The width of the pier narrows down from six to four lanes, approximately 250m before the evacuation route starts. At normal walking pace (i.e. 5 km/h) these evacuation routes take approximately 12 minutes to the shore. From the shore to the safety zones at least another 20 minutes must be counted.

The street pattern in zone 2 is mainly grid based, with occasional diagonal streets and one pedestrian area, namely Baquedano Square. The number of inhabitants of evacuation zone 2 is 70,024 [SINTIA, 2010]. The area is considered to contain most jobs of the entire city [Municipality.of.Iquique, 2013], leading to a large number of people present at daytimes. Evacuation routes have been marked, but are not exuberantly communicated by means of signs. Only close to the safety zone and meeting points signs can be found on regular base. Even though stated by the government [Municipality.of.Iquique, 2013] that only one direction streets heading to the sea have are chosen as evacuation routes, there is clearly a large number of streets that have traffic in the other direction as well. From the fifteen evacuation routes in zone 2, this holds for seven, namely Esmeralda, San Martin, Vicente Zegers, Manuel Buines, Ernesto Riquelme, Jose Joaquin Perez and Cespedes y Gonzalez.

The evacuation routes usually have a minimum width of one traffic lane plus park lane and maximum width of two traffic lanes plus two parking lanes (at both sides of the streets). A lot of cars are parked transverse to the street. Pavements decrease in quality roughly from West to East; the presence of ramps for wheelchairs is not consistent. On average the streets have a slight slope angle (ranging from 1° to 3°). At night this might make it difficult for inexperienced or unprepared people to navigate.

The line of the safety zone is formed by the following streets: 18 de Septiembre; 21 de Mayo; Arturo Pérez Canto; Héroes de la Concepción; Sold Pedro Prado. The first three are one-way streets and relatively quiet. Héroes de la Concepción and Sold Pedro Prado (named Avenida Salvador Allende in Municipal evacuation plans [Municipality.of.Iquique, 2013]), however, are busy two-way streets. It's possible, not to say likely, that much car traffic will pass through these streets in case of tsunami evacuation with the direction to A16.

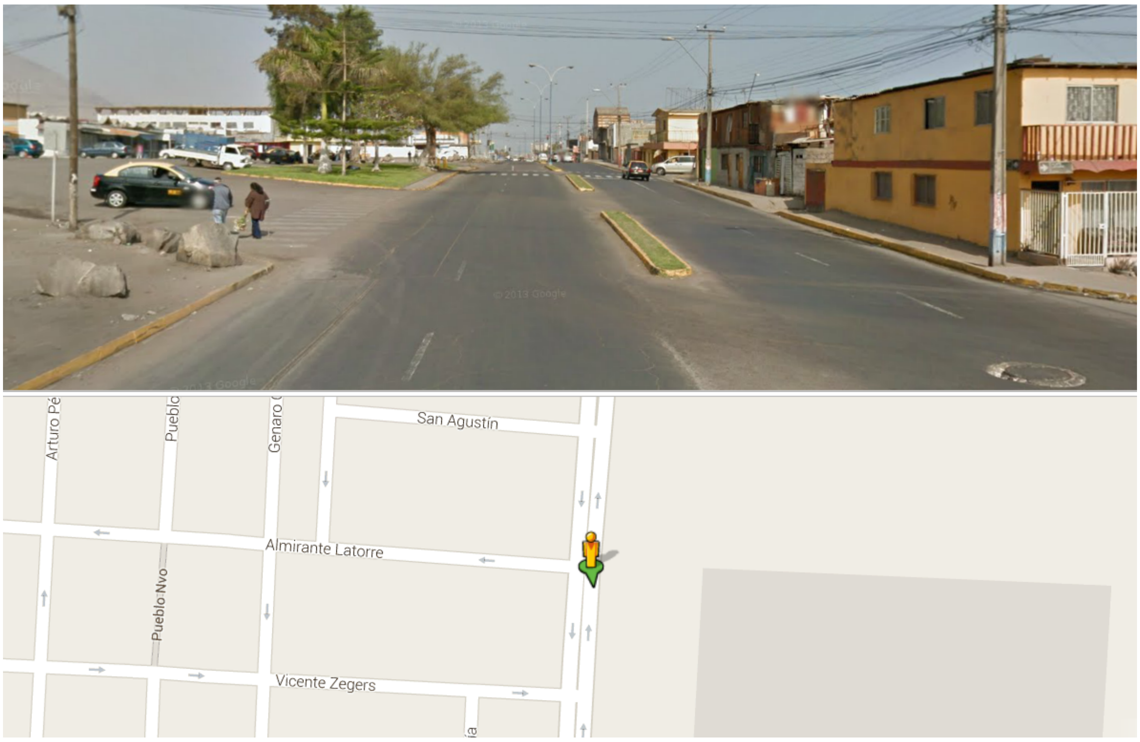


FIGURE 3.17: Sold Pedro Prado (named Avenida Salvador Allende in Municipal evacuation plans [Municipality.of.Iquique, 2013]) and Almirante Latorre section [GoogleStreetview, 2013]

Based on vertical shelter analysis in evacuation zone 2, eight buildings have been found suitable for vertical evacuation, see 3.4.

Results for evacuation zone 2 (port and center

The following results have been derived; below is indicated to which objective the results are related.

- Dangerous area of population in the East near the Safety Zone (objective 1)
- Several evacuation routes out of downtown (objective 2)

- One evacuation route for port (objective 2)
- Road infrastructure is not sufficient enough to evacuate all people (objective 3)
- Bottlenecks on evacuation routes Manuel Buines, Vicente Zegers and Orella [Municipality.of.Iquique, 2013] (objective 3)
- Some meeting points identified with signs (objective 4)
- Street for meeting point is 10 till 12 meters wide [Lagos et al.] (objective 4)
- 8 vertical shelters available (objective 5)

With the findings on road infrastructures we are a few steps away from modelling the evacuation of pedestrians in Iquique. For a detailed description of the pedestrian flow simulation methodology find 2.6. In the next subsections the qualitative analyses of this simulation are applied for Iquique forming the first achievement of conducting the simulation. The qualitative analyses capture the current knowledge on pedestrian behaviour and are conducted by literature study, see sections 3.5.5 and 3.5.6.

3.5.4 Knowledge on psycho-behavioural aspects

For future research a simulation would be the main tool for assessing proposed (policy) measures under various conditions (e.g. at night or during the day).

A short check can be performed on the choice for focus on pedestrian evacuation. A drill in Iquique in 2013 revealed a preference of people evacuating by car rather than by feet, even though car use during evacuation has been prohibited. Even though car traffic is very likely to interfere with pedestrian movements during evacuation, the main reasons for choosing the (pedestrian) Agent Based Modelling approach (i.e. ability to explore interrelation between individual behaviour and evacuation patters at macro-level, possibility of step-wise model improvements, short distances) hold their grounds.

This behaviour can be for various reasons. In order to get a clue on stated preference, a survey has been carried out. In the following subsections most of the psycho-behavioural factors of influence on evacuation processes has been elaborated on.

3.5.5 Knowledge on psycho-behavioural aspects

Recent studies on people's behaviour during a tsunami are based on both revealed and stated preferences. Data on stated preference concerns interviews about the 2005 earthquake, while data on revealed preference comes from several evacuation drills, held in various regions in the country. Data on revealed preference in Iquique is based solely on one of these drills held in August 2013, because in recent history its area has not been confronted with casualties resulting from a tsunami event.

The results of the description below are mainly based on interviews with psychologist Paula Repetto, who's attached to the CIGIDEN research center, and with Vanessa Bravo, who works for the Municipality of Iquique and is responsible for emergency operations.

People's intelligence concerning the tsunami hazard

Psychological studies reveal that in general Chilean people are aware of the earthquake and tsunami hazard. Depending on the exact region they live in, most people have had several experiences with (heavy) earthquakes (above 7.0 Mw.). The 1960 Valdivia quake is usually taken as the best example of a devastating earthquake and tsunami that people have branded in theirs minds [CIGIDEN research center, 2013].

People's preparedness for a tsunami (mitigation)

Even though aware of the tsunami risk, there's only a small amount of people that actually have prepared themselves to the utmost. Examples of little preparedness are:

- Tools that could be essential during evacuation (such as flash lights, clothing and food packages) are only put set by few;
- Knowhow on available time for evacuation is scarce; studies show that the amount of time that people think they have available ranges from three 3 till 120 minutes;
- Only people living at the peninsula (evacuation zone 3) consider vertical evacuation in their plans. Except for elderly or disabled people, most people in other zones prefer to walk or run to the safety zone. This comes from the experience with earthquakes, during which shaking buildings are not deemed safe to seek shelter

and is underpinned by official policies that don't involve vertical evacuation or even discourage it (ONEMI);

- Knowhow on evacuation routes is scarce; from 230 respondents 40% did not know how to get to the safety zone;

- Use of evacuation signs in the streets is not used that much; from 230 respondents 37% did not see the signs;

- Scarce use of evacuation maps, which is a result of the variety of distributed maps and the disregard of using them.

Several involved authorities (SHOA, ONEMI and the municipality) have distributed different maps, from which the lot is regarded as useless, due to a lack of readability and details. Moreover, due to experiences with the 2010 tsunami event, ONEMI has a very negative image concerning its reliability. Finally, navigation is bothered by a Chilean habit to take the Andes Mountains as constant anchor point for orientation. Instead of using maps, people do have a radio available to receive updates and information from authorities. To this end some people regard internet as a second best option. The favourable use of radio comes from a historic reason (it has been the first large-scale means of communication in this rather isolated area) [CIGIDEN research center, 2013].

People's response

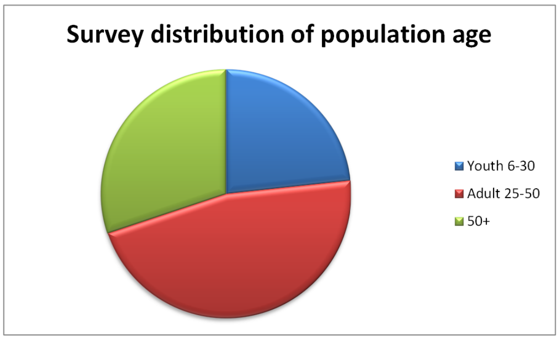
During the 2010 (Maule) earthquake little panic has been reported. However, some examples of irrational behaviour of Iquique residents during the drill in 2013 can be recognized:

- People working in the nearby (and safe) Alto Hospicio catch acquintances by car, not obeying the policy to avacuate be feet.

- A lack suitable capacity between Alto Hospicio and Iquique will emerge into congestion.

- The desire to make use of public transport modes, mostly by taxi.

The difficulty with psychological research on the topic in Iquique is that revealed data is only based on evacuation drills, which do not stand under life threatening conditions [CIGIDEN research center, 2013].



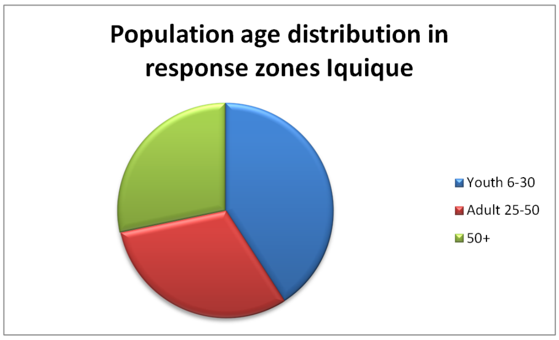


FIGURE 3.18: Distribution population age of the survey and Iquique.

3.5.6 Results from stated preference survey

To achieve a better tsunami hazard plan, the way people behave is an important input variable. In an ideal way one would be able to define the processes suitable for the population, however the opposite is true. When comparing the so called stated preferences of people acting during evacuations to the revealed preferences we can find a gap of preferences. This gap should be overcome by means of declaring the differences. The stated preferences can be defined by conducting surveys. For the revealed preferences a real evacuation case is needed, which is for Iquique not available. Therefore, the results from this survey are presented rather straightforward.

Stated preferences of people can differ because of cultural aspects, experiences with evacuations and more. In order to approach the logic these preferences are primed to be found by use of a social survey. The questions will state the preferences on vertical evacuation or up-hill evacuation, the dependency on the tsunami alarm, by which mode to evacuate and how to prepare for an evacuation.

The survey has been conducted with response of 73 people present in the unsafe zones of Iquique. No distinction of age, sex or any other characteristic has been made for asking response. The survey has been carried out among all ages varying from 12 till 100 years old and among both sexes on 3 different days of the week. As can be seen from figure 3.18 the population in the survey corresponds not quite the population of the zones in Iquique where the response was given with a total of 17.305 people. As from the figure 3.18 can be seen, the proportions of the different categories of age rather differ for adults and youth. This can be explained by a few facts. Firstly, the fact that the numbers of population are derived from [SINTIA, 2010] which displays where people lived in 2010

Percentage	Matter
97.26	Knows what to do in case of a tsunami alarm
95.89	Knows what to do in case tsunami alarm rings right now where they are being surveyed
93.15	Would evacuate by feet
90.41	Is aware of tsunami danger in the unsafe area
87.67	Is aware of the safety zone in Iquique
72.60	Feels less safe in vertical evacuation building than going to safety zone
68.06	Lives or works in the not safety zone
59.72	Would evacuate vertically if this is the indicated evacuation point
41.10	Makes it to the safety zone within 8 minutes from anywhere in the unsafe zone
23.29	Waits for tsunami alarm to evacuate after feeling a very strong earthquake

Table 3.15: Stated Preferences inhabitants Iquique unsafe area

can change from current survey results of 2013.
Secondly, it should be considered that the survey has been conducted on the streets, not to households in this area, where were a lot of commercial activities. So the survey distribution rather displays the population in the commercial centers of these zones than the people living there. This is important to take into account when simulating a day or night scenario, with the survey population displaying the overday distribution and the sectra 2010 information the night distribution.
Furthermore, in the Zofri area no people registered are living there, although this area has been surveyed. This has as result that the data from the survey on population distribution and the data from SINTIA data differ. The survey data are found to be picturing the population in day-scenario and therefore the results of this survey can be used to determine the stated preferences of the people in Iquique during day-time. Please find figure 3.19 for the zones in which the survey has been conducted.

It has to be noticed that the questions are nominal scaled with the only option to answer 'yes' or 'no'. As such the observations made with this survey have a qualitative goal rather than being used for further quantitative analyses. For the topics related to

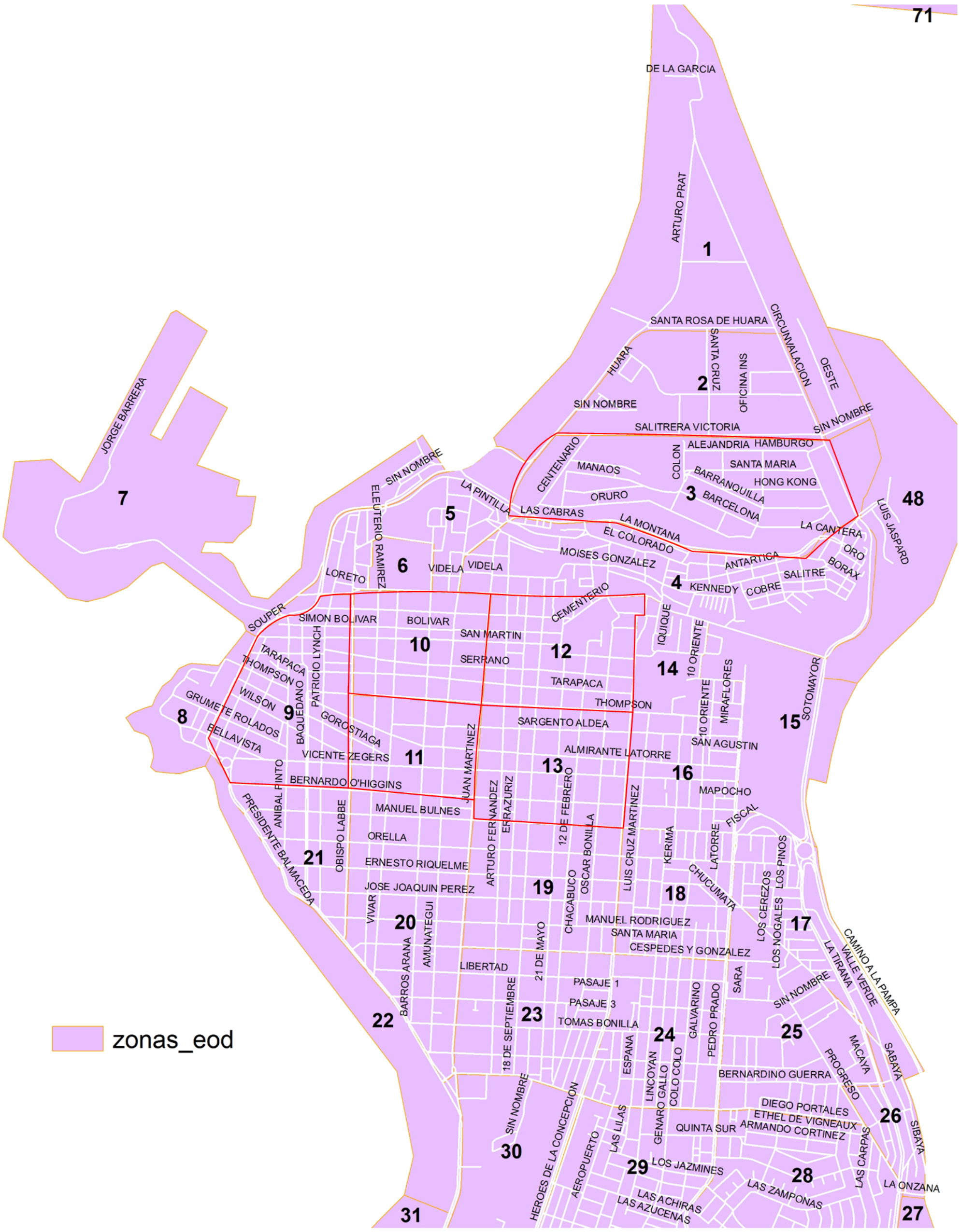


FIGURE 3.19: Survey zones Iquique

emotion open questions have been used. A lot of notes have been made as this subject was of emotional value to the majority of recipients. When preferred, this survey can be extended with interval or ratio variables in order to study the logic in quantitative matters. For this conceptual case, this survey reveals sufficiently the stated preferences of inhabitants of Iquique.

In the survey of Iquique a more one-sided answer was given to the majority of the questions, which shows unanimity for certain preferences. It is remarkable that the majority is aware of the danger, aware of the safety zone and knows what to do in case the tsunami alarm rings. Whereas, the minority really thinks they can make it to the safety zone within the minimum time of 8 minutes from where they are being interviewed in the unsafe area. Furthermore, the majority feels less safe to evacuate vertically than going to the safety zone. Although the small majority would actually consider vertical evacuation if this was the evacuation point indicated to them.

In the drill of 2013 it has been experienced that people took the car to evacuate to higher grounds, although from this survey you wouldn't expect that behaviour to happen as the majority answered to evacuate by foot. A reason for this might be the fact that only pedestrians have been interviewed. Within the context of this survey, people might have answered within the possibility of evacuating from that moment on.

3.5.7 Concluding remarks on TIL aspects

This subsection concerns a small summary on evacuation processes and addresses weaknesses and knowledge gaps.

Findings in the organization

The involvement of the municipality in the operational emergency processes in not direct, but functions via ONEMI by the CLE. The operations of the municipality are rather intern and there is no direct formal link between the municipality and ONEMI in case of emergency. No clear actor-dependent operations and co-ordination decisions could been distinguished between those 3 actors. Also the regional ONEMI (OREMI) has no clear relation with the CLE or Red Cross and therefore their responsibility during an emergency is not clear. Also in this case no clear relationship has been found among

the CLE and the Red Cross in order to coordinate the aid to people.
Furthermore, Zofri and the Port Authorities are barely linked to the municipality. Zofri and the Private Port Authority have their own evacuation plans. No link has been found establishing the supervision of those evacuation plans by any governmental organization.

Timing of the different actions is in this phase of study not clear. SHOA's role towards citizen alarming is unclear. The coastal alarm rings approximately 2 or 3 minutes after the earthquake according to [Municipality.of.Iquique, 2013]. However, in the evacuation plan of the municipality is stated that 10 minutes after the earthquake the maritime alarm rings and 13 minutes after the earthquake the coastal alarm.

Findings in the Road Infrastructure characteristics and population

Next to the organizational part there are some challenges left on determining the actual population living in Iquique per district. Data of various sources on the population numbers differ much. Furthermore, in focus zones Zofri and Downtown and the Port the following weak points on infrastructure characteristics have been found. To start with Zofri, the only commercial evacuation route is dangerous, too steep, to narrow and therefore not suitable. The evacuation route out of the port is probably wide enough, but the pedestrians will not make it to the Safety Zone in time. The evacuation routes in downtown will most likely not be sufficient, causing congestion and more panic with the most stressing points at Manuel Buines, Vicente Zegers and Orella [Municipality.of.Iquique, 2013]. Vertical schelter should be considered as urgent measure to minimize victims for as well the Port as downtown.

Findings on behaviour

Involved authorities (SHOA, ONEMI and the municipality) have distributed different maps, from which the lot is regarded as useless, due to a lack of readability and details. Moreover, ONEMI has a very negative image concerning its reliability on coordination during an emergency. Finally, navigation is bothered by a Chilean habit to take the Andes Mountains and the Ocean as constant anchor point for orientation, which are not always visible. People thrust the information on the radio and this medium is part of the communication towards citizens by the municipality. Instead of using maps, people do have a radio available to receive updates and information from authorities.

The following irrational behaviour has been identified in last drill in Iquique in 2013. Many people went from uphill Alto Hospicio to downtown and Zofri to try to catch relatives (such as children and elderly people) by car, not obeying the policy to evacuate by feet. The desire to make use of public transport modes, mainly taxis, was evident. However, comparing this result with the survey on stated preferences, the majority of people would evacuate by feet.

Knowledge gaps

When comparing the stated preferences of people acting during evacuations to the Revealed Preferences we can find a gap of preferences. The difficulty with psychological research on the topic in Iquique is that Stated Preferences both by means of surveys or drills, do not hold under life threatening conditions [Municipality.of.Iquique, 2013]. To grasp these features within an evacuation simulation, more research is needed.

Furthermore, to actually reveal the flow of evacuation processes more detailed interviews, manuals, protocols and instructions should be considered. With the current data no clear statement on the timing of processes could be set. Further analyses are needed in order to determine the coordination among the main emergency stakeholders, communication lines and responsibilities. All information will contribute to minimize victims in the end when critical process chain can be established.

Chapter 4

Evaluation of the Case Study

As part of the framework, the progress in all activity areas of tsunami risk management should be evaluated. This can also be done for the case study, Iquique. In this chapter, current tsunami hazard management practice is evaluated using RAMS. This is followed by a summary of the recommendations for improvement in the various activity areas.

4.1 Evaluation using RAMS

As mentioned in section 2.2, the framework includes the evaluation of the tsunami risk management to rate the current situation and any future progress. In this section are the RAMS criteria are here used to evaluate the current tsunami risk management in Iquique. This can be done using four criteria: reliability, availability, maintainability, and safety. This is done for the current situation in Iquique.

4.1.1 Reliability

The first criterion is reliability, which judges Iquique's ability to minimise loss of life and economic damage during tsunami events. Currently Iquique's plan is focused on evacuation which should save as many lives as possible during the tsunami event. Iquique is actively implementing evacuation plans that should reduce victims during tsunami events. However, there are already clear signs of weaknesses that reduce the reliability of the current plan. First, the current prediction of flooding is not clear. There are two predictions given, one by the SHOA, which is not very reliable due to the complexity of models and their input; and one by ONEMI, which is only based on the 30 meter contour lines. It is hard to say which of the two lines is correct. This means that any plans developed, based on these predictions, are potentially unreliable as well. Also evacuation routing does not always consider factors like obstruction due to slope failure or dangers from gas stations. Furthermore some routes are simply too narrow, and it can already be predicted that evacuation would be too slow. A perfect example here is the *Puerto 10*, which is the most important and only evacuation route from the Zofri shopping zone to the safe area. Not only is this route too narrow, there is also a big chance of obstruction due to slope failure. Furthermore evacuation signs are often difficult to read which could be a danger, specially for visitors who do not know the city by heart. Finally, there are no official vertical shelters used, making successful evacuation out of some areas very difficult.

Regarding the economic damage currently still little is known on how to assess this. Although [Mas et al., 2012b] developed methods for Chile to make a first estimate on probabilities of damage, these are still very rudimentary. Allocating monetary values to these losses is even more ambiguous since methods from other countries have to be used that are not comparable with Chilean standards. Additionally a lot of factors that actually contribute to the total economic damage are still not clear.

4.1.2 Availability

The second criterion is about how well the system can be kept in a functioning state. This rates how plans can succesfully be implemented for all activity areas for tsunami risk management. Weaknesses in communication is an important factor for successful implementation of the contingency plan. The first problem arises between ONEMI and the municipality of Iquique, who do not always appoint the same routes for evacuation and communicate to the people separately, resulting in confusion about the best routes. Secondly, results from surveys have shown that the map that is used to communicate evacuation plans is not always used by citizens, schools, etc., who often choose their own routes without communicating these choices to the governmental organisations. Finally, updates in plans are communicated via the radio, which can be missed. Therefore, organisations that distribute evacuation maps, like tourist offices often have outdated maps without knowing that updates have been made. Another limit in current practices is the need for detailed information, for example on bathymetry and topography which are expensive to attain.

4.1.3 Maintainability

This criterion can be used to rate the maintainability of current management practices in Iquique. This will show how sustainable the plans are and the effort necessary to stay prepared for the tsunami hazard. Due to the simplicity of the current plan, maintenance become easier. Evacuation routes have multiple functions, so maintenance becomes part of the city's *standard* maintenance activities. There is however a rapid growth in population in Iquique, so maintenance and expansion of infrastructure will have to account for this. Finally, current predictions on tsunami events will also have to be maintained since topographic and coastline changes will effect the flooding and characteristics of a potential earthquake change with time.

4.1.4 Safety

The final criterion is safety, which judges if the current management practice has any safety issues that could harm the citizens of Iquique or the surrounding environment. The current plans have few issues for safety. From conducted surveys it is clear that the people of Iquique are aware of the danger, but do not allow it to affect their daily lives. One part of the current plans is to limit the evacuation routes to roads in which the traffic flows in the same direction, which should reduce accidents. This however will reduce the reliability of the plans.

4.2 Improvement of Current Tsunami Management

Following the evaluation of the current tsunami risk management in Iquique this section evaluates the new plan with all the changes proposed in chapter 3. Proposals for each activity area are evaluated using the RAMS criteria.

4.2.1 Prediction

One of the products of this report is a new prediction made in the form of a hazard map. Using computer models, bathymetry, and details on earthquake scenarios, multiple floods were predicted.

As can be seen in figure 4.1 different lines exist for indicating the safe zones. Primarily a clear difference can be seen between the flooded area as calculated by the

NeoWave simulations and the SHOA flood line. Secondly it seems that ONEMI based their evacuation line on the 30 meter contour line. This is supported by comparing the line to the topographic data used for the modelling and by interviews with the municipality of Iquique [Municipality.of.Iquique, 2013]. The line used on the evacuation maps distributed by the municipality is based on this line; it follows the nearest available pathways. Exact details on which methods and data SHOA used for their models is unknown. However based on correspondence with Universidad.de.Valparaiso [2013] it can be concluded that the seismic scenario that was used for their calculations is comparable, but less severe, to the Chlieh scenario used for the NeoWave modelling. A presumption would be that SHOA moved their line inland to account for uncertainties, since their results will and have been used to create evacuation maps. The current safety line, as used by the municipality, seems to be a very safe approximation compared to the other predictions. The NeoWave model results do contain uncertainties, but then again this already seems to be accounted for by SHOA. Since ONEMI bases their safety lines on the 30 meter topography line, it is very easily available, whereas inundation lines resulting from hydraulic modelling are very costly, both in time and money. Detailed hydraulic modelling resulting in a more accurate prediction of the actual inundation leads to a better assessment of the actual hazard. Unreal presentations of safety lines are unsafe in case this lines lies more seaward than the actual inundation. This is not expected to happen. However, an exaggerated presentation is also unfavorable. This concerning the behavior of people like unnecessary panic or rejection of economic activities in certain areas.

In the three codes described in section 3.4.7, the hydraulic loads are estimated by means of flow velocities and inundation depths. Two methods to determine these parameters are used, namely an analytical way using only the runup and by directly using local results from the NeoWave model. The runup as input for the analytical way is highly dependent on the quality of historical observations. Next to this the assumptions only are a reasonable approximation at very specific locations. The reliability of the model output is directly dependent on the quality of the model results. This is strongly dependent on used grid sizes, output time intervals, resolution of model input, etc. Inclusion of the built environment in the topographic data is important to make a sound estimate, especially regarding the flow velocities. This can be done by using for example data gathered by LiDAR flights. However, the state of the art of inundation models still limits the reliability of results. For the analytical approach only the runup level and

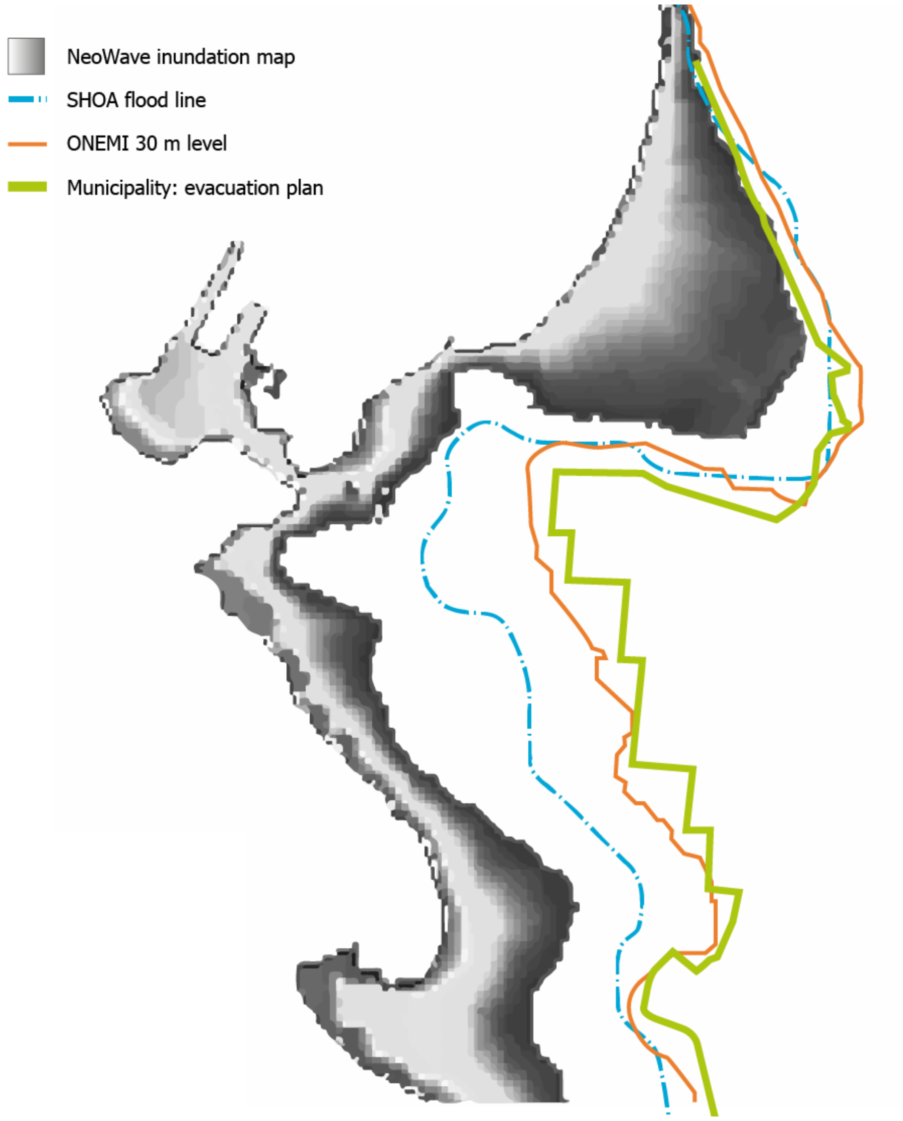


FIGURE 4.1: Different predictions of the tsunami event and mitigation

local ground elevation have to be known. For the numerical model more specific information is required. There is a big variation in the magnitude of the hydraulic forces that are calculated, especially if the input is used originates from the unreliable analytical approximations. For this reason the highest hydraulic loads of the three different codes is used, with input from the model. The fluctuation of the output for the model and the approximations per code is illustrated in figure 3.8. Here the output from the model is considered to be more accurate, but still sensitive to several factors like: the seismic scenario used, quality of input data, and state of the art of models. An underestimation of inundation depth or flow velocities could lead to an unsafe situation.

For future investigations regarding the suitability of existing structures for vertical evacuation it is recommended to use direct results from inundation modelling if available. Some uncertainties will still remain but can be accounted for by doing a sensitivity analysis or using safety factors.

4.2.2 Mitigation

In this report, a few proposals are made to improve current evacuation plans. These proposals, like possible vertical shelters or improvements for route usability will improve the evacuation process. Using vertical shelters shortens the distance that people will have to move, reducing the time needed to get to safety. The proposed improvements for existing routes are mainly focused on avoiding blockages due to secondary hazards like landslides, which will ensure that paths remain clean and easy to use.

Urban plans should take into account the risk on tsunami flooding and can be used by local governments to prevent the exposed risk on the population. The ramps on the commercial evacuation route should be widened to increase throughput and be less steep. Leveled ramps starting from the roof of the Zofri mall can help to diminish the amount of victims by cause of not being able to reach higher ground. It is likely that slope failure at Puerto 10 and A16 will occur during an earthquake tsunami event. It is advised to use an embankment in combination with a ditch. This will improve the current plans and ensures better evacuation out of Zofri and a clear way in and out of Iquique. The method is cheap and the associated technology is not complicated. The new structures should be maintained, but the costs will stay low due to the slow weathering processes in Iquique. However the implementation of this operation should not hinder traffic on the A16, this will form no issue for the *Puerto 10.* Other evacuation opportunities can be found in vertical evacuation shelters. For downtown area the possibility of vertical evacuation should become serious option. It is advised to used 20 existing buildings for vertical evacuation in Iquique. The practice of vertical evacuation will create new possibilities for the areas that are difficult to evacuate. The current built environment can be used in a very efficient way and no new structures have to be build, but policies, together with new certifications, should be adapted to make this possible. The existing structures are maintained by the current owners according to the building law. A point of attention is the flow of people during the evacuation, this should be managed with care. Furthermore, meeting points should not be located in unsafe areas in means of exposure to open electricity and gas. There should be enough space for people to evacuate further than those meeting points because the slogan is 'the higher, the safer'.

4.2.3 Response

The last product of this report regards the direct reaction after the tsunami event. This is also the last activity area which is attended and no further attention is given to the recovery.

It is recommended to the local government, ONEMI, OREMI, SHOA, CLE and Intendant to derive an evacuation strategy conform a reliable, available, maintainable and safe way. This means that a clear hierarchical structure and division of responsibilities is necessary among these actors. The communication, coordination of activities, incentives on different topics regarding political agendas, should be shared in order to derive consensus on the plan of attack. The urgency of these severe risks on the population should be of prior attention to all related agencies.

For the case of Iquique this means that a robust and integral tsunami hazard plan will become available in which the aim is to minimise victims and economical damage. In this plan a structured hierarchical emergency organization is set up by involving all emergency related institutions. Activities are distributed fairly among the involved actors regarding level of power, interests and resources. Those activities are ordered in time, time they consume and on criticality in the total process gain success on the evacuation.

Chapter 5

Conclusions and Discussion

5.1 Conclusions of the research

The aim of this report is to determine how victims and economic damage due to tsunami flooding can be minimised in the city of Iquique. This can be answered by means of the sub questions given in chapter 1. In this section the answers to these questions are summarised.

5.1.1 What are the weaknesses of current evacuation plans?

Based on an assessment of current tsunami hazard management, several weaknesses were found. These were found for each activity area from points of view of varying disciplines in combination with the other subquestions. These included weaknesses in evacuation routes, policy implementation, governmental parties, prediction practices, and unawareness of secondary hazards and multiple evacuation options.

5.1.2 What are the hydraulic boundary conditions for flood risk?

In order to determine hydraulic boundary conditions for the following research on Iquique, three scenarios have been made and one historical check has been done. After modeling these scenarios, the conditions described by [Chlieh et al., 2011a], with an earthquake of 8.8 Mw, have been chosen as hydraulic boundary conditions. These results concern a runup of 11.99m max and 10.46m average, an inundation level of 9.84m max, and an approximate arrival time of 11 minutes. Marked on the map of Iquique, these results are (almost) everywhere less negative on prediction of runup levels than inundation predictions from governmental organizations.

5.1.3 To what extend do geo-technical conditions influence the possibilities of evacuation?

For Iquique several geo-technical analyses have been performed in order to see how reliable infrastructure will remain after a tsunami generating earthquake. Slopes nearby the main pedestrian exit from the Zofri area, as well as the highway A16, have been found instable, and thus harmful for evacuating possibilities. Slopes in safety zones in higher grounds are deemed stable (based on information of the Municipality). Scouring of sidewalks seems likely, but this won't interfere with evacuation because it will only start during flooding. There's a lack of knowledge on liquefaction of quaywalls in the port, which could be disastrous for port evacuation routes. Analysis on all foundations of buildings suitable for vertical evacuation has revealed no problems.

5.1.4 To what extend can the built environment improve the possibilities of evacuation?

The built environment can contribute to tsunami risk management by providing reliable vertical shelters. Yet in Iquique, only few examples of used vertical shelters can be found. The minimum necessary to implement this in current practice, is certification (based on analytical approach). In order to make the first moves towards such an offical certification, a method to check high buildings for the possibilities for evacuation has been developed. After a check on buildings' location and height, a structural analysis on hydraulic loads, and a comparative analysis for seismic loads, 21 buildings in Iquique have been marked as reasonably suitable for vertical evacuation.

5.1.5 Which evacuation processes are organized in case of an expected tsunami flooding?

In Iquique several governmental organizations are involved with tsunami hazard management, and they all use different evacuation maps. For the public this results in a rather unreliable mess of plans, but because people have some experience with earthquakes, a reasonable part of the people knows what to do in case of a (approaching) tsunami event. Escape times based on current evacuation plans are not at all viable (for both arrival times expected by the municipality and arrival times derived from tsunami models) and urban planning does not appear to be adjusted for evacuation processes. During evacuation use of cars is prohibited, which is reckoned beneficial for the overall evacuation process, but also unrealistic. Currently, no evacuation model simulations are used to assess the successfulness of mitigating measures, but this could be done with a Agent Based Modelling approach.

5.1.6 How can victims and economic damage be minimised due to tsunami flooding in the city of Iquique?

In this report, this question was answered with a multidisciplinary approach. Tsunami risk management was introduced, including the four main activity areas: prediction, mitigation, response, and recovery. For each activity, weaknesses in current evacuation plans were identified and attempts were made to resolve them. In cases that this was not possible, knowledge gaps were identified for further research. In other cases options were proposed to improve on the current plan.

5.2 Discussion

Following the conclusion of the research done, a few discussion points remain. In the following section the methodology of the authors is discussed. This is followed by a few final recommendations for follow up research.

5.2.1 Discussion on the author's methodology

Multidisciplinary Approach

Tsunami risk management is a very multidisciplinary subject. It is the combination of understanding physical, social, and economical phenomena. Within each area a long list of disciplines are needed to completely understand the processes involved. For this project the contributing disciplines were mainly hydraulic engineering, geo-technical engineering, structural engineering, systems engineering, and transport, infrastructure, and logistics engineering. Although all engineers, working with such a team demands thrust in each other, patience, and good communication. This will only be harder and more important as the project expands and includes disciplines like psychology and economy. Therefore it was good to start with a small fraction of disciplines to create a partially integral product within the time set for this project. For further development it will be necessary to involve many more disciplines. The gain from this approach will be an integral management of the tsunami risk, where all aspects surrounding the event are addressed.

Using a case study

For this research, a choice was made to develop the framework for tsunami risk management in Chile with a case study. The case study in itself is useful to stress the importance of the research and acts as a starting point. In addition, a better understanding can be achieved for policies, human behavior, and many details that could be overlooked. It will however focus research on one particular case which is undesirable when making a framework for all Chile, which has many variations in climate, geology, and culture. This is why one case is not enough to create a successful framework and other cities should be included.

Project Focus

The main goal of this project is to minimise loss of life and economic damage during tsunami events in Chile. The difficulty of such an extensive subject is that links between different processes are very important but hard to define. Therefore the focus of this project was to combine just a few aspects of tsunami risk management and identify and describe the links. Using this methodology helps understand how the project can expand and stay organised until it has included all the necessary subjects.

Furthermore the project was started within a few boundary assumptions and focus points. First the focus was on Iquique which was chosen for its economic importance, proximity to rupture zones, and potential for tsunami attacks. Secondly a choice was made to consider tsunamis that were generated by the subduction zone of the coast of Chile. When looking at evacuation these types of tsunamis are most critical since they have the smallest arrival time. In addition, tsunamis generated by the subduction zone is relevant for all of Chile. Finally the *recovery* of the system after the tsunami event was beyond the scope of this report. This allowed the focus to be more directed towards the other three activity areas. It should however be clear that this fourth activity is important and should be included in management practices.

5.2.2 Recommendations for future research

In this section recommendations are given on future research, that could help improve the framework. In the future, this framework should provide all methods to establish integral tsunami hazard management plans. The following research can be done for each activity area:

5.2.3 Prediction

- Modeling inundation depth using more sophisticated models.
- Identify and quantify the damages caused by inundation.

5.2.4 Mitigation

- Quantify extent of geo-technical risks.
- Include seismic duration in analysis of stability.
- Analyse capacity of buildings used for vertical evacuation.
- Investigate the properties of foundations of evacuation shelters and their effect on stability.
- Investigate the implementation of vertical evacuation as policy.
- Determine how various mitigation measures are coordinated.
- Determine how differences between mitigation measures arise.
- Find the relation between human behaviour and infrastructure characteristics.

5.2.5 Response

- Determine how decision processes can be clarified.
- Find the important criteria that should be included in evacuation plans.

5.2.6 Further aspects of tsunami risk management

- Quantify the norms to use when evaluating risk management plans.
    - What is the acceptable loss of life?

    - What are acceptable economic losses?

- Identify other disciplines that should be included in tsunami management research.

- Quantify the extent of economic damage of the tsunami attack.

- Determine the psychological factors concerning evacuation behaviour.

Appendix A

Appendix A

This appendix contains further details of Tsunami history in Chile.

A.1 History of tsunamis in Chile

Table A.1 shows a small recap of significant tsunami events in Chile. It is clear that tsunamis are very common in Chile, the reason why tsunami risk management is so interesting to this country.

Year	**Location**	**Magnitude**			**Run-up Height**
		M_r	M_s	M_w	[m]
1562	South Central Chile	-	8.00	-	16
1570	La Concepcion	8-8,5	-	-	4
1575	Corral	8.50	-	-	4
1604	Arica	8.70	8.40	-	16
1647	All Chile	8.50	-	-	-
1657	La Conception	8.00	8.00	-	4
1730	La Conception	8.70	8.70	-	16
1751	La Conception	8.50	-	-	3.5
1819	Caldera	8.50	-	-	4
1822	Valparaiso	8.30	-	-	3.5
1835	Quiriquina	8-8.2	8.50	-	13
1837	Ancud	>8.0	8.50	-	2
1849	Coquimbo	7.50	7.50	-	5
1851	Huasco	7-7.5	-	-	3
1859	Caldera	7.5-7.7	7.70	-	6
1868	Arica	8.80	8.80	-	20
1877	Mejilones	8.80	8.80	8.5-8.8	21
1918	Caldera	7.60	-	-	5
1922	Chanaral	8.40	-	-	9
1928	Constitucion	7.90	-	-	1.5
1943	Los Vilos	8.10	-	-	1
1960	Ancud & Valdivia	9.50	8.60	9.5	15
1966	Caldera	7.80	-	-	0.8
1985	Valparaiso	8.00	-	-	1.2
1995	Antofogasta	8.00	-	-	2.8
2010	Pichilemu	-	-	8.80	3

TABLE A.1: This table shows the eventful tsunami histoy of Chile. The Magnitudes are given in Richter scale (M_r), surface wave magnitude (M_s), and/or moment magnitude (M_w). [Disaster.Prevention.Institute.Kyoto.University], [SHOA]

Appendix B

Appendix Framework for Tsunami Risk Management

This Appendix contains elaborations on the framework explained in this report. First the methods used to determine the seismic coeffcient (k) are explained. This is followed by an eloboration of the liquefaction potential and how this can be found with the help of CPT and SPT's. This is followed by a comparison of building codes, tsunami characteristics relevant to structural calculations, and the resulting hydraulic and seismic loads on vertical evacuation structures.

B.1 Finding the Seismic Coefficient k

In this report, a screening process is used to determine if slopes are likely to fail during seismic events. This analysis is based on a Pseudo-static method where the horizontal vibration caused by the earthquake are represented by a pseudo-static coefficient, k. Only horizontal vibrations are taken since the origin of the earthquake is very deep and the foremost seismic will be S-waves traveling upwards causing horizontal vibrations. Although the analysis method is relatively simple, finding k is quite complicated. k is the peak value of spatially average acceleration across the sliding mass divided by gravitational acceleration Blake et al. [2002] and is dependent on earthquake magnitude, distance, slope orientation, and local geological features. Since k is dependent on so many variables, it is very complicated to find its true value. In this report two values are used, one conservative value ($k = 0.4$) and another less conservative ($k = 0.3$). The first was found from research done at the municipality of Iquique. Here building codes for *Edificio*

Matiz were found in which it was mentioned that the engineers used 0.4 as the seismic coefficient to calculate the seismic loads on the walls of the foundation and basement. The other value, $k = 0.3$ is taken from literature in which the value of k is clearly dependent on the magnitude of the earthquake. Figure B.1 shows the values of k as it has been suggested by various authors based on back analysis and laboratory testing. It is clear that there is a large uncertainty when determining k, which is probably why the engineers of *Edificio Matiz* decided to be extra conservative.

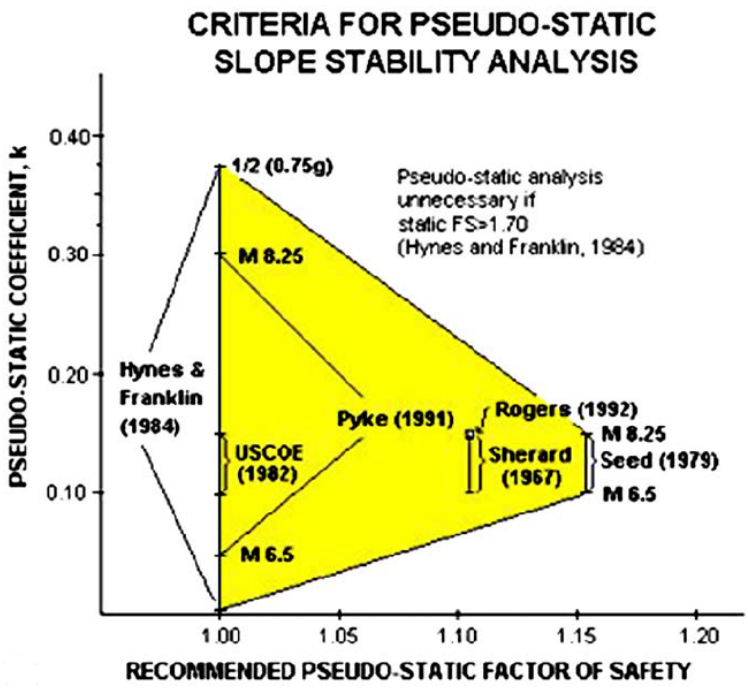


FIGURE B.1: Range of possible k values as a function of factor of safety (F_s) and multiple sample magnitudes (M_w). The analysis done in this report uses $F_s = 1.0$ and $M_w = 8.25$. [Baker et al., 2006]

B.2 Calculating Liquefaction Potential Using CPT and SPT

As mentioned in section 2.4, it is possible to determine the potential for liquefaction (PL) for layers of soil using CPT's (cone penetration test) and SPT's (standard penetration test). It is useful to extend preliminary site investigations with an analysis of PL when building structures that could be useful for vertical evacuation. Since the SPT is more common in Chile, this method is elaborated in this section, although the two are very similar.

Determining PL can be done using FoS(factor of safety) (deterministic) or based on reliability (probabilistic). If the deterministic is used, FoS is the ratio CRR/CSR, where CRR is the cyclic resistance ratio and CSR is the cyclic stress ratio. CSR is the stress induced by the earthquake and is a function of the magnitude (M_o) and distance to the hypocenter[1]. CRR is the resistance of the soil to cyclic loading and related to the number of blows (N_{60}), effective overburden pressure(σ'_v), and the percentage of fines (F_s).[Hwang et al., 2004]

Due to the many uncertainties it is wise to use a probabilistic approach rather than the deterministic and find the probability of liquefaction. This can include the probability of earthquake occurrence and magnitude or a specific earthquake scenario. In this case CRR and CSR are assumed to have a log-normal distribution [Hwang et al., 2004]. Following, a reliability index (β) can be found and used to determine the probability of liquefaction. Figure B.2 taken from [Hwang et al., 2004] shows the input and following steps necessary to determine liquefaction probability. Furthermore figures B.3 and B.4 show the correlation between data collected from the site investigation and the necessary input variables for calculation of PL.

Finally, although SPT is common in Chile, CPT is better for liquefaction analysis since data is continuous. Which is specially useful when determining lateral spreads and differential settlements [Martin and Lew, 1999]. It is also important to include boreholes samples to the investigation to verify CPT or SPT data.

[1]Singular point in the fault where the stress is released, directly below the epicenter

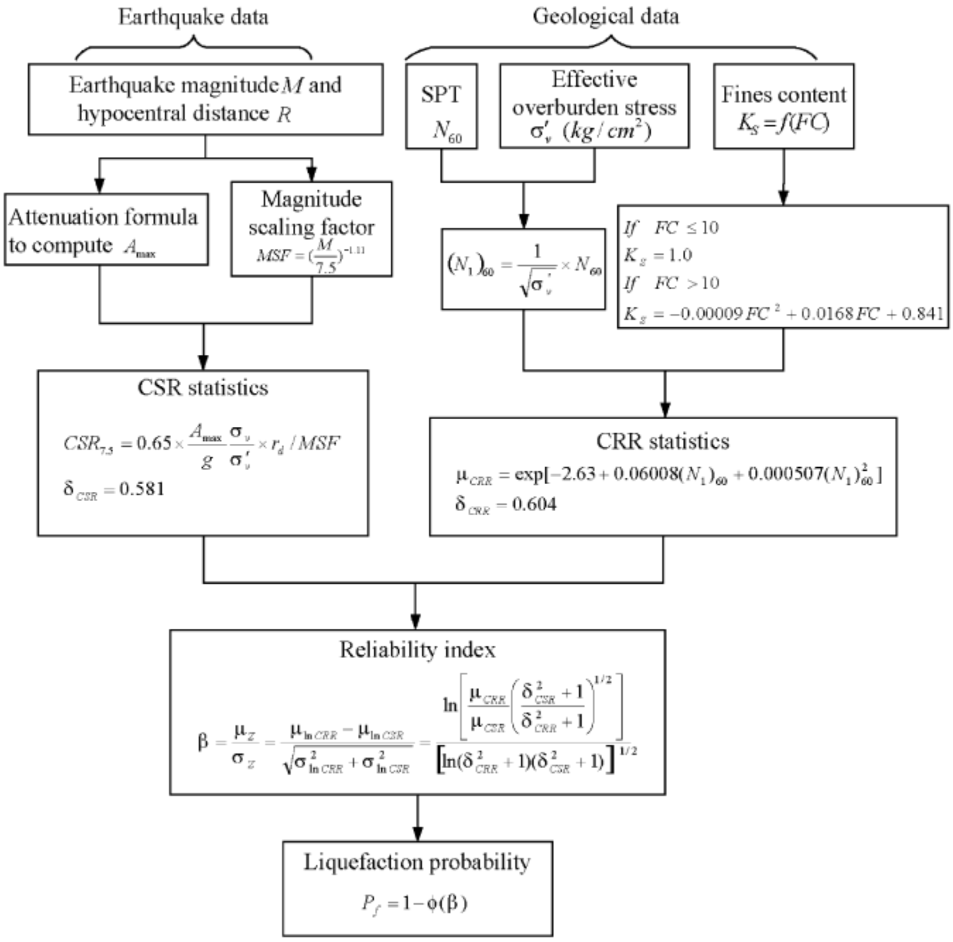


FIGURE B.2: Flowchart depicting the calculation steps to find the probability for liquefaction. [Hwang et al., 2004]

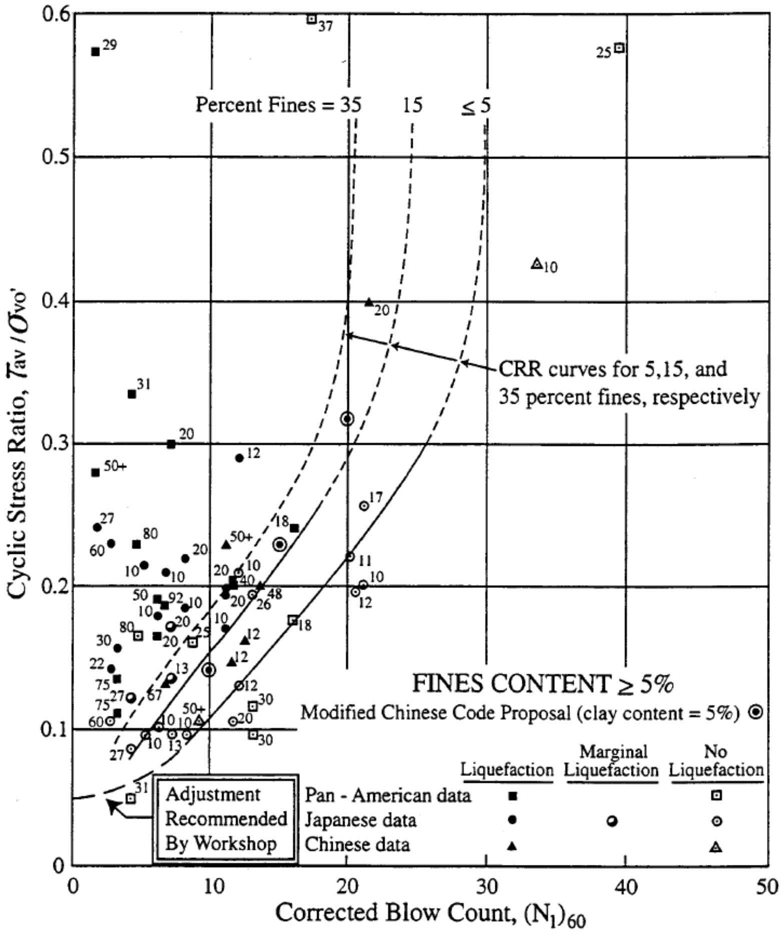


FIGURE B.3: Correlation between CSR and corrected blow count for earthquake magnitude M=7.5[Martin and Lew, 1999]. CSR should be adjusted for other magnitudes using MSF (Magnitude Scaling Factor)

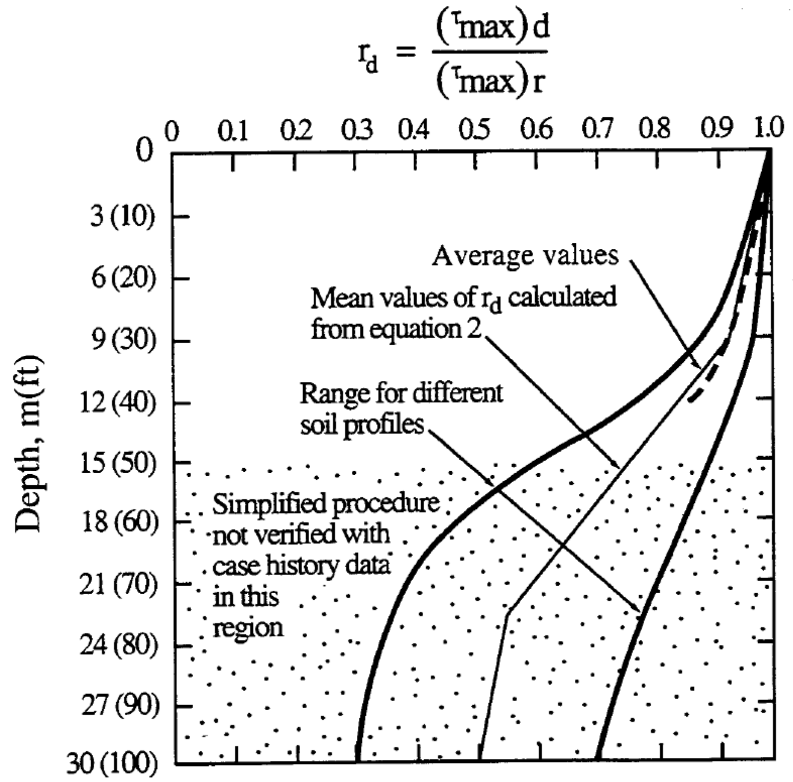


FIGURE B.4: Correction factor for depth of soil layer. [Martin and Lew, 1999]

B.3 Comparing building codes

B.3.1 The Tsunami Characteristics

The analytical solution can be used to determine flood velocities (u) and the momentum fluxes (du^2) at a point of interest. This section shows the methods and equations given in the different standards.

Inundation Depth (d)

In the analytical approaches, it is assumed that the runup level (R) is indicative for the inundation height (h). All codes agree that the inundation depth can be easily approximated, accordingly $d = R - z$ [m]. The only information necessary is a flood map to determine the runup level. However, there is a discrepancy about two other assumptions. The density of the sea water, which is in normal situations around 1025 [$kg\,m^{-3}$]. The FEMAP646 [2012] uses a specific density $\rho_s = 1100$ [$kg\,m^{-3}$] [FEMAP646, 2012, p. 79]. Besides that they also use a design runup level (R^*), where $R^* = 1.3R$. This 0.3 safety factor is based on empirical data from past tsunami surveys and covers

Parameter	Units	Description
b	m	Width of the loaded element
c	-	Hydrodynamic mass coefficient
d	m	Inundation depth
g	m s^{-2}	Gravitational acceleration
h	m	Inundation height
h_S	m	Surge height
k_i	-	Combined stiffness of impacting debris
		and impacted structural element
l	m	Flood line
m_d	kg	Mass of debris
x	m	Distance from maximum runup location to point of interest
y	m	Point of application of force
z	m	Ground elevation
u_p	m s^{-1}	Flow velocity
A	m^2	Projected area normal to the flow
C_d	-	Drag coefficient
CM	-	Center of mass
F_h	N	Hydrostatic force
F_i	N	Impact force
F_d	N	Hydrodynamic force
MSL	m	Mean Sea Level
R	m	Runup level
R^*	m	Design runup level (used in the FEMA code)
V_w	m^3	Volume of water displaced by the structure
α	rad	Beach slope
ρ_s	kg m^{-3}	Density of sea water
γ_s	N m^{-3}	Specific weight of sea water

Table B.1: Parameters and variables used in illustrations and equations potential variability in the output of the model. However, it is unclear if the runup level (R) already has an amplification factor.

Flood Velocity (u)

To determine the flood velocity via an analytical approach some assumptions and simplifications are made. With this assumptions Ho and Meyer (1962) give a first estimation of the maximum runup velocity, see equation B.1 [Yeh et al., 2005, p. 15]. In equation B.2 the exact solution is presented by Shen and Meyer in 1963 [FEMAP646, 2012, p. 145]. The solutions are based on one-dimensional fully nonlinear shallow-water-wave theory given a uniformly sloping beach.

$$\frac{u}{\sqrt{2lg\alpha}} = \sqrt{1 - \frac{x}{l}} \tag{B.1}$$

$$u = \sqrt{2gxtan\alpha} \tag{B.2}$$

The maximum runup velocity occurs at the leading tip and according to Yeh et al. [2005] this provides an upper envelope for the flow velocity, so we can talk about u_{max}. Because a real beach is not uniformly sloped the FEMAP646 [2012, p. 145] presents it as function of the ground elevation in equation B.3.

$$u_{max} = \sqrt{2gR^* \left(1 - \frac{z}{R^*}\right)} \tag{B.3}$$

Momentum flux (du^2)

The momentum flux is the value of the product of water depth and the square of flow velocity. The maximum value is needed to calculate hydrodynamic forces. When the momentum flux is direct output from the model it is important to search for $(du^2)_{max}$ instead of $h_{max}u^2_{max}$. Yeh et al. [2005, p. 15] developed an exact solution algorithm based on earlier studies, see equation B.4. This is a conservative method to estimate the maximum momentum flux. It can be determined for a given location (x) if the maximum runup distance (l) is known for a uniform beach slope. However, a uniform beach slope is in reality seldom the case. Therefore the FEMAP646 [2012, p. 148-149] expresses the momentum flux as a function of the ground elevation (z) instead in equation B.5.

$$\frac{hu^2}{g\alpha^2 l^2} = 0.11\left(\frac{x}{l}\right)^2 + 0.015\left(\frac{x}{l}\right) \tag{B.4}$$

$$\left(hu^2\right)_{max} = g(R^*)^2\left(0.125 - 0.235\left(\frac{z}{R^*}\right) + 0.11\left(\frac{z}{R^*}\right)^2\right) \tag{B.5}$$

The Chilean Standard Project uses the same assumptions and equations as FEMAP646 [2012] standard [NTM007, 2011, p. 7, 8 and 17]. There is however one difference, it is assumed that the specific weight of the sea water is higher, $\rho_s = 1200 \quad [kg\, m^{-3}]$ [NTM007, 2011, p. 15].

B.3.2 The Hydraulic Loads

There are four types of hydraulic forces distinguish in the standards. The hydrostatic, hydrodynamic, impact and other forces. These forces are defined according to studies of Yeh et al. [2005]. In this section are the different forces defined. The different standards give a variety of equations to determine the hydraulic loads. The parameters in these equations are dependent of the tsunami wave event, the location and the dimensions of the structural object. An overview of the different equations is presented in table B.2.

Hydrostatic force

The hydrostatic force can be divided in lateral and vertical hydrostatic forces. The lateral hydrostatic force occurs as consequence of a pressure caused by a difference in water depth on to opposite sides of a structure. This happens when slow or still water encounters a building and the force will always act perpendicular to the applied surface. This force is to be considered not dominant, unless the structure is very wide. For buildings with breakaway walls, these are non-structural walls that breakaway by a certain minimum force, on ground level this force is irrelevant. The buoyant force is a vertical hydrostatic force on a structure or structural member that is partial or completely submerged. The force will act vertically through the center of mass of the displaced volume. This is a concern for basements, empty above-ground and below-ground tanks, swimming pools, and wooden frame structures. It could be important with rapid increase of water level and should always be considered with other lateral forces.

Hydrodynamic force

The hydrodynamic force is applied when water flows around a structure and is a function of flow velocity and structure geometry. It includes frontal impact at the upstream side, drag along the sides, and suction at the downstream side. This force is induced by water that moves with moderate to high velocities. The surge force is caused by the leading edge of a surge of water that hit a structure. It is computed as a force per unit width on a vertical wall. According to Palermo [2008], the surge force may be assumed to be nine times the hydrostatic force for the assumed inundation depth. The point of application of the resultant surge force is located at the inundation depth above the base wall.

Impact force

The impact or debris force is a result from debris that clash against a structure. This can be any object transported by flood water. A few assumptions are made: the speed of the object is equal to the flood velocities and the object strikes at water level. The biggest uncertainty is the duration of the impact. Palermo [2008] point out that there is a lot of uncertainty about calculating with the impact load. Advised is to apply the most critical loading situation, a concentrated load acting horizontally, with a magnitude of 455 kg (1000 pound) acting on 0.093 m^2 (1 square meter).

Other forces

These consist of breaking wave and foundation forces. Two breaking wave forces are of interest, waves breaking on small-diameter (e.g. columns and piles) elements and waves breaking against walls. The breaking wave force may not be relevant for the tsunami force on onshore buildings, because tsunami waves tend to break offshore and approach the shore as a broken bore.Foundation forces are not excessively discussed. However, the code notes that potential for scour and liquefaction around structural foundations must be considered, but provides no guidance.

	FEMA P-646 (2012)	Chilean Standard Project	Honolulu Building Code
Hydrostatic force	$F_h = \frac{1}{2}\rho_s\, g\, b\, d^{*2}$ (B.6a) $y = \frac{1}{3}\, d^*$ (B.6b) $d^* = 1.3R - z$ (B.6c)	$F_h = \frac{1}{2}\gamma_s\, b\, d^2$ (B.7a) $y = \frac{1}{3}\, d$ (B.7b)	$F_h = \frac{1}{2}\rho_s\, g\, \left(d + \frac{u_p^2}{2g}\right)^2$ (B.8a) $y = \frac{1}{3}\left(d + \frac{u_p^2}{2g}\right)$ (B.8b)
Buoyant force	$F_b = \rho_s\, g\, V_w$ (B.9)	$F_b = \gamma_s\, V_w$ (B.10)	$F_b = \rho_s\, g\, V_w$ (B.11)
	(y) point of application in center of mass		
Drag force	$F_d = \frac{1}{2}\rho_s\, C_d\, b\, \left(d\, u^2\right)_{max}$ $C_d = 2.0$ $\left(d\, u^2\right)_{max} = g\,(R^*)^2\left(0.125 - 0.235\frac{z}{R^*} + 0.11\left(\frac{z}{R^*}\right)^2\right)$ (B.12) $R^* = \begin{cases} 1.3R \text{ FEMA} \\ 1.0R \text{ Chile} \end{cases}$		$F_d = \frac{1}{2}\rho_s\, C_d\, A\, u_p^2$ (B.13a) $C_d = \begin{cases} 1.0 \text{ circular piles} \\ 2.0 \text{ square piles} \\ 1.5 \text{ wall sections} \end{cases}$ (B.13b)
Surge force	$F_S = 1.5F_d$ (B.14)		$F_S = 4.5\rho_s\, g\, d_S^2$ (B.15)
Impact force	$F_i = 1.3(u_p)_{max}\sqrt{k_i\, m_d\,(1+c)}$ (B.16)	$F_i = \frac{500}{g}\left(\frac{u_b}{\Delta t}\right)$ (B.17a) $\Delta t = \begin{cases} 1.0 \text{ wooden structures} \\ 0.1 \text{ RC structures} \\ 0.5 \text{ steel structures} \end{cases}$ (B.17b)	$F_i = m\frac{du_p}{dt}$ (B.18)

TABLE B.2: Equation comparison according to different codes

B.4 Seismic Design Load ($\mathbf{Q}_{seis}$)

The seismic design load is determined according to some specifications given in Chilean standards.

Loads

1. Live Loads

   - General Areas: 2 kPa
   - Corridors: 5 kPa
   - Roof: 5 kPa. Due to the use in an extreme event.

2. Seismic Analysis

   - Building category: II [NCh433, 2009, Table 4.1]
   - Seismic Zone: 3 [NCh433, 2009, Figure 4.1]
   - Soil type: I or II [NCh433, 2009, Table 4.3]
   - Response Factors: R = 6 and R_0 = 9 [NCh433, 2009, Table 5.1]
   - Design spectrum: [NCh433, 2009, Section 6.3.5]

$$S_a = \frac{IA_0\alpha}{R^*}, \quad \text{where} \quad \alpha = \frac{1 + 4.5\left(\frac{T_n}{T_0}\right)^p}{1 + \left(\frac{T_n}{T_0}\right)^3} \tag{B.19}$$

$$R^* = 1 + \frac{T^*}{0.10T_0 + \frac{T^*}{R_0}} \quad or \quad R^* = 1 + \frac{NR_0}{4T_0R_0 + N} \tag{B.20}$$

$$\text{Eccentricity:} \quad ecc = \frac{z_k}{h} \tag{B.21}$$

   - Baseline shear: [NCh433, 2009, Section 6.2.3]

$$Q_0 = CIP, \tag{B.22}$$

In this case C can be found using equation B.23 and the seismic weight equation B.24.

$$C = \frac{2.75A_0}{gR}\left(\frac{T'}{T*}\right)^n \tag{B.23}$$

Table B.3: Checklist for during a site visit

General	
Name	-
Address	-
Identification number	ROL
Occupancy	-
Date of Construction	year
Stories	nbr.
First floor characteristics	open/closed
Services	what and where?
Gastank	yes/no, where?
Basement	yes/no
Location:	
Distance from shore to floodline	l
Distance to shore	x
Ground elevation	z
Roof:	
Accesiblity	yes/no, how?
Space available	m^2
Specific	
Structural:	
Type of construction	RC, steel or wood
Material strength	type
Story height	
Height	h
Width	b
Depth	b'
Hydraulic:	
Angle building compared to grid	α
Runup level	R
Inundation depth	d
Flow velocity	u
Momentum flux	du^2
Geo-technical:	
Foundation system	-
Foundation plan	-
Ground conditions	-
TIL:	
Capacity	nbr.
Accessibility	m
Surrounding layout	-

Table B.4: Factors for design spectrum specific for Iquique

Factor	**Value**	
I	1.00	-
A_0	0.40	g
S	1.00	-
T_0	0.30	s
T'	0.35	s
n	1.33	-
p	1.50	-

$$P = 1.00\text{DL} + 0.50\text{LL}. \tag{B.24}$$

Factors to determine design spectrum

Table B.5: Parameters according to Building Category [NCh433, 2009, Table 6.3]

B. Category	**I**
1	0.6
2	1.0
3	1.2
4	1.2

Table B.6: Parameters according to Seismic Zone [NCh433, 2009, Table 6.2]

Seismic Zone	**A0**
1	0.2
2	0.3
3	0.4

Table B.7: Parameters according to Soil Type [NCh433, 2009, Table 6.1]

Soil Type	S	T_0	T'	n	p
1	0.9	0.15	0.20	1.00	2.0
2	1.0	0.30	0.35	1.33	1.5
3	1.2	0.75	0.85	1.80	1.0
4	1.3	1.20	1.35	1.80	1.0

B.5 Objective tree and Means-end diagram

B.5.1 Objective tree and Means-end diagram setup

The figure B.5 shows the objectives of the tsunami hazard plan combined with the four activity areas discussed in the introduction 1. Summarizing this figure, it shows that more knowledge is required in order to conduct a better tsunami hazard plan generally applicable in Chile. In order to do so, CIGIDEN needs to know how to achieve this objective. This is why another analysis is conducted, the so-called Means-end analysis, see figure B.6. This analysis shows which means CIGIDEN possess to actually achieve the stated objective. Because the objective is the same in the Means-end diagram as in the Objective Tree, the two analyses contribute directly to the answer why a framework proposal in needed and how CIGIDEN can achieve this.

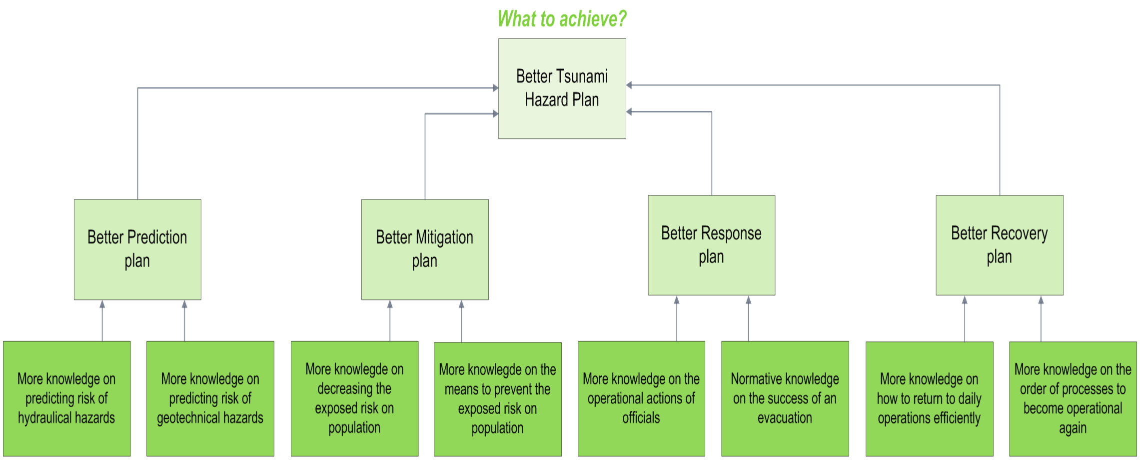


Figure B.5: Objective Tree for Research Purposes on Tsunami Hazard Plans

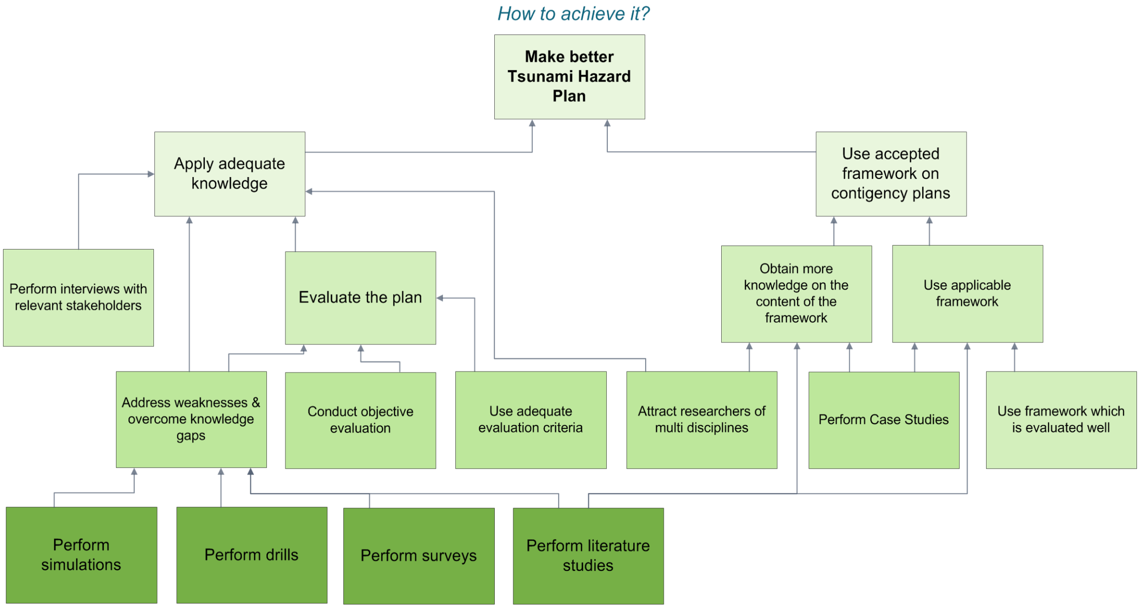


FIGURE B.6: Means-end diagram for Cigiden

B.5.2 Use of Objective tree and Means-end diagram

The figures are now being elaborated upon further. The main goal is to achieve a better tsunami hazard plan. This plan is divided over four activity areas in which CIGIDEN as a research center is aiming to obtain more knowledge. By combining figures B.5 and B.6, it can be concluded that the framework is necessary for obtaining more knowledge to overcome the defined knowledge gaps. For that reason the framework is both part of the bottom layer of the Objective Tree and the second layer of the Means-end diagram. Which shows that this framework proposal is meant as a start to achieve a *better tsunami hazard management plan*.

B.6 Systems engineering

B.6.1 Framework System analysis

In this subsection the system that covers the tsunami event and all possible measures (in all activity areas) has been pictured and analyzed. For a detailed description of the case study system analysis, see subsection 3.5.1.

The need for system analysis

In order to reach consensus about which (discipline related) factors to include in the framework, a system should be defined. The main advantage of conducting a system analysis is that it enables structuring of a complex problem. A disadvantage is that this system analysis is dependent on the analysist' perception of the concept and restrictions (and thus necessarily incomplete). The system can be subject of change within the coming years which is not taken into account here. Despite the disadvantages, to study the system is rather useful to eliminate at least the bad alternatives [B.Enserink et al., 2010].

What is a system?

What is meant with a 'system'? A system is the study environment in which all subjects of significant relevance are included for conducting research. In order to describe this system one needs to conceptualize the system by modeling it. This model is the conceptualization of the system and the first step in our system analysis approach.

Causal Relation Diagram

The model used is the so called Causal Relation Diagram in which external factors, performance factors and factors of means are distinguished. In this diagram the causal relations among the various factors are studied upon. Because of the multidisciplinairy context of tsunami risk management problem the different disciplines distinguished are also pictured in this causal relation diagram. Please find figure B.7. To read this diagram one can start with an external factor and follow the arrows till arriving at a performance factor. In order to know which factors are of influence on a certain performance factor, the other way around is advised so starting with the performance factor back to the external or means factors. The causal relations are described in order to derive a certain logic among the factors to not only leave the possibility for further qualitative analyses but also for quantitative analyses. The positive relation shows that with the increase of factor A, factor B will also increase. The negative relation shows that with the increase of factor A, factor B will decrease. When all factors and relations are described one can derive which means influence a certain performance positive or negative. This path of performance is important in future policy and or solution implementations.

It becomes clear whether or not the different factors are interrelated or to which category and discipline they belong. The category 'factor of means' depicts the possible means the problem owner has to change this factor. For example, the municipality of the city

FIGURE B.7: Causal Relation Diagram

Iquique can change the amount of vertical evacuation buildings so the Vertical Evacuation area available is a mean (although it is influenced by external factors) in order to achieve the objective Total Safety Zone area. The external factors are factors on which no one has a possible influence and which are in this context of tsunami risk management unpredictable. For example, the factor 'Moment of Magnitude experienced' is total out of anyone league to influence it. The factors of performance are the factors which depict the objectives of the problem owner or are criteria of success for evacuation. In this case the problem owner of the system is a local government or a coordinating governmental organization..

Derivation of factors

The performance factors are derived by talking, questioning, and picturing the stated preferences of the problem owner regarding the problem definition. The so called objective tree in which the main objective is constructed out to different smaller objectives can help to structure the objective focus for the problem and find the adequate scope for the problem definition. Besides, the so called means-ends diagram can help to answer the question how to achieve the objective(s) by determining the relevant means of the problem owner per objective. In the case study these analyses are conducted for Iquique and so to use as example, please find the chapter 3.5.1.

The objective tree for improving any tsunami hazard plan by conducting research is shown in figure B.5. The main question answered by this analysis is: "What to achieve?". The objective tree is related to the question "How to achieve my goal"?. It has to be noticed by the reader that with changing the problem owner this diagram changes due to fact that every problem owner has its own specific means and objectives. As example for the framework this means-end diagram for our client CIGIDEN is pictured in figure B.6.

The Means-end diagram is the final analysis for deriving the factors influencing the objectives. When it is clear which actor will perform the final framework for their own tsunami hazard plan, the chart will change into their specific goals and means as such to derive an appropriate Causal Relation Diagram with their own performance criteria and specific means. This diagram is shown for providing an example of the use of this analysis.

Problem owner dependency

When applying this framework one has to keep in mind that the choice of problem owner is most important for the change of the system diagram regarding the factors of means and factors of performance. Please keep in mind that the Objective Tree and Means-end diagrams presented in this section are aimed for CIGIDEN with its outcome a framework for providing a tsunami hazard plan. Wheareas the Causal Relation Diagram presented, shows the factors influencing the Tsunami Risk Management objectives in this tsunami hazard plan. This means that the presented Causal Relation Diagram is not directly related to the Objective Tree and Means-end diagram presented for CIGIDEN, rather for the case study. A Causal Relation Diagram for CIGIDEN is not necessary to provide, as the research question 'How to conduct a framework' is not context dependent. In contradiction to the tsunami hazard plan, which is highly context dependent. For this reason the causal relation diagram has been presented to you as system scope for the case study.

In order to focus further on the case study, the causal relation diagram is necessary to describe the system of research subjects. For the case study this causal relation diagram can be directly applied. In fact the case study results of the Objective Tree and the Means-end diagram of Iquique are to be find directly in this same causal relation diagram. As for the fact that this causal relation diagram is a description of the system in which tsunami hazards are important, he system does not change for the case study Iquique. Therefore, the Objective Tree and Means-end fit needless to this causal relation diagram of the framework.

B.6.2 Actor analysis

A framework is worthless if it is not applicable to the real world. This real world consists of actors that are (in different degree) contributing to tsunami hazard management. Actor analysis should give the client insight in the handling objectives of different actors involved. This insight can help the client to derive the strategy to overcome opposent arguments and keep the key actors involved. In order to provide the client with a proper stakeholder analysis in this section the general actorcharts for Chile are provided. Also is stated how these charts have been designed and what should be changed when applying this for a case study.

Identify Stakeholders of Significance

The question is which stakeholders should take part in the diagram and which not, as to say which stakeholders are significant involved in tsunami hazard management? To answer this question different approaches can be used. The analyist can start with think of all potential contributers or search with literature and help of the world wide web to find all stakeholders affiliated with the topic. This list can be categorized per group of actors. With the actorlist step 2 can be to map the different stakeholders for level of interest and power. When it is clear which stakeholders have a high level of interest and high power, step 3 is to map those actors to hierarchical and formal relations. This map can be the input for further actoranalyses to evaluate the organization and the current way the actors work together. It is important to notify any relation which is case dependent, like emergency coordination as is done in figure B.8.

The following actorchart is applicable in all cases in Chile when the few gaps in the chart are filled in. First the local government should be filled in. Next to that, the 'key players', 'context setters' and 'subjects' which are actors of high power and/or high interest in the topic should be fitted in the diagram. As third step the user should check the relations defined if they are still applicable and add any missing relations. This should result in a case specific actorchart usable to know which actors should be contributing and to which extent they can. Also this achievement is the first step to derive solutions on coordination and organizational level.

The user can decide upon adding more categories of actors or divide them differently. The colours can help to indicate the different groups. In this chartstakeholders coloured else than grey are directly related to emergency operations. When being able the user should further specify the different hierachical and formal relations with specific laws, protocols or agreements. This will help to be precise on proposing alternative solutions.

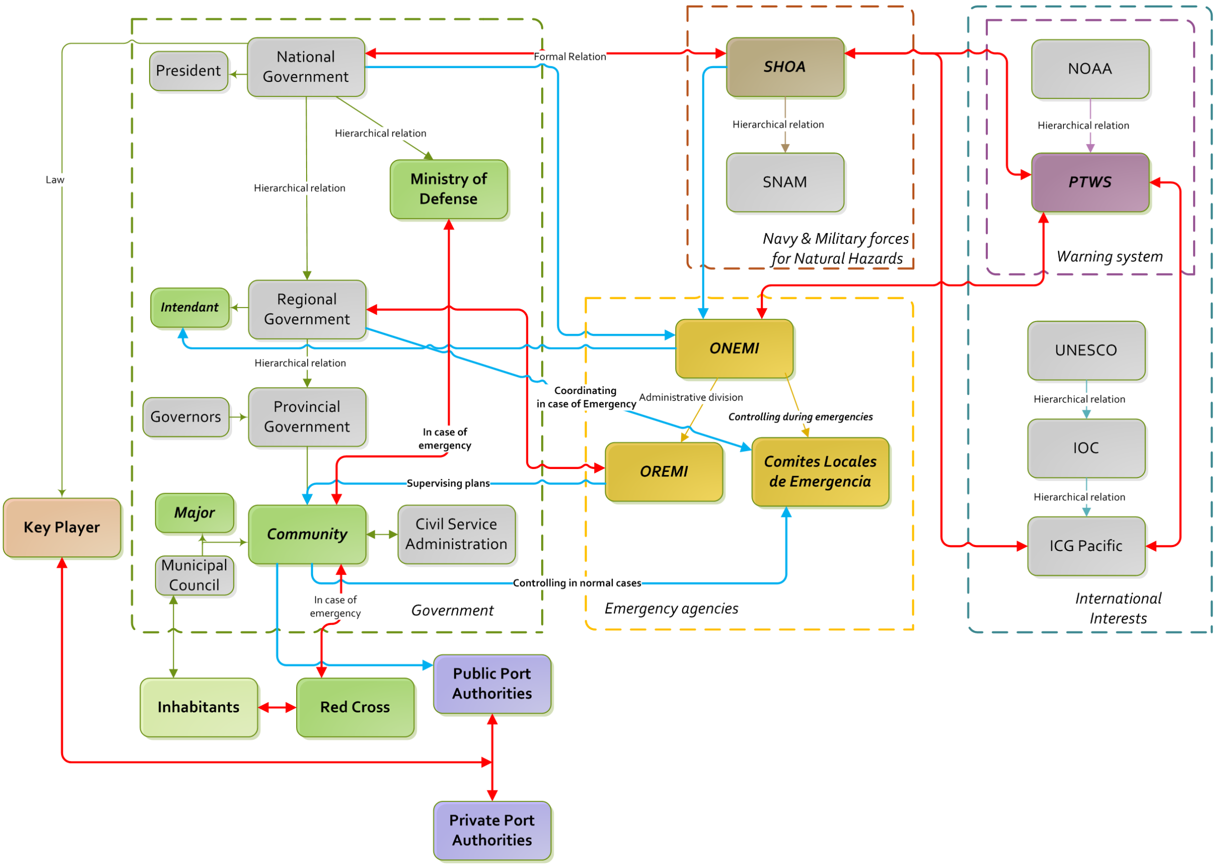


Figure B.8: Actorchart Chile

B.6.3 Flow chart

Evacuation Processes

When the actors are identified and classified one is ready to go deeper into the matter of evacuation processes. The evacuation consists of different phases with different processes and actors involved. In order to gain structure within the broad context of evacuation processes a so called flowchart can be designed to help to identify and order the different activities, decisions and events. In this section first these evacuation activities are identified and secondly the order of these evacuation processes are determined and linked to their performer (actor).

Order Evacuation Activities

One can imagine that different activities contribute to the final state of evacuation, namely that everyone is being saved from the tsunami hazard. How to derive at this stage of 'closing' is the question we will answer. Four different activity areas or phases are defined for the evacuation of a city. The first is the dectecting phase, the second the evacuating phase, the third the guarding phase and the fourth the closing phase. It is known that with a signal of a coming earthquake national organizations are awakened. This signal is the earthquake. It is the question if this earthquake will be big enough for causing a tsunami. Therefore, different activities contributing to the detection of the earthquake and a possible tsunami are categorized in the first phase. These will of course always be the first activities to happen in order to start the following phases of evacuation. Furthermore, it is known that the closing phase can only be started when the evacuation and guardening of the evacuation is over. So the evacuation and guardening of the evacuation should be in the middle. The evacuation start as soon as the tsunami is forecasted and a decision to evacuate is given or an earthquake of great magnitude is experienced by the inhabitants.

The evacuation and guardening phases start at a similar moment. It is hard to determine which moment exactly and which activity is the incentive except for the earthquake or tsunami forecast. It is known that ONEMI together with SHOA should decide upon evacuation. However, it is imaginable that the inhabitants will directly start the evacuation when a severe earthquake magnitude is experienced. When the start of the evacuation is given, the guardening of the evacuation by the governmental organizations begins. This guardening is pictured as the anticipation on performing more evacuation activities, as for the reason to safe more people, or give instructions to the CLE (Comites Locales de Emergencia) also to inform the people on further provisions.

When the decision to stop the evacuation is given the evacuation is ended. It is the question which organizations actually coordinate the closing phase, municipality, SHOA, ONEMI or OREMI or the CLE? In this diagram is it assumed that ONEMI and the SHOA decide together if the evacuation time consumed was sufficient and that the next activity area of tsunami hazard management can be started as to be named the recovery. ONEMI needs the information of SHOA to decide this, so it can also be stated that only ONEMI makes this decision. It is also imaginable that ONEMI together with the municipality or regional government decide upon this. However, no information was found on this specific topic.

Possibilities for extension of the flowchart

For the client is it important to notice that adding more processes to the flowchart is possible, but that this will lead to broadening of its scope. The flowchart aims at addressing most important activities, necessary to start and end evacuation of the city. In order to define precisely the time of processes and related actors, further research or interviews should be carried out (when possible).

It is important for any addressment of weaknesses in the current system of evacuation processes to first perform actor analysis in combination with the evacuation processes analysis (flowchart) first. This will help to define and structure the system, and it will immediately point out first weaknesses.

B.7 Transportation engineering

B.7.1 Analysis on evacuation routes

In order to get an idea on which evacuation routes and meeting points in safety zones are currently available, the place of interest must be scanned. The following objectives have been indicated:

1. Identify dangerous zones and specific dense cumulations of people

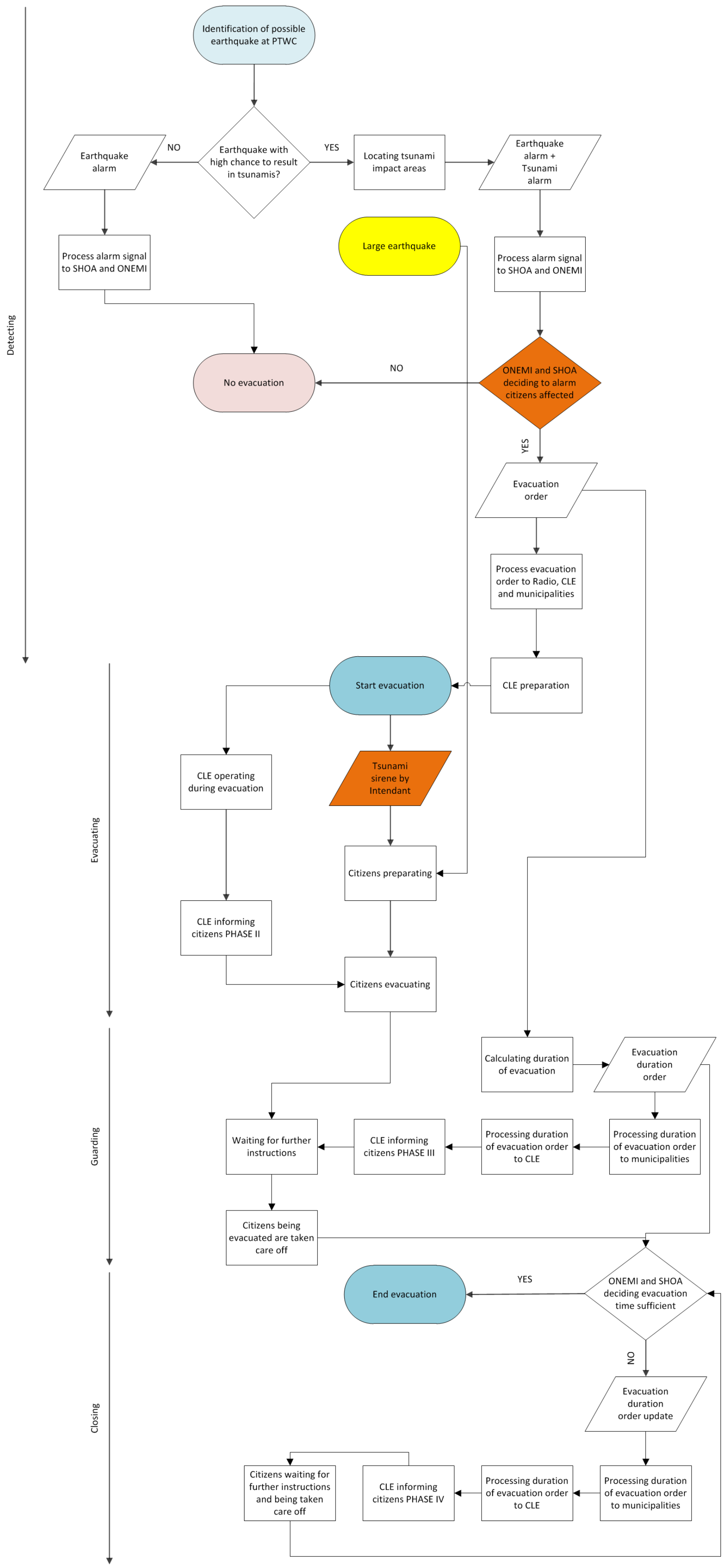


FIGURE B.9: Flowchart Chile

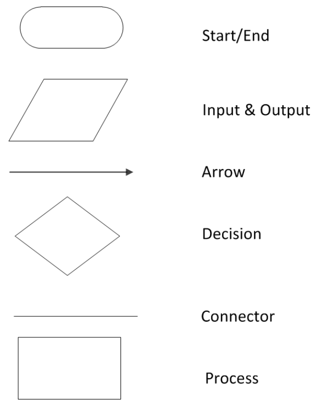


Figure B.10: Flowchart Chile Legend

2. Identify evacuation routes in dense cumulations
3. Identify road infrastructure characteristics and suitability for evacuation
4. Identify suitability of meeting points in higher grounds
5. Identify suitability of vertical shelters

Identification of dangerous zones and specific dense cumulations of people

In order to get an overall idea on people at risk and determine specific points of interest, the following questions need to be answered:

- How many people live in the area of interest?
- How is the residential distribution of these people in the area of interest?
- Based on residential distribution, can there be found or made a classification of risk for aggregated zones (for a night scenario)?
- Are there any (aggregated) zones that have a considerable higher risk at night than others?
- How is the job distribution in the area of interest?
- Based on job distribution, can there be found or made a classification of risk for aggregated zones (for a day scenario)?
- Are there any (aggregated) zones that have a considerable higher risk during the day than others?

- Are there any specifc dense cumulations of people left in the area of interest (that aren't yet derived from zonal analyses?
- What are the expected distances from these places to safety zones?
- How can all these places be prioritised?

Identification evacuation routes in dense cumulations

In order to check on possibilities for evacuation of specific dense cumulations and to recognize weaknesses in practice, the following questions need to be answered.

- Is the dense cumulation public accessible or is it private property?
- How many exits for pedestrians are available?
- What are the dimensions of the exits?
- Can the exits be used by people with special needs (people with physical disabilities)?
- How are evacuation routes marked?
- Can the evacuation alarm be heard throughout the entire place?
- Are the there any obstructions that might harden evacuation processes?
- Does appear car evacuation from the dense cumulation probable?
- Are there any objects that might harden evacuation processes from parking areas?
- Could car evacuation conflict with pedestrian evacuation?
- What objects can be identified that might be harmful during evacuation (e.g. loose containers)?

Identification of road infrastructure characteristics and suitability for evacuation

In order to check whether road infrastructure is fit for evacuation of city zones, the following questions need to be answered:

- How wide are the pavements?

- How wide are the streets? (minimum and maximum)
- How are the streets provided with road markings and traffic signs?
- How many cars can be found alongside the streets?
- Are these cars (partially) blocking the evacuation routes?
- Are there any other obstacles that can be found in or next to the streets?
- How accessible are the roads for people with psysical disabilities?
- Is it easy to recognize in what direction streets should be taken to evacuate?
- Are changes of main street directions recognizable?
- Is there information on the preference of people regarding their choice of road to evacuate to?
- Are there any signs that lead to buildings suitable for vertical evacuation, instead of safety zones?
- Is the use of evacuation signs consistent (or can there be found various different signs)?
- How does this all apply during night times?

Identification of suitability of meeting points in higher grounds

In order to check whether meeting points in safety zones in higher grounds are fit for people to evacuate to, the following questions need to be answered:

- Is the meeting point inside or outside a building?
- What are the characteristics of the safety zones?
- What are the dimensions of the safety zones?
- Are the boundaries of the safety zones marked well?
- What facilities do the safety zones offer?
- Are the meeting points big enough (also part of research question)
- Are the meeting points suitable to evacuate to (also part of research question)

Identificaton of suitability of vertical shelters

In order to check whether vertical shelters (safety zones in buildings) are fit for people to evacuate to, the following questions need to be answered:

- How many entrances are available to enter the building?
- How wide are the (first or main) entrance(s) to the buildings? (minimum and maximum)
- How many stairs are available to reach higher floors in the building?
- How wide are the stairs? (minimum and maximum)
- How many floors and spaces are available within the building to evacuate to?
- Are these spaces publicly accessible, or should they manually opened?
- Can the buildings suitable for vertical evacuation easily be found, via an evacuation route?
- Are there any facilities for people with physical disabilities?

B.7.2 NetLogo setup

For simulation of ABM scenarios, use of the NetLogo software is proposed. NetLogo is world-wide known multi-agent programming. In NetLogo simulation, numerical simulation of tsunami flooding can be incorporated. This combination could lead to answer how evacuation practice will really proceed and what predominant evacuation mechanisms are.

Architecture of the agent

The agent architecture consists of 4 layers according to [Mas et al., 2012a]:

Layer 0 Decision to evacuate (timing)

Layer 1 Shelter decision

Layer 2 Path finding by using A* algorithm

Layer 3 Speed adjustment

Input for simulation model

According to [Mas et al., 2012a], the following input is used for simulation:

- GIS for spatial input ;
- Roads, shelter locations and safe area;
- Tsunami departure curves and Evacuation departure curves;
- Start time for agents (timing of response) using S(igmoid)-curves based on population;
- OD matrices and density of areas;
- Heights of building environment and possible shelters;
- Narrow streets and other dimensions of streets and functionality and priority of use;
- Survey Revealed Preference and Stated Preference departure times;
- Rayleigh distribution similar to case in hurricane evacuation;
- Numerical simulation of flooding as input for departure time function and casualties estimation;
- Culture related behavioral conditions during emergency.

B.7.3 Literature scan on people's behaviour during evacuation

The table of scenarios 2.2 has pointed out that specific knowledge is required on people's behaviour and predominant evacuation phenomena. Therefore, in this subsection a literature scan has been performed over 23 sources.

Agent behaviour points of interest

The following points of interest have been indicated:

- Determination of different speeds of agents, related to agent characteristics: age, disabilities etc), 9 sources
- The influence of road characteristics (slopes, obstacles and level of service) on the (different) speeds of agents; 4 sources

- Will the agent die as soon as the wave reaches him, or at a certain inundation level or flow velocity? 6 sources
- The choice between a random path (route) assignment from a uniform distribution or a path set by the user; 8 sources
- Inclusion of road capacities during path decision (or is only the shortest route started with?) 6 sources
- Will agents decide to evacuate vertically, when this is shorter(?); 2 sources
- Do agents have another choice to evacuate to when entering congested areas? 3 sources
- Timing distributions; Wait for siren or not? 11 sources
- What's the influence of panic on the agent's behaviour? 8 sources
- What's the influence of information provision from authorities (radio, smartphone etc) on the agent's evacuation behaviour? 9 sources
- What's the influence of information provided by evacuation signs? 5 sources

Agent behaviour literature outcomes

Consensus or clear assumptions on:

- What speed agent could have concerning age and health
- When do agents die concerning water levels (approx. 1m)

Lack of knowledge and/or discussions on:

- Influence of road capacity on agents' speeds
- Agent's route choice and re-routing capabilities
- Time of departure, panic behaviour and risk perception (all hugely influenced by psychological factors)

Evacuation phenomena points of interest

- Occurrence of congestion, will agents run into a large crowd during evacuation? 2 sources
- Occurrence of congestion at vertical shelters 1 source
- Dedication to evacuation plans: Movements of agents in opposite direction, in order to save relatives; no sources
- Dedication to evacuation plans: use of vehicles, even though illegal; no sources
- Ability of emergency agencies to do their work (especially in providing information to evacuated people in safety zones; no sources

Evacuation phenomena outcomes

Only "faster-is-slower effect" is known [Helbing et al., 2000].

Appendix C

Appendix Case Study Iquique

In this appendix elaborations used in the case-study are mentioned. First the hydraulic input for the Neowave model is elaborated. This is followed by information of the built environment and infrastructure in the zones of Iquique.

C.1 Neowave modelling for Iquique

Bathymetry and topography

As described in section 3.2 batyhmetric and topographic data was obtained from GEBCO, SHOA, and SAF. Topographic and GEBCO data were related to MSL whereas the SHOA soundings were related to LAT. These soundings have been adjusted for this difference using information from IOC [UNESCO-IOC, 2013]. Using historical tidal data from a gauge in the port area this difference was estimated to be 0.75 meter. An overview of this is shown in figure C.1.

Some points were added manually using GIS software to account for inconsistencies compared to recent Google Earth satellite images and findings from the field visit. This was especially the case for the port area, in which a recently built jetty was not included. And for an area close to the shore between latitudes 20.17° S and −20.19° S datapoints were missing.
Two local deepenings were smoothed out for the finest grid since they caused numerical instability.

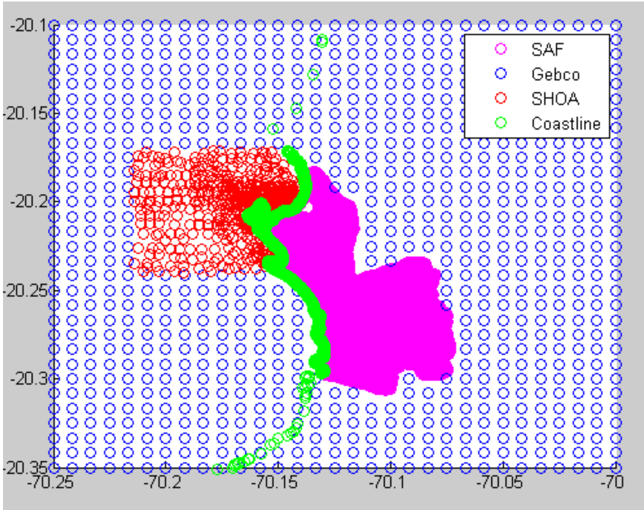


FIGURE C.1: Overview of bathymetric and topographic data used

Using Matlab's *TriScatteredInterp* function this data was interpolated using triangular, linear interpolation. Four nested grids were created, with resolutions of 2 minutes, 30 seconds, 6 seconds, and 1 second. The result for the coarsest and finest grid are illustrated in respectively figure C.2 and figure C.3. As described in section 3.2.2 high resolution bathymetric data was only available for latitudes 20.17° S to 20.24° S. The boundaries of the finest grid (grid 4) were adjusted to these constraints. Fortunately study zones were results from the hydraulic modelling were needed for other disciplines were all located within these boundaries.

Model parameters

To calculate initial surface deformations for static, uniform ruptures NeoWave requires certain input parameters. These have been summed up for the four investigated scenarios in table C.1.

Other relevant parameters that are kept constant for all scenarios are shown in table C.2.

Comparison of results

In this section the results of the NeoWave modelling for the different seismic scenarios are shown. This is done by showing the results on runup in figure C.4. As described in section C.1 detailed bathymetric data was only available for a limited zone. Therefore the comparison is limited to these latitudes.

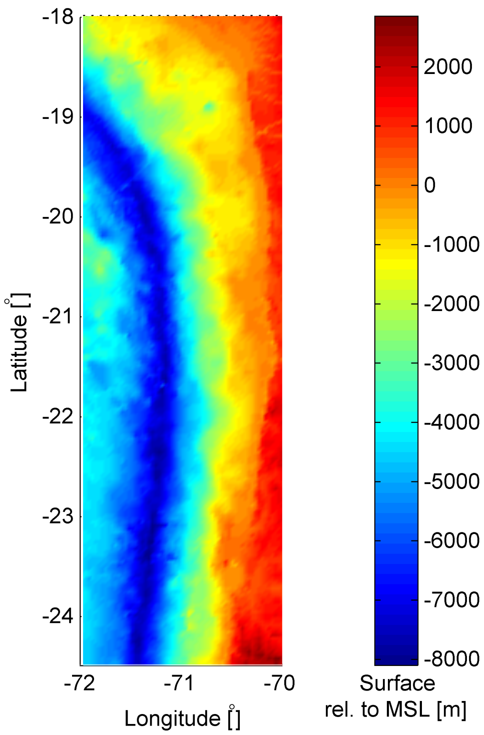


Figure C.2: Interpolated data to coarsest grid

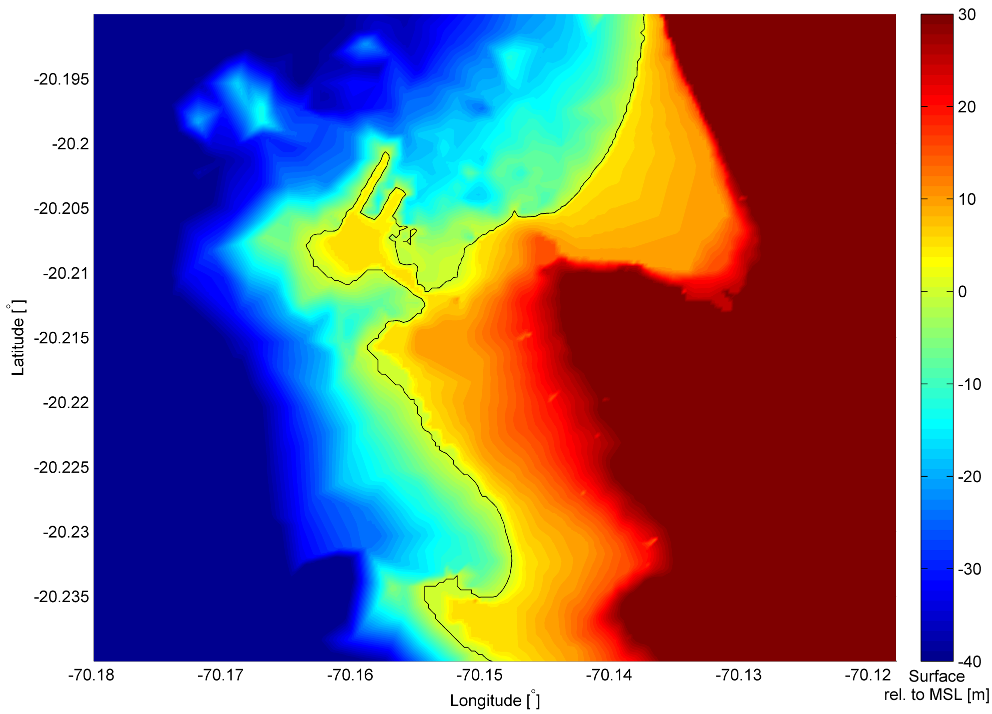


Figure C.3: Interpolated data to finest grid

TABLE C.1: NeoWave input parameters for deformation calculation

Parameters	**Chlieh**	**Metois - Loa**	**Metois - 3 faults**			**Loa historica**	
			Loa	Paranal	Camarones		
$\mathbf{T}_{rise}$	0	0	0	0	0	0	s
$\mathbf{T}_{init}$	0	0	0	0	0	0	s
$\mathbf{D}_0$	1207d2	3.98	3.98d2	2.83d2	2.42d2	14.14d2	cm
lonR	288.67	288.67	288.7	288.5	288.67	288.67	deg E
latR	-22.578	-22.5	-22.5	-24.5	-20.2	-22.5	deg N
dR	40.696d5	40.696d5	40.696d5	40.696d5	30.0d5	40.696d5	cm
L	420d5	188.7d5	188.7d5	133.2d5	247679.3d5	299.0d5	cm
W	125d5	125d5	125d5	125d5	92.146d5	125d5	cm
strike(ϕ)	0	0	0	0	328.3757	0	deg
dip(δ)	19	19	19	19	19	19	deg
rake(λ)	100	100	100	100	90	100	deg

NeoWaves uses the notation d, where $d = E$.

TABLE C.2: Constant variables for all scenarios.

Constants			
gravitational acceleration	g	980.0	cm^2/s
earth radius	R_0	6370.0E5	cm
earth angular velocity	ω	7.2919E-5	1/s
Okada parameter	ν	1.0	-
Okada parameter	λ	1.0	-
tidal amplitude	z_{0tide}	75.0	cm
Manning relative coefficient	n	$0.025 * 0.215443469$	$s/cm^{1/3}$
model run time	T_{fin}	14400	s

C.2 The build environment of Iquique

In this section the input, variables, and results used in the calculations on stability of vertical evacuation buildings are shown. Table C.3 shows the parameters of flooding relevant to calculations. Table C.4 shows the buildings considered for evaluations and table C.6 shows the results of the stability calculations.

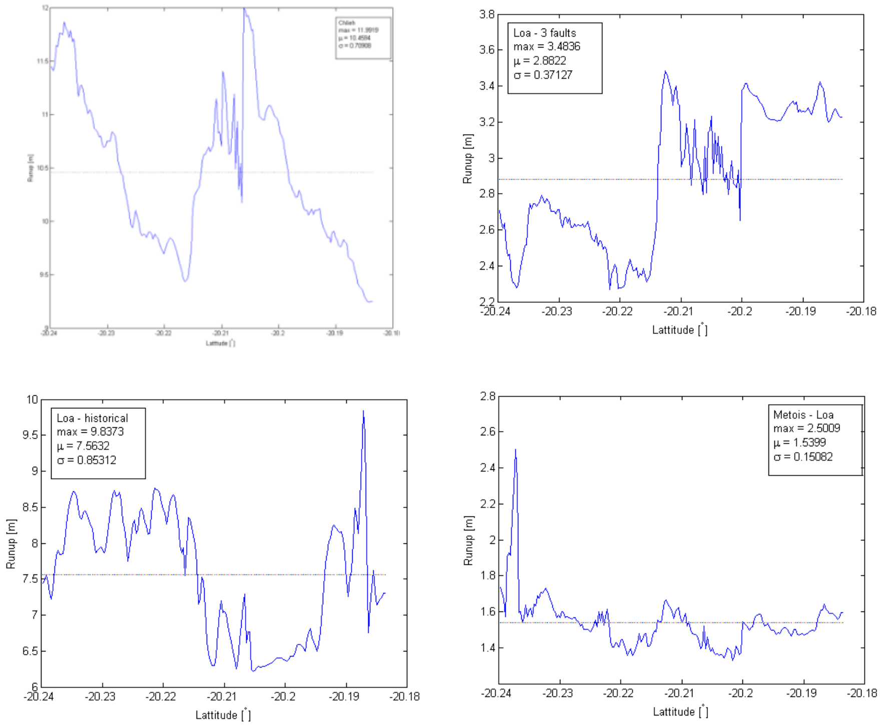


FIGURE C.4: Runup results plotted as function of the lattitude for four different seismic scenarios.

Table C.3: Hydraulic Parameters

Building	**z** [m]	**l** [m]	**x** [m]	**R** [m]	**R*** [m]	α [rad]	**d** [m]	**u** [m/s]	**d u**^{2} [m^3/s^2]
5	6.18	1330	802	28.14	36.59	0.0212	4.55	0.86	0.0
6	10.29	1079	93	14.82	19.26	0.0137	1.20	1.44	29.7
9	3.79	1018	648	13.39	17.41	0.0132	6.19	1.16	40.6
10	3.79	1172	709	13.47	17.51	0.0115	6.12	0.86	28.0
11	3.79	1018	740	13.39	17.41	0.0132	6.04	1.24	45.1
21	10.49	1202	62	12.67	16.47	0.0105	0.54	0.56	11.0
22	10.34	771	31	12.07	15.70	0.0157	0.45	0.28	1.9
29	8.78	863	463	12.27	15.95	0.0142	1.65	0.39	30.3
30	8.72	617	216	12.27	15.95	0.0199	1.65	1.25	51.0
31	8.90	524	123	12.00	15.60	0.0229	1.41	1.13	27.5
38	7.96	401	154	11.25	14.63	0.0281	1.58	1.20	20.8
39	9.50	463	31	11.11	14.45	0.0240	0.40	0.58	3.2
40	13.11	709	0	11.29	14.68	0.0159	0.00	0.00	0.0
41	5.56	740	432	11.32	14.72	0.0153	3.61	1.40	62.6
42	8.41	863	432	10.75	13.98	0.0125	0.77	1.82	34.5
43	8.80	925	154	10.97	14.26	0.0119	0.64	1.82	34.5
50	8.79	617	308	12.16	15.81	0.0197	1.03	0.66	11.7
52	8.99	709	93	12.09	15.72	0.0171	1.36	1.49	22.5

TABLE C.4: Building List and relevant parameters

Building	**Storeys**	**Height**	**Width**	**Depth**	**S.Zone**	**S.Type**	**B.Cat**	α	**Weight**	$\mathbf{R_0}$	**Coef C**
1	21	52.50	18	41	3	1	2	0.524	152035	9	0.35
2	25	62.50	13	37	3	1	2	0.349	117965	9	0.35
5	23	55.66	13	36	3	1	2	0.349	105595	9	0.35
6	22	56.90	14	31	3	1	2	0.000	93666	9	0.35
9	21	50.82	15	18	3	1	2	-0.262	55623	9	0.35
10	16	38.72	10	16	3	1	2	-0.611	25114	9	0.35
11	32	80.64	12	26	3	1	2	-0.262	97943	9	0.35
21	12	28.92	29	43	3	1	2	-0.349	146797	9	0.35
22	17	41.14	14	18	3	1	2	0.262	42026	9	0.35
29	23	57.27	15	40	3	1	2	0.000	135378	9	0.35
30	10	24.20	18	19	3	1	2	0.000	33550	9	0.35
31	16	38.72	12	25	3	1	2	0.000	47088	9	0.35
38	28	67.76	16	30	3	1	2	0.000	131846	9	0.35
39	15	36.30	14	24	3	1	2	0.000	49442	9	0.35
40	7	16.94	12	32	3	1	2	0.000	26369	9	0.35
41	21	50.82	19	24	3	1	2	-0.052	93941	9	0.35
42	17	41.48	11	52	3	1	2	-0.384	95392	9	0.35
43	15	36.30	13	20	3	1	2	0.524	38259	9	0.35
50	24	60.72	7	41	3	1	2	0.524	67571	9	0.35
52	18	43.56	12	22	3	1	2	0.000	46617	9	0.35

Table C.5: Hydraulic Loads

Building	FEMA			NCh			CCH		
	Data	Approx	% dif	Data	Approx	% dif	Data	Approx	% dif
5	4023	294547	7322%	4023	154227	3834%	5197	531908	10235%
6	2770	23041	832%	2770	6158	222%	421	9504	2257%
9	5729	29656	518%	5729	14822	259%	5783	60227	1041%
10	4458	26749	600%	4458	13385	300%	5143	52443	1020%
11	8344	42819	513%	8344	21397	256%	7224	96292	1333%
21	1368	14595	1067%	1368	2196	161%	91	3082	3387%
29	3919	19031	486%	3919	4758	121%	732	37260	5090%
30	2942	9179	312%	2942	2330	79%	479	11587	2419%
31	2159	10448	484%	2159	2387	111%	427	8746	2048%
38	2121	12325	581%	2121	3162	149%	619	16825	2718%
39	231	5611	2429%	231	698	302%	33	1310	3970%
41	5819	18153	312%	5819	7301	125%	2556	36214	1417%
42	5104	15122	296%	5104	2918	57%	385	27583	7164%
43	1943	5617	289%	1943	981	50%	125	3238	2590%
50	1550	18750	1210%	1550	4585	296%	309	33941	10984%
52	1583	9277	586%	1583	2105	133%	402	4810	1197%

C.3 Evacuation Processes

Identifying the order of processes among emergency actors

When the actors are identified and classified one is ready to go deeper into the matter of evacuation processes. The evacuation consists of different phases with different processes and actors involved, see figure C.5 and its legend in figure C.6. In order to gain structure within the broad context of evacuation processes a so called flowchart can be designed to help to identify and order the different activities, decisions and events.

Phases of evacuation processes

One can imagine that different activities contribute to the final state of evacuation, namely that everyone is being saved from the tsunami hazard. How to derive at this

Table C.6: Stability Check

Building	Baseline Shear		Overturning		Uplift	
	V$_{sis}$ [kN]	**V**$_{hyd}$ [kN]	**M**$_{sis}$ [kN-m]	**M**$_{hyd}$ [kN-m]	**Weight** [kN]	**Buoyant** [kN]
5	9755	5197	361990	160399	105595	22983
6	9105	2770	345395	41937	93666	5630
9	5703	5783	193228	154935	55623	18028
10	3750	5143	96790	70735	25114	10558
11	6219	8344	334353	147930	97943	20340
21	42924	1368	827578	105245	146797	7219
22	5488	112	150513	8592	42026	1222
29	12507	3919	477514	84745	135378	10670
30	14530	2942	234419	58440	33550	6086
31	7031	2159	181481	29669	17088	4568
38	9734	2121	439727	67768	131846	8173
39	8591	231	207892	10156	49442	1441
40	14758	0	166662	0	26369	0
41	9632	5819	326341	182770	93941	17769
42	12457	5104	344465	29213	95392	4751
43	6647	1943	160869	12627	38259	1792
50	5946	1550	240693	12276	67571	3176
52	5703	1583	165621	24829	46617	3874

stage of 'closing' is the question we will answer. Four different activity areas or phases are defined for the evacuation of a city. The first is the dectecting phase, the second the evacuating phase, the third the guarding phase and the fourth the closing phase. It is known that with a signal of a coming earthquake national organizations are awakened. This signal is the earthquake. It is the question if this earthquake will be big enough for causing a tsunami. Therefore, different activities contributing to the detection of the earthquake and a possible tsunami are categorized in the first phase. These will of course always be the first activities to happen in order to start the following phases of evacuation. Furthermore, it is known that the closing phase can only be started when the evacuation and guardening of the evacuation is over. So the evacuation and guardening of the evacuation should be in the middle. The evacuation start as soon as the tsunami is forecasted and a decision to evacuate is given or an earthquake of great magnitude is experienced by the inhabitants.

The evacuation and guardening phases start at a similar moment. It is hard to determine which moment exactly and which activity is the incentive except for the earthquake or tsunami forecast. It is known that ONEMI together with SHOA should decide upon evacuation. However, it is imaginable that the inhabitants will directly start the evacuation when a severe earthquake magnitude is experienced. When the start of the evacuation is given, the guardening of the evacuation by the governmental organizations begins. This guardening is pictured as the anticipation on performing more evacuation activities, as for the reason to safe more people, or give instructions to the CLE (Comites Locales de Emergencia) also to inform the people on further provisions.

When the decision to stop the evacuation is given the evacuation is ended. It is the question which organizations actually coordinate the closing phase, municipality, SHOA, ONEMI or OREMI or the CLE? In this diagram is it assumed that ONEMI and the SHOA decide together if the evacuation time consumed was sufficient and that the next activity area of tsunami hazard management can be started as to be named the recovery. ONEMI needs the information of SHOA to decide this, so it can also be stated that only ONEMI makes this decision. It is also imaginable that ONEMI together with the municipality or regional government decide upon this. However, no information was found on this specific topic.

C.3.1 Road Infrastructure Analyses

The road infrastructure analysis of Iquique has besides zone 1 and 2 resultated in findings on the other zones 3,4,5. These will now be presented.

Findings on zone 3 (residential)

Zone 3 is for a large part a residential area, along with the beach area of Cavancha beach. The area contains jobs because of the commercial beach area, including hotels, the Iquique Casino and a large mall Las Americas, but not as many as zone 2. The street pattern in zone 3 only has some grid structure in the northern half, but in the southern part this structure is abandoned for irregular patterns, containing both right angles (in the west) and curved bends (in the east). Without a good map it is fairly easy to get lost in this part of Iquique.

The number of inhabitants of evacuation zone 3 is 34,130 [SINTIA, 2010]. The peninsula has an evacuation distance of at least 20 minutes. Therefore, this particular area has set up their own vertical evacuation procedures, even though this is not publicly approved by the government [Municipality.of.Iquique, 2013]. Evacuation signs in the beach area aren't placed in numerous numbers. Close to the safety zone and meeting points, signs can be found. Because of the street layout, there is no single evacuation route that leads straight to the safety zone. The evacuation routes usually aren't wider than one traffic lane plus park lane, with the exception of the biggest road Tadeo Haenke in the South that has two traffic lanes in each direction plus park lanes. On average the slope angles in zone 3 range from 2.5° to 10° (only in the east), making it easier to choose the right evacuation direction.

The line of the safety zone is formed by the following streets:

- Sold Pedro Prado;
- Trece Oriente;
- Pedro de Valdivia;
- Ejercito de Chile;
- Sold Pedro Prado.

The characteristics of these streets are as follows: Trece Oriente (mainly), Pedro de Valdivia, and Ejercito de Chile are quiet two-way streets with a fair amount of space. Sold Pedro Prado, however remains a busy road.

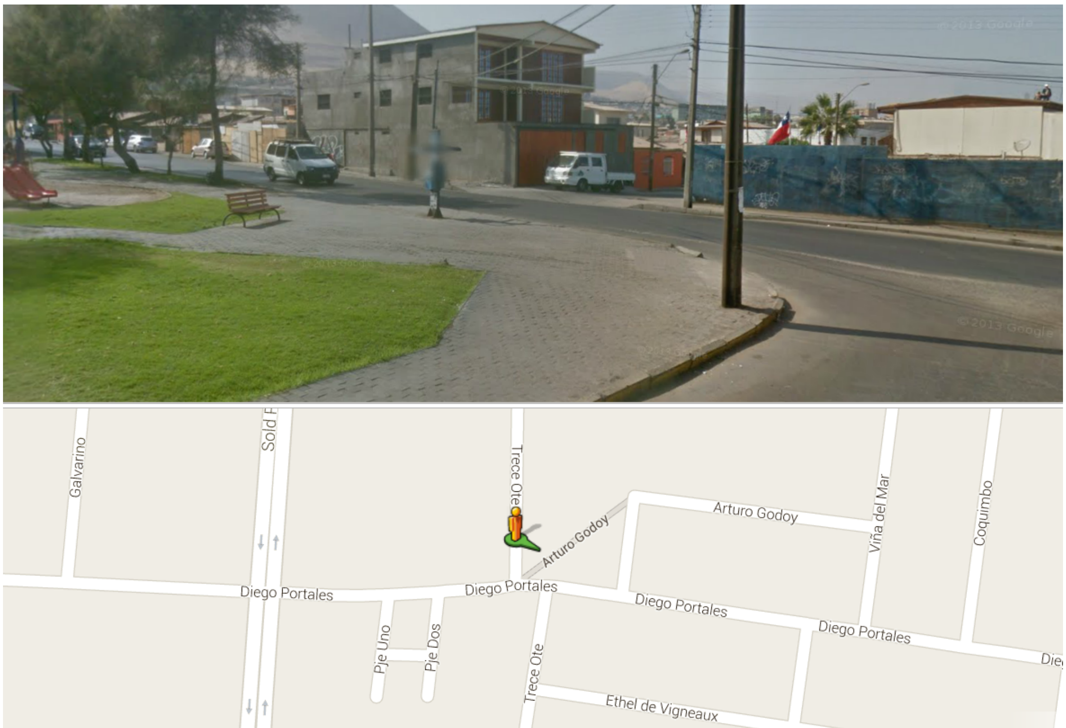


FIGURE C.7: Trece Oriente and Diego Portales section [GoogleStreetview, 2013]

In evacuation zone 3 ten buildings have been assessed for structural analysis. Seven buildings are deemed suitable for vertical evacuation.

Main findings zone 3

1. Dangerous zones and specific dense cumulations of people

   Not being identified

2. Identify possibilities for evacuation in dense cumulations

   Several evacuation routes indicated to uphill safety zone area

   Pensular evacuation vertically

3. Identify road infrastructure characteristics and suitability for evacuation

   Not being identified

4. Identify suitability of meeting points in higher grounds

   Some meeting points identified with signs

5. Identify suitability of vertical shelters

   Some vertical shelters available

Findings on zone 4 (residential)

Zone 4 in particular a residential zone, next to Brava beach. Similar to zone 3, zone 4 has some grid structure, but again with irregularities; streets usually are not parallel to the coastline. The municipality of Iquique reckons evacuation zone 4 to contain the most the residential homes and therefore the most critical zone at night [Municipality.of.Iquique, 2013], but this isn't consistent with the number of inhabitants 57,552, stated by SINTIA [SINTIA, 2010].

Evacuation routes here are among the shortest in Iquique. At normal walking pace (5 km/h) these routes can be walked within eight minutes. The downside of this is the large slope that lies inbetween the area and the safety zone. The slope angles in zone 4 range from 1.5° to 7°, only with a smaller deviation than the slopes in zone 3. These slopes make it almost impossible to head for the wrong evacuation direction. Nevertheless, zone 4 faces a severe problem in the evacuation. The presence of some large blocks cause long detours for evacuation routes starting from several sites along the coast. Basically, these sites lack decent straight evacuation routes. Next to this, evacuation routes in zone 4 (in contrast to other zones) consist of multiple roads. These roads don't always follow up on each other smoothly; at several places right angles in the evacuation routes make orientation rather difficult. The evacuation routes usually have a minimum width of one traffic lane plus park lane and maximum width of two traffic lanes plus two park lanes (at both sides of the streets).

The line of the safety zone is formed by the following streets:

- Sold Pedro Prado;
- Presidente Salvador Allende Gossens;
- Diagonal Francisco Bilbao.

The characteristics of these streets are as follows: only Presidente Salvador Allende Gossens is a quiet two-way road, but Sold Pedro Prado and the Diagonal Francisco Bilbao are both busy two-way roads

Main findings zone 4

1. Dangerous zones and specific dense cumulations of people

   Not being identified

2. Identify possibilities for evacuation in dense cumulations

    Several evacuation routes indicated to uphill safety zone area

3. Identify road infrastructure characteristics and suitability for evacuation

    Not being identified

4. Identify suitability of meeting points in higher grounds

    Some meeting points identified with signs

5. Identify suitability of vertical shelters

    Some vertical shelters available

Main findings zone 5 (residential)

Evacuation zone 5 is a residential zone, stretched out from the border with zone 4 in the north to the most southern parts of Iquique. In its street pattern it shows a lot irregularities, with streets usually not parallel to the coastline. Because of the average (safe) height of the zone, there are only two evacuation routes determined, both within a very short distance of the safety zone. For this reason, this evacuation zone is not elaborated on further.

Main weaknesses of Zofri zone 5

1. Dangerous zones and specific dense cumulations of people

    Not being identified

2. Identify possibilities for evacuation in dense cumulations

    Several evacuation routes indicated to uphill safety zone area

3. Identify road infrastructure characteristics and suitability for evacuation

    Not being identified

4. Identify suitability of meeting points in higher grounds

    Some meeting points identified with signs

5. Identify suitability of vertical shelters

    Some vertical shelters available

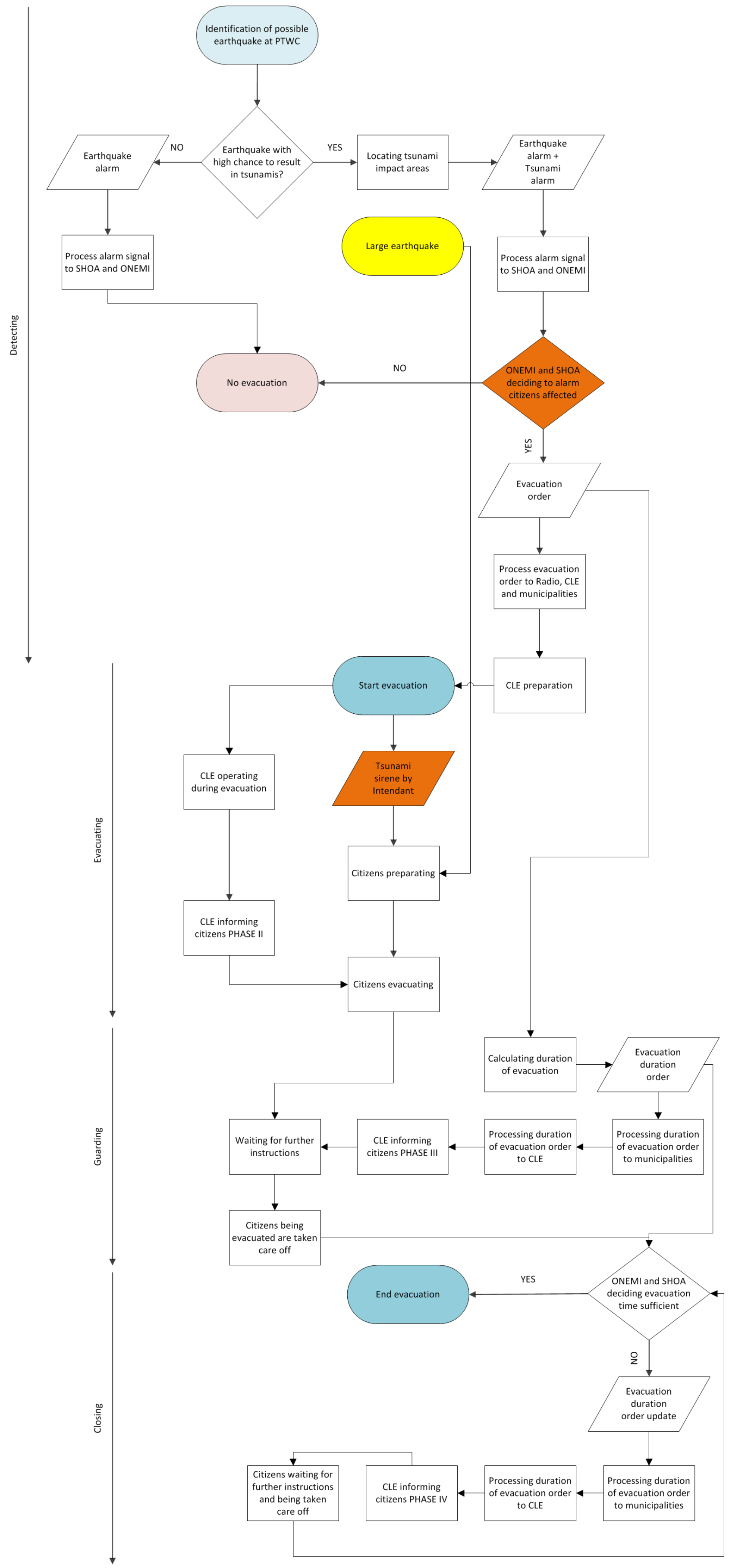


FIGURE C.5: Flowchart Emergency

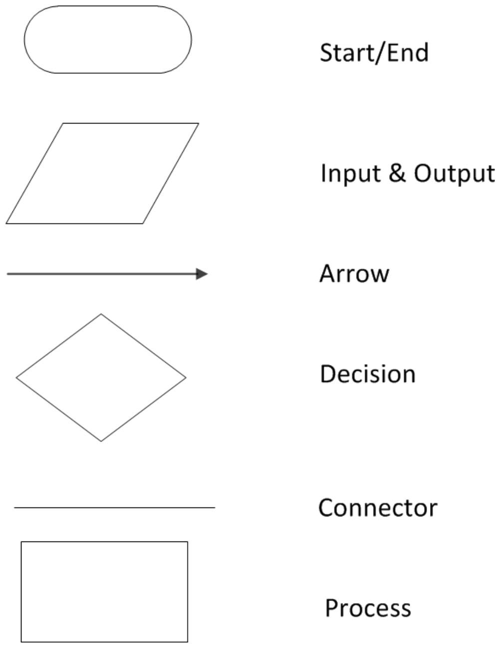


FIGURE C.6: Flowchart Legend

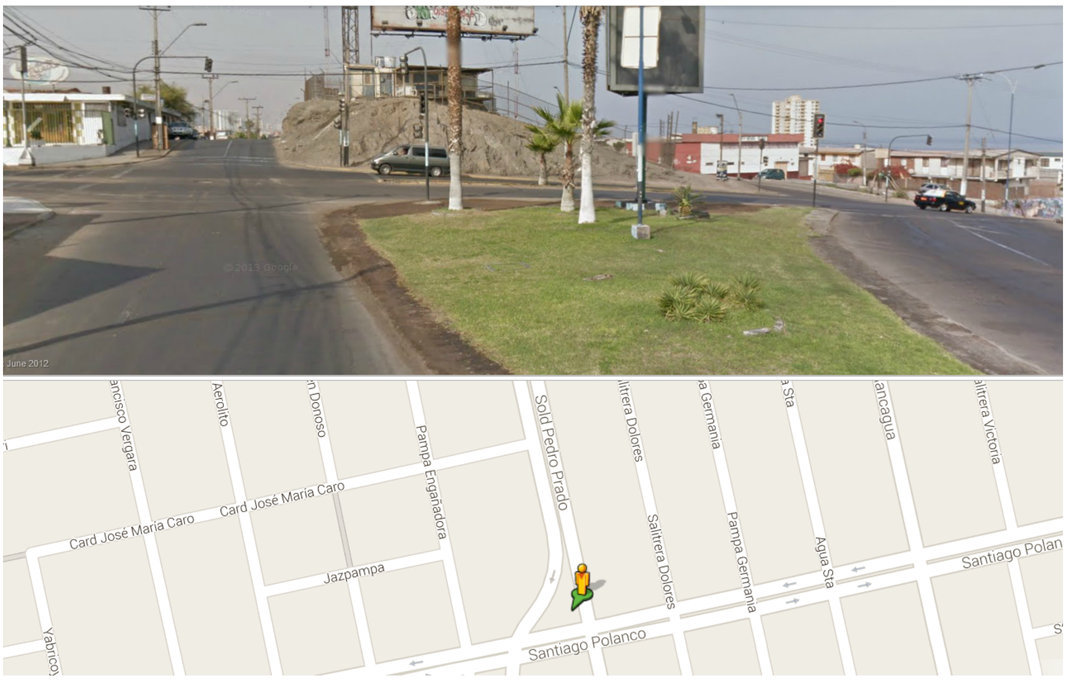


FIGURE C.8: Sold Pedro Prado and Santiago Polanco section [GoogleStreetview, 2013]

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