

Tsunami resiliency of transport systems

The development and application of a tsunami resiliency assessment method

Marieke van Dijk - 4248546



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by
M. (Marieke) van Dijk
student number: 4248546

In partial fulfillment of the requirements for the degree of

Master of Science

In Transport Infrastructure and Logistics
at the faculty of Civil Engineering and Geosciences
of the Delft University of Technology

Thesis committee:

Prof. Dr. Ir. B. van Arem (chair)
Dr. A. Pel
Dr. J.A. Annema
Dr. Ir. J. Bricker

Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in “Transport, Infrastructure and Logistics” at the faculty of Civil engineering and Geosciences of the Delft University of Technology.

The aim of my research has been to clarify the concept of ‘tsunami resiliency’ and make it more tangible and less complex. Tsunamis and earthquakes are terrible disasters, and I found it satisfying to work on a small piece of the overall puzzle, trying to figure out what could lead to a tsunami resilient transport system.

At the very start of my research, I was able to go Japan and visit Yuriage, a small village which was impacted greatly by the 2011 tsunami. Seeing how badly damaged this village was, and how determined the governmental agencies were to rebuild this area was really impressive. I would like to thank the Delft Deltas, Infrastructures & Mobility Initiative (DIMI) for providing the opportunity to visit Japan with other TU Delft students.

Another word of thanks goes out to my TU Delft supervisors Prof. Dr. Ir. B. van Arem, Dr. A. Pel, Dr. J.A. Annema and Dr. Ir. J. Bricker for providing me with feedback throughout my entire graduation process.

A last word of thanks goes out to my friends and family. I feel very lucky to have been surrounded by so many involved and caring people.

I wish you all a happy read!

Marieke van Dijk

Rotterdam, August 2018

Summary

Earthquakes and follow up tsunamis damage houses, infrastructure and the land itself. This destruction makes it harder for people to evacuate from the area and for emergency traffic and relief goods to access the area. It is of great importance that a resilient transport system is in place to accommodate these functions. Generally said, such a system should be able to absorb the impact of a disaster and maintain functional to facilitate outbound evacuation traffic and inbound emergency services during and directly after the disaster. On the longer term, a resilient transport network is a network that returns faster to its original functional state than a non-resilient network, when it is impacted by an event that disrupts their functioning. With concerns about more frequently occurring water related disasters with higher impacts due to climate change, it is understandable that resilient systems are desired (MLIT, 2015). However up to this date, there is no guidebook on how to build a tsunami resilient transport system, or even what comprises it. Current resilience research is insufficient to determine the resilience of transport systems hit by a tsunami. This main research question of this thesis therefor is: *“How to assess the tsunami resiliency of a transport system?”*

A literature research is performed to analyze the different approaches for the assessing of resiliency for different types of systems. The assessment methods could be categorized as qualitative, semi-quantitative and quantitative. The qualitative methods provide theoretical frameworks to qualitatively determine the resiliency, the semi-quantitative methods add indicators to the theoretical frameworks to qualitatively score the indicators. The quantitative models add formulas and derived actual resiliency values. Since this research is the first that looks into the tsunami resiliency of transport systems, the choice is made to start with the developing of a theoretical framework and the derivation of factors having an effect on the tsunami resiliency.

The assessment method developed in this research is designed for transport authorities or other transport related policy makers. The use of the method provides insight in the strong and weak points of an existing transport system, can compare two transport systems on their tsunami resiliency or can be used as guideline when designing a new transport system.

The aim of the method is to assess the tsunami resiliency of a transport system. In order to do so, an understanding is needed on what a tsunami resilient transport system is. This is done by means of a hierarchical structure with tsunami resiliency at the top. The further down in the decomposition, the more detailed and tangible the subjects will become. The subjects at the bottom of the hierarchy should be usable for the assessing of tsunami resiliency. The subject can be qualitatively or quantitatively measured and are derived from observations of the system of interest. An overview of all the subjects, or factors, is visualized in Figure I. The factors are color coded; red factors are disaster related factors, blue factors are ‘ability to cope with a disaster’ related factors, yellow factors are resource related factors and green are ‘ability to recover’ related factors.

To assess the tsunami resiliency by means of these derived factors, they need to be measurable. All factors are given a means to measure them along with a best and worst case outcome. The best and worst cases for every factor are used as to develop a scoring range from 1-5. This overview forms the final assessment matrix.

The developed tsunami resiliency assessment method is tested by applying it on the island of Oahu. This Hawaiian island is chosen because of its location in a seismic and tsunami risky area. The method is tested on a worst case scenario for Oahu; a close source tsunami caused by an earthquake. Problems that are expected to arise in case a tsunami and earthquake impact Oahu are the inundation of almost



Figure 1: Overview of tsunami resiliency factors for transport systems

all airports, destruction of ports and inundation of the coastal roads. During evacuation problems are expected in some densely populated or areas with limited possibilities to evacuate, which could be further decreased in case bridges collapse due to earthquake shaking. Oahu is dependent on other parts of the world for their supply. After a disaster, relief goods and recovery materials need to be brought in from elsewhere. There is a need for a good access point to supply the goods to, that remains usable after a disaster and provides options to distribute the goods on the island.

It is possible to assess the tsunami resiliency of a transport system by using the method as developed in this research. This provides a first step in exploring the tsunami resiliency. However, it is difficult to use the method as a decision making tool because the derived factors do not have weights and some of the factors required further research because they are lacking a proper scoring range. It is recommend research the factors further in order to use the method as a decision making tool.

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1. Introduction

On March 11 2011, a magnitude 9 (Mw) earthquake shook the north east coast of Japan (Steffen, 2011). The epicenter of the earthquake was located 130 kilometers east of Sendai and caused a tsunami which hit the east coast of Japan causing chaos and destruction (Sample, 2011). Due to the many disasters Japan has faced, there are advanced warning-, defense- and recovery mechanisms in place (Birmingham, 2011). Although an early warning was given when the earthquake happened, and several defense infrastructures were in place at the coast where the tsunami hit, the impact was still enormous. The tsunami reached heights that were not accounted for and destroyed several of the defensive structures that were supposed to protect the land behind it causing severe flooding with all its consequences (Onishi, 2011). This is a recent example of the possible devastation of such a disaster, but throughout history many tsunamis have occurred all over the world (Long, Dawson, & Smith, 1989). There are concerns about more frequently occurring water related disasters with higher impacts because of climate change and the possible occurrence of higher magnitude earthquakes that are expected to hit (MLIT, 2015).

Earthquakes and follow up tsunamis damage houses, infrastructure and the land itself. This destruction makes it harder for people to evacuate from the area and for emergency traffic to reach it. It is of great importance that a resilient transport system is in place to accommodate these functions. Generally said, such a system should be able to absorb the impact of a disaster and maintain functional to facilitate outbound evacuation traffic and inbound emergency services during and directly after the disaster. On the longer term, a resilient transport network is a network that returns faster to its original functional state than a less resilient network when it is impacted by an event that disrupts their functioning. That such a system is desired is understandable. However up to this date, there is no guidebook on how to build a tsunami resilient transport system, or even what comprises a tsunami resilient transport system. So if there is a desire for a tsunami resilient transport system but the knowledge on how to (re)design such a system is missing. Current resilience research is not sufficient to determine the resilience of a transport system hit by a tsunami. It is not known what the impact of such a disaster is on the performance of the transport system, or even what the right measure(s) of performance should be. If there is a way to assess tsunami resiliency, it will become possible to determine whether a transport system is tsunami resilient. It will also become possible to analyze current systems for possible future disasters in order to prepare for them in a better way. This research will therefore focus on the design of an assessment method for tsunami resiliency.

The main research question of this thesis is: *“How to assess the tsunami resiliency of a transport system?”*

Chapter 2 will discuss the scope and methodology of this research. Chapter 3 will give the objective of this research and derive requirements for the solution. This is followed by a literature review of system resilience research up to this date in Chapter 4. The next chapter will take the insights from the literature review and will derive factors affecting the tsunami resiliency of a transport system. This will lead to a systematic holistic overview of what comprises tsunami resiliency. This overview will then be used to determine the resiliency by scoring the derived factors. That will in turn be used to assess the transport system on Oahu on its tsunami resiliency. The method will be validated in Chapter 7 by means of an expert and peer validation. Chapter 8 will answer the research questions and lastly give recommendations for further research.

2. Scope and methodology

In this chapter the scope and methodology of this thesis research will be explained. It will begin with the problem statement, followed by the aim and objectives of this thesis. The subchapter 'scope' will explain the boundaries of this research and will give some definitions of terms important for this research. The final subchapter will elaborate on the research methods used to conduct this research.

2.1 Research methods

For this thesis several research methods are used. The aim of this research is to design a tsunami resiliency assessment method. In order to design this method, several steps need to be taken. The methodology of Peffers, Tuunanen, Rothenberger, & Chatterjee (2007) is used. They developed their methodology so that designers can approach a design problem in a systematic way. They have developed and applied their method on four cases with different characteristics. Their method is chosen for this research because it turned out to be effective for all four cases, one including the design of an assessment method. This method divides the design process into six steps that are comparable with methods as given by Howard, Culley, & Dekoninck (2008):

1. Identify the problem
2. Define the objectives and requirements of the solution
3. Design and develop solution
4. Demonstrate the use of the solution
5. Evaluate the solution
6. Communicate the solution

The problem identification clarifies the problem and shows the (societal) relevance of solving this problem. A field trip to the Tohoku region, visits to the disaster location, interviews with a transport professor and student and presentations by teachers and students of the Tohoku University provided insights in the difficulties related to transport systems suffering from disasters. The transport system plays a vital role during and after a disaster. A functioning transport system in case of a disaster allows for better evacuation and higher accessibility of the area for emergency services and relief goods. With concerns for an increased frequency and an increased intensity of natural disasters, including tsunamis, there is a need for resilient systems. However, it is not known what comprises a tsunami resilient transport system. The problem is explained in more detail in the next section.

The defining of the objectives and requirements of a solution is derived from the previous step; the problem identification. Currently it is not possible to design tsunami resilient transport systems because it is unknown what a tsunami resilient transport system is. The problem will be solved by providing better insights into the factors affecting the tsunami resiliency of a transport system and by designing a method that will be able to assess it. In order to design such a method, it is necessary to identify what the method should be able to do more precisely. This is determined by the requirements and are derived based on the interviews held in Japan, data retrieved in Japan and personal observations during the field trip.

The design and developing of the solution is the step where "the artifact is created" (Peffers et al., 2007). Such artifacts can be constructs, models, methods, etc. For this thesis, this step is the design of the actual assessment method. This step includes determining the methods' functionality, its design and the creation. In this step the composite indicator model theory is used. An indicator model is the combining of a set of indicators that represent the dimensions of a topic that cannot be described by means of only one indicator. The model can summarize and clearly show how a system is performing with regard to the defined indicators and not lead to an absolute measure (Nardo et al., 2008). The benefits of using the composite indicator model for the topic of tsunami resiliency assessment is that it is easy to interpret and it can be used as a policy decision support tool. A point of attention is that when the indicators are poorly constructed they can lead to simplistic or wrong conclusions or even be misused to support a desired policy. However, these problems can be prevented when the

indicators are derived in a transparent way and tested thoroughly. The entire method as explained by Nardo et al., (2008) consists of ten steps and could not be fitted to the timeframe of this thesis research. The first two steps provide a theoretical framework and include data selection and can be used as to make the assessment method. Further steps in the developing of the composite indicator model consist of the operationalization, normalization, weighting and aggregation of indicator values and perform a sensitivity analysis on these values.

The demonstration of the method serves the purpose of showing whether or not the method is usable and works. For this thesis the designed assessment method will be applied to the island Oahu, part of Hawaii. This case study will show whether the assessment method is able to determine the tsunami resiliency of Oahu's transport system on a qualitative level.

The evaluation of the solution serves as a validation step. Here the designed method and its applicability to Oahu will be reflected upon. Since it is not possible to compare the outcomes of the method with existing data because the method itself is new, an expert validation is used to validate the method. Two interviews are conducted with Tina Comes, a resilience researcher at Delft University of Technology. The first interview focused on the decomposition of the concept of 'tsunami resiliency' for transport systems. The second interview focused on the method itself and its application on Oahu. Also a small test is performed to check on the reproducibility and clarity of the method. Peers are asked to fill in the assessment matrix for Oahu with the same data that is used in this research. The outcomes of the peers are compared to the outcomes in this research.

The communication of the solution can be described as the overview of the five previous steps. It should be communicated what the initial problem and relevance are, how the solution looks like and works and justify its design to the proper audience. Since this research is the final step to obtaining the Master of Science degree, the communication will be done by means of this master thesis report, a paper and a public presentation and defense.

2.2 Problem statement

The welfare of society is dependent on a reliable and continuous flow of goods and services. This is provided by infrastructure systems including the transport system (Nan & Sansavini, 2017). In case of a tsunami the transport system is of vital importance. Prior to the tsunami impact, it accommodates evacuees to leave the area and after the tsunami impact it enables emergency services to reach the area. After the tsunami it is important that people stranded in the disaster area can be reached. They need food, supplies and possibly medical support. The destruction or damaging of the transport system also has a national impact. Due to disasters parts of the transport system can be isolated, causing losses in human mobility and flow of goods leading to economic losses (Tatano & Tsuchiya, 2008).

When designing a transport system there are several scenarios to consider. Firstly the day to day functioning of the system without disturbances, so for instance what the service rate of the system is during peak hours. Secondly, minor disturbances with a high probability are taken into account. For example congestion or a malfunctioning section of rail causing the transport system to perform less than in the usual situation. Lastly large disturbances with low probabilities should be taken into account. Examples are natural disasters. This last category is hard to plan for due to its stochastic nature. It is impossible to design a resilient system for every large disturbance that could occur at some point in time. Some areas are more likely to be impacted by specific disturbances than others. Japan for example is prone to earthquakes and tsunamis due to its proximity to several tectonic plates (Israel, 2011). Tsunamis cause huge damage because of the combination of an earthquake, a force of water and the debris that is left behind when the water recedes.

Certain parts of the world are prone to tsunamis due to their position on the earth's shell. In these parts of the world a tsunami resilient transport system could be useful. Such a transport system will

suffer less damage when a tsunami impacts it and will recover faster from the effects compared to a 'regular' transport system. The resilient system is visualized in Figure 1 by the striped line. The regular system is visualized by the regular line.

Unfortunately there are too many unknowns to design a tsunami resilient transport system. It is not known what a tsunami resilient transport system exactly is. It is not known what the 'quality' in Figure 1 is, or what factors affect it. There is a lot of research on reliable and robust networks, and on resiliency of communities (Morin & Floch, 2008). But Mattsson & Jenelius (2015) observe in their paper that research on transport resiliency mainly focuses on vulnerability, which does not include the post-disaster phases of response and recovery.

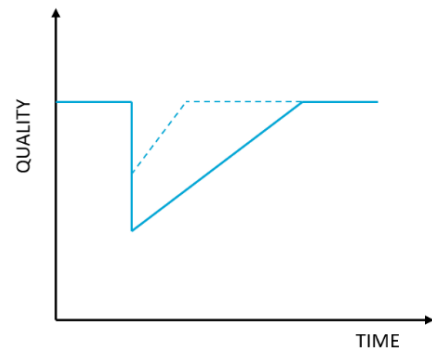


Figure 1: A resilient and a less resilient system

There are many examples of tsunamis and earthquakes damaging infrastructures and there are many examples of things that 'could have been better', but there is no general assessment method or checklist to see how tsunami resilient a transport system is. Therefore the rebuilding criterion in Japan after the 2011 tsunami is to rebuild the destroyed systems in such a way that they can withstand a tsunami with the same size as the last one (Okumura, 2017). In order to design for a tsunami resilient transport system it is necessary to know what comprises a tsunami resilient transport system.

2.3 Aim and objectives

The aim of this research is to design a method that can be used to qualitatively assess the tsunami resiliency of a transport system. In order to fulfil the aim of this research, several steps need to be taken which are formulated as objectives in the section below.

- To explore the current research on systems resilience
- To determine what factors contribute to a tsunami resilient transport system
- To derive indicators from those factors
- To explain how to measure these indicators
- To use these insights to develop a method able to assess the tsunami resiliency of a transport network
- To explain how to use the developed assessment method

2.4 Research questions

The aim and objectives lead to a main research question and several sub questions. The main research question for this thesis is: "How to assess the tsunami resiliency of a transport network?"

In order to answer this main question, the following sub questions need to be answered:

- How can the resiliency of systems be assessed?
- What are indicators for a tsunami resilient transport system?
- How can these tsunami resiliency indicators be measured and what would be (un)desirable values?
- How can a set of indicators determine the tsunami resiliency of a transport system on a qualitative level?

2.5 Scope: definitions

Tsunami

A tsunami is defined as a long and high sea wave which is caused by an earthquake or other disturbance (English Oxford Living Dictionaries, n.d.-b). Other disturbances can be volcanic eruptions or underwater landslides (International Tsunami Information Center, n.d.). The disturbance in this research that affects the transport system is a tsunami caused by an earthquake. This earthquake can either be close to the transport system to be assessed, but can also be on the other side of an ocean. An earthquake close to Japan can cause a tsunami impacting Hawaii for example.

Function of the transport system

The transport system enables people and goods to move from location to location using the modalities as listed in the next subsection.

Modalities

This research will take land, water and air based modes into account. These include:

- Road based modes (car, bus, cycle, walk)
- Rail based modes (train, tram, metro)
- Water (ships and ferries)
- Air (aircraft and helicopters)

Geographical scope

The geographical scope of this research will be the (hypothetical) area that can be impacted by an earthquake and by a tsunami. The choice can be made to scope based on organizational or political boundaries, for example a city or country.

Time horizon

This research will look into transport systems in their current state in order to give an advice on the anticipation of an earthquake and tsunami.

Type of transportation

In transportation the general distinction that is made, is between the transport of people and of goods. When assessing the tsunami resiliency of a transport network the transport of people seems most important during a tsunami. People want to evacuate from the danger to a safe area and need the transport system to do so. After the disaster it is important that those people are not isolated and have access to medical help and to supplies. The supply of relief goods is also of importance after the disaster. Therefore the transportation of both people and goods are taken into account.

2.6 Conclusion

This chapter gives an overview of the scope and methodology for this thesis. The problem in this research is the current inability to determine the tsunami resiliency of a transport system. The aim of this research is to design an assessment method capable of qualitatively assessing a transport system on its tsunami resiliency.

3. Objectives and requirements for a tsunami resiliency assessment method

This chapter will describe the objectives and the requirements for the assessment method that is to be designed. Besides the defining of the design objective it is necessary to state which requirements need to be met before starting the actual design of the assessment method in order to scope the design possibilities. This chapter will give direction for the design by means of explaining the objective and the requirements, chapter 4 explains existing assessment methods and resilience research and in chapter 5 the actual method will be designed.

3.1 Objective

The objective is to be able to qualitatively assess the tsunami resiliency of a transport system.

3.2 Requirements analysis

The purpose of a requirements analysis is to refine the objectives and requirements and to identify and define constraints that limit a solution. Requirements are capabilities or characteristics that somebody needs or wants (Robertson, 2001). Requirements of a system are translated into a (re)design of that system. By performing a requirements analysis the understanding of the function, performance and interface(s) will become clearer (Leonard, 2005). These systems engineering principles are mostly used for the design of physical systems where requirements are usually originating from many stakeholders. Using a basic form of a requirement analysis for designing a tsunami resiliency assessment method is still useful. It clarifies what the method should do, up to what level of detail the method should be useful and by whom the method should be used. Requirements will be derived based on the five open ended questions and on information retrieved during the site visit to Japan.

3.2.1 Five questions to derive requirements

To give an understanding of the function, the performance and interfaces of the assessment method, the five open-ended questions are asked (Leonard, 2005).

What is the method for?

The tsunami resiliency assessment method should be able to qualitatively assess the tsunami resiliency of transport systems. When following the method, it should be possible to compare two transport systems on tsunami resiliency. Not in the sense that the outcome will be that system A is 5% better than system B, but in the sense that the method provides the relative position of one system with regard to the tsunami resiliency factors that are determined. When using the method, it should be possible to identify weaknesses and thus points to improve in transport systems.

Who will use the method?

The method should be used by a transport authority or another transport related policy maker. They are the ones who plan, design and monitor transport systems and could benefit from an increased understanding on factors that have an effect on the tsunami resiliency of transport systems.

When will the method be used?

The method can be used at any time to analyze existing transport networks in order to assess and possibly improve them. The method can also be used as a guide when designing a new transport system, or when rebuilding a damaged one. The method can then be used to assess the newly designed system on its tsunami resiliency and show how to improve the tsunami resiliency.

Where will the method be used?

The method should be applicable for regions from all parts of the world. The geographical scale will be determined by the scope the transport system is planned for.

How will the method be used?

The method should be easy to interpret, follow and adjust. The method consists of the factors that that can be followed to gather information on the different tsunami resiliency related factors for the transport system. With that information it will become possible to assess the transport system by means of a scoring matrix which lists all the factors with a range. When this matrix is filled in, this should give an overview of the transport system specific factors that contribute to or decrease the tsunami resiliency.

3.2.2 Lessons learned from the Great East Japan Earthquake – visit to Japan

This thesis project is part of a larger research which is funded by the Delft Deltas, Infrastructures & Mobility Initiative (DIMI). DIMI supports an integral approach when finding solutions for societal problems that are related to the natural and built environment (“Delft Deltas, Infrastructures & Mobility Initiative,” n.d.). In that context, multiple TU Delft students visited Tohoku to study the tsunami, its effect on the natural and built and environment and possible steps to take after the tsunami within their own discipline. Within that group this thesis will focus on the tsunami resiliency of transport systems. During the visit, presentations were held by researchers of the Tohoku University. Together with interviews, presentations of the municipality of Natori City and the Ishinomaki Community Center this forms a source which contained several statements and observations that are useful for the developing of a tsunami resiliency assessment method. The statements and observations are generalized into implications for the transport system so that they can be used in the design phase of the assessment method and are listed in Table 1.

Table 1: Implications for the tsunami resiliency assessment method derived from Japan site visit.

Statement/observation	Source	Implication
Not necessarily bad to evacuate by car, sometimes even inevitable, but there must be a plan for this. People drowned in their cars due to congestion during the 2011 evacuation.	Interview Anna Takayasu (Appendix A).	There must be a plan for evacuation by car to increase the evacuation efficiency.
Vertical evacuation can help to decrease the demand and increase the probability of a successful evacuation.	Workshop at Tohoku University and site visit to Yuriage.	Decreasing the evacuation distance increases the evacuation efficiency.
Even when seismically designed infrastructure is used, it can become unusable (railways were unusable because the power supply lines were detached and damaged, while the infrastructure itself was not damaged too severely)	Interview professor Makoto Okumura (Appendix A). Visit to Ishininomaki Community Center.	The type of infrastructure has an effect on the resiliency of the transport system. The functioning of the transport system is related to the functioning of other infrastructural systems (power, communication)
The type of infrastructure (road or rail for example) has an effect on the recovery speed (roads are easier to	Paper of professor Makoto Okumura. (Okumura & Kim, 2018)	The type of infrastructure that is used has an effect on the resiliency of the transport system.

access than rails and thus easier to repair)		
Governmental structure has an effect on the recovery after a disaster: municipalities have to compete with each other for rebuilding funds.	Interview professor Makoto Okumura (Appendix A), (International Research Institute of Disaster Science Tohoku Universitu, 2013)	Governance has an effect on the resiliency of the transport system; the 'right' governance can decrease the recovery time.
Information propagation during and after disasters plays a role in the way the transport system is used. People share (incorrect) information through social media, causing people to use or not use certain parts of the transport system.	Presentation Anna Takayasu. (Appendix A)	Information people receive has an effect on the route choice of people.
After the GEJE temporary airline routes were established, bus companies quadrupled their transportation capacity, free shuttle bus services were implemented replacing a subway line.	Paper and interview professor Makoto Okumura. (Okumura & Kim, 2018), (Appendix A)	Redundancy in routes by different modes helps to restore the functionality of the transport system.
Efficient tsunami evacuation includes informing people (including visitors) so they feel the need to evacuate and immediately take action as described in the evacuation plan.	Paper professor Makoto Okumura. (Okumura & Kim, 2018)	Tsunami evacuation requires a well communicated evacuation plan.
Groups of elderly people required special assistance during evacuation.	(International Research Institute of Disaster Science Tohoku Universitu, 2013)	Personal characteristics have an effect on evacuation.

3.3 Conclusion

In this chapter the objectives and requirements are stated. The objective of the method that needs to be designed is to be able to qualitatively assess the tsunami resiliency of a transport system. A basic requirements analysis lead to the following requirements. The method should be:

- able to qualitatively indicate the tsunami resiliency of the system
- able to compare two systems on different aspects of tsunami resiliency.
- be able to detect weak points in transport systems in order to show where to improve
- used by transport planners
- usable at any time to analyze existing transport systems
- usable when designing a new transport system, or rebuilding a damaged one
- applicable for regions from all parts of the world
- easy to interpret and follow
- leading to an overview of factors that contribute or decrease tsunami resiliency
- taking the implications of the GEJE for the transport system into account

4. Literature review resilience research

The aim of this research is to develop a method capable of assessing the tsunami resiliency of a transport system. Since no literature exists on this topic, the aim of this chapter is to gather literature on the resiliency assessment of other systems. Research on resiliency assessment of systems on a more general level exists. Research also exists on tsunami resiliency of communities, disaster resiliency of infrastructure networks and the consequences of the 2011 Great East Japan Earthquake (GEJE) on the built environment. This chapter will begin with a summary of resilience research. This will be followed with a summary of resilience assessment methods and a discussion on the usefulness of these approaches for the assessment of tsunami resiliency for transport networks. Insights obtained in this chapter will serve as a basis for the design of the tsunami resiliency assessment method in the next chapter.

4.1 Development of resilience research

The Oxford Dictionary gives two definitions of resilience: *“The capacity to recover quickly from difficulties; toughness”* and *“The ability of a substance or object to spring back into shape; elasticity”* (English Oxford Living Dictionaries, n.d.-a). Several authors (Haines, 2009; Reggiani, Nijkamp, & Lanzi, 2015; Rose, 2007) recognize the broad variety in definitions for resilience. The general concept of resilience started being used in the 70’s in ecological system research, based on prey-predator differential models developed in the 30’s (Holling, 1973). However, the concept of resilience also proved useful for other systems, for example in the field of psychology, enterprises and biology. Every system has a desirable state which can be disturbed by external events. A short term example is a disaster, a long term example is climate change (Rose, 2007). Hosseini, Barker, & Ramirez-marquez (2016) give an overview of system resilience research of the last decade. The literature that is found is divided into four different domains; organizational, social, economic and engineering. This division has also been used by Bruneau et al. (2003). Their terminology is largely overlapping except for the fact that Hosseini et al. (2016) speak of the ‘engineering’ domain, while Bruneau et al. (2003) speak of the ‘technical’ domain. In Figure 2 the terminology of Hosseini et al. (2016) is used. The following section will explain more about the different domains, concluding with where to fit the transport system.



Figure 2: Four domains for resilience. Image by author

Economic domain

Bruneau et al. (2003) describe economic resilience as the capacity to reduce direct and indirect economic losses resulting from a disturbance. Rose (2007) describes it as *“the inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses”*. A distinction is made between static and dynamic resiliency. Static economic resilience is defined as the ability of a system to maintain its function when shocked. Dynamic economic resiliency also takes implications of repair and speed of recovery into account.

Organizational domain

Organizational resilience addresses the need of businesses to respond and adjust to continually and rapidly changing business environments. Hosseini et al. (2016) and Bruneau et al. (2003) describe it as the capacity of organizations to make decisions and take actions that help to achieve greater robustness, redundancy, resourcefulness and rapidity. Sheffi (2005) describes it as *“the company’s*

ability to, and speed at which they can, return to their normal performance level following by disruptive event”.

Social domain

Social resilience takes the resilience capacities of people into account. This can be an individual, but also a group, community or an entire environment (Hosseini et al., 2016). Capacities means the ability of these people to deal with a disturbance. This includes the predicting of risks, the mitigating of negative consequences and the recovering to the initial functioning (Adger, 2000; Rose, 2009).

Engineering domain

Hosseini et al. (2016) conclude that the concept of resilience in this domain is relatively new compared to the domains listed above. Youn, Hu, & Wang (2011) state that the resilience of a system is the sum of the passive survival rate and proactive survival rate of that system, which can also be said as the reliability and restoration capability of that system. Bruneau et al. (2003) define the technical resilience of a system as the ability of a physical system to perform on an acceptable or a desired level when subjected to disturbances.

Transport system

Transport system resiliency is not yet defined by other authors, but the resilience of an infrastructure system is defined by the National Infrastructure Advisory Council Critical Infrastructure Resilience (2009) as the ability of the system to predict, absorb, adapt and rapidly recover from a disturbance. According to Hosseini et al. (2016), infrastructure systems are a subdomain of the engineering domain because their construction and restauration requires engineering knowledge. The infrastructure forms a part of the transport system, but this system also consists of people and services. So, the argument can also be made that a transport system is a subdomain of the social or the economic domain because when a transport system is not resilient, this has an effect on people and the economy because of its supporting role.

4.2 Assessing of system resilience

Several authors have captured the resilience of different types of systems. The definitions and assessment methods that are used are of a wide variety. This paragraph will discuss the different types for the assessment of tsunami resiliency of transport systems. Two different approaches are used, namely qualitative and quantitative assessment.

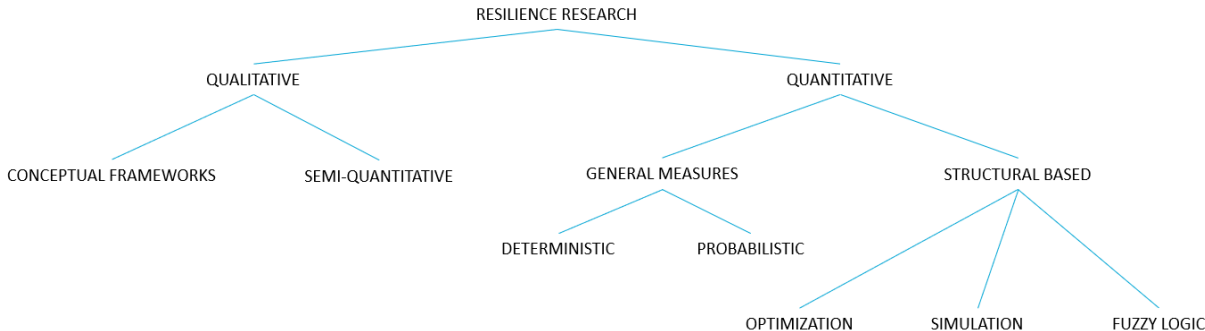


Figure 3: Different approaches of assessing resilience.

Figure 3 gives an overview of the different approaches and how they are categorized by (Hosseini et al., 2016). No assessment methods for tsunami resiliency of transport systems exist– qualitative or quantitative. Before being able to quantitatively assess resiliency, firstly a qualitative assessment is needed. The qualitative assessment methods will therefore be discussed in more detail than the quantitative methods. The following section will explain more about the approaches.

4.2.1 Qualitative assessment

Qualitative assessment of systems is divided in two branches; conceptual frameworks and semi-quantitative assessment methods. These two approaches will be discussed in the next sections.

4.2.1.1 Conceptual frameworks

Several authors have proposed and created conceptual frameworks to assess the resilience of a system. This section will give an overview of these frameworks.

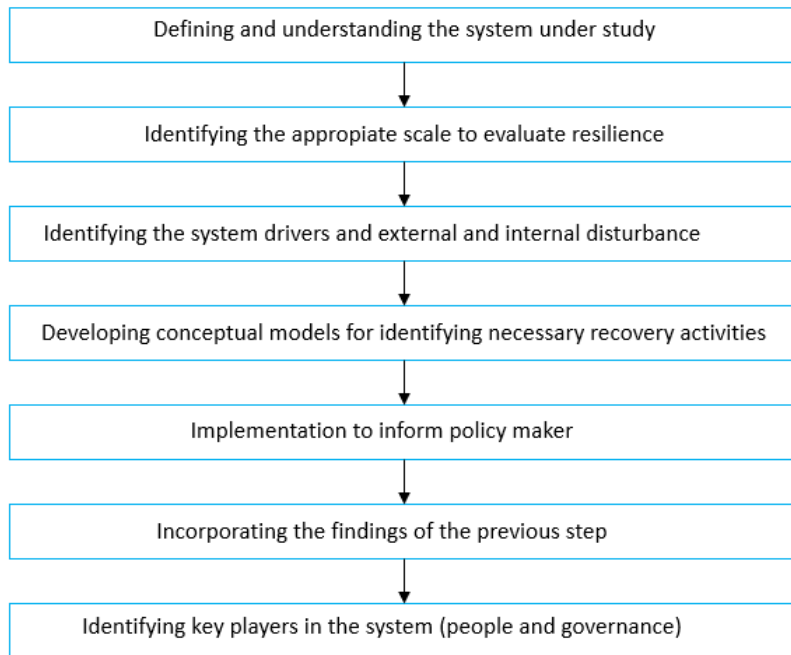


Figure 4: Steps to take in order to evaluate resiliency of social-ecological systems based on (Resilience Alliance, 2010)

Figure 4 shows a generic framework for the evaluating of social-ecological system resilience (Resilience Alliance, 2010). It is presented in a practical work sheet for planners of social-ecological systems. This framework could also be applicable for other domains of resilience as the steps are not domain specific.

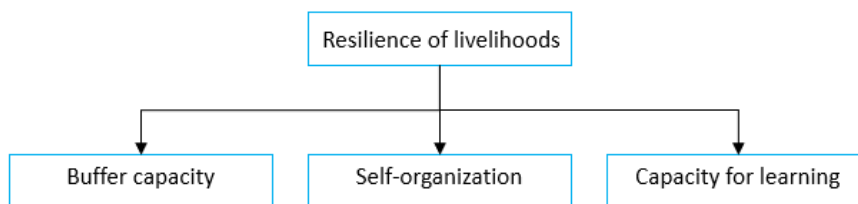


Figure 5: Three dimensions of social-ecological systems resilience (Speranza, Wiesmann, & Rist, 2014)

The framework in Figure 5 can be used for the assessment of resilience in the context of social-ecological dynamics. The example system they use is a farming system. Resilience is divided into three different domains. Buffer capacity is the amount of change or stress a system can handle without a decrease in performance. Self-organization is explained as “the emergence of society through inherent social structure” and capacity for learning means the ability of the system to adapt to changes. These three dimensions are divided into different detailed indicators that can be scored using a Likert scale from zero to five capturing the contribution of that indicator to the overall resilience of farming systems.

Sterbenz et al. (2010) illustrate their definition of resilience by means of Figure 6. The operational and

service space of a system are divided into three different regions. The operational space is divided into normal, partially-degraded, and severely-degraded regions. Similarly, the service space is divided into acceptable, impaired, and unacceptable regions. This leads to nine states, or “regions” which are used to evaluate the resilience of a system. The system can operate under three conditions; normal, partially degraded or severely degraded. The state of operation has an effect on the functioning of the system. In order to place a system on the axes, indicators need to be defined together with values representing their (un)acceptable functioning. However, their paper does not include an example using the state space representation.

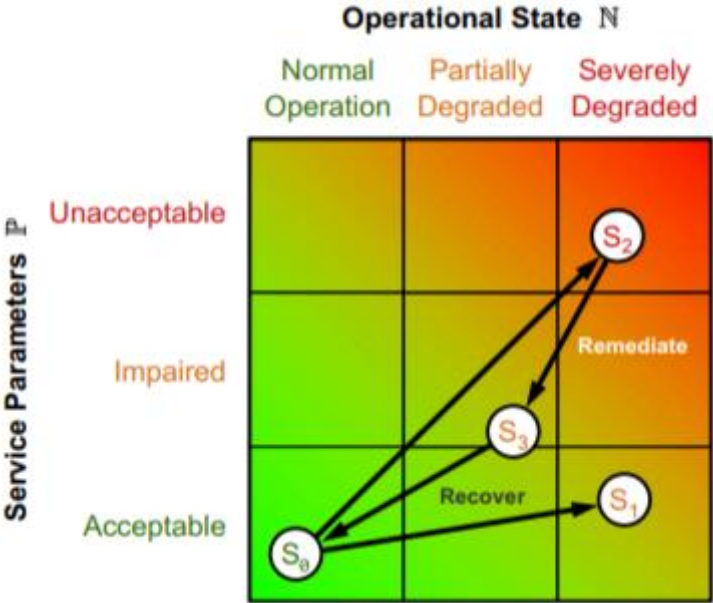


Figure 6: Resilience state space (Sterbenz et al., 2010)

According to Bruneau et al. (2003), seismic resilience for communities consists of four properties. They are visualized in Figure 7.

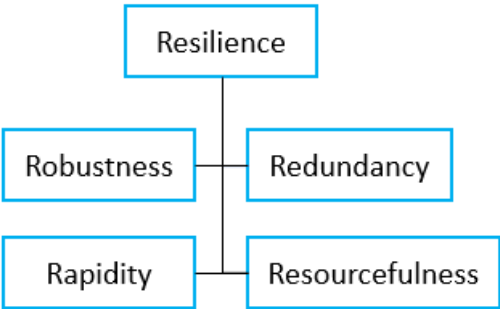


Figure 7: Four properties of resiliency (Bruneau et al., 2003)

Robustness refers to the ability of a system to withstand a given level of stress without suffering degradation or loss of function. Redundancy refers to the ability of a system to substitute for elements that have a loss of function (i.e. if one part stops working, another part can -partially- take over). Resourcefulness stands for the capacity to identify and prioritize problems and allocate resources to solve them in the case of a disruption. Rapidity is defined as the capacity to solve problems in case of a disruption in a timely manner in order to contain losses and avoid future disruption. These four properties have different indicators. A distinction is made between the properties on the left and right

in Figure 7. Robustness and rapidity are the desired “ends” that are accomplished through resilience improving measures. Redundancy and resourcefulness are measures that define the “means” by which resilience can be improved. For example, the resilience of a system can be improved by adding elements, creating redundancy. An overview is given per domain (technical, social, economic and organizational) and per property, leading to a set of indicators varying from qualitative to quantitative.

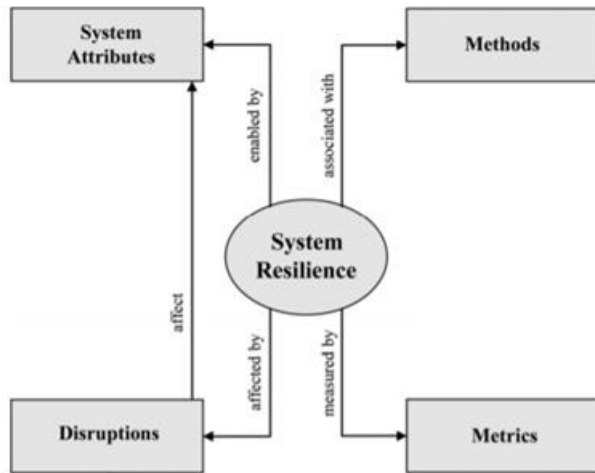


Figure 8: Conceptual framework for the engineering of system resilience (Madni & Jackson, 2009).

Madni & Jackson (2009) give a conceptual framework for the engineering of system resilience. They define four categories that are shown in Figure 8. Attributes are for example the complexity and organization of the system. Disruptions can be natural or man-made, or external or internal. Methods to achieve system resilience are for example probabilistic prediction methods, or proactive risk management. The metrics that are given as examples are the time/cost it takes to restore functionality.

4.2.1.2 Semi-quantitative assessment

This assessment method makes use of indices in order to assess the resiliency of systems. The system’s attributes are first determined and can consist of for instance; redundancy, robustness; vulnerability, flexibility. Those attributes are then scored on a scale from 0-10 or on a percentage scale from 0-100. This approach has been used by Cutter et al., 2008; Pettit, Fiksel, & Croxton (2010). This method can be interpreted as a conceptual framework as well. The authors first state what resiliency comprises for their system and then try to score those factors but without using formulas. By taking the extra step of scoring, this method is classified as semi-quantitative.

4.2.2 Quantitative assessment

This section will elaborate on the possibilities for quantitative assessment of system resilience. They will not be explained in great detail, but it will show current practices. The first distinction that is made in quantitative assessment is between general measures and structural based models.

4.2.2.1 General measures

General resilience measures are defined by Hosseini et al. (2016) as measures that “provide a quantitative means to assess resilience by measuring performance of a system, regardless of the structure of the system.” In practice this comes down to a measure of the system performance before and after a disruption. These measures can be characterized as deterministic or probabilistic, depending on which system behavior needs to be described.

4.2.2.2 Deterministic approaches

These approaches do not include uncertainty into the metric that is used to assess resiliency. Several authors (Adams, Asce, Bekkem, Toledo-durán, & Asce, 2012; Paolo, Reinhorn, & Bruneau, 2010; Sahebjamnia, Torabi, & Mansouri, 2015; Zobel, 2011) use a form of the resilience triangle model for a resilience assessment. t_0 represents the time where the disturbance starts to affect the system under study and t_1 is the time where the system reaches the same quality as before the disturbance (see also Figure 9). Bruneau et al. (2003) calculate the resilience of the system (RL) by using Equation 1

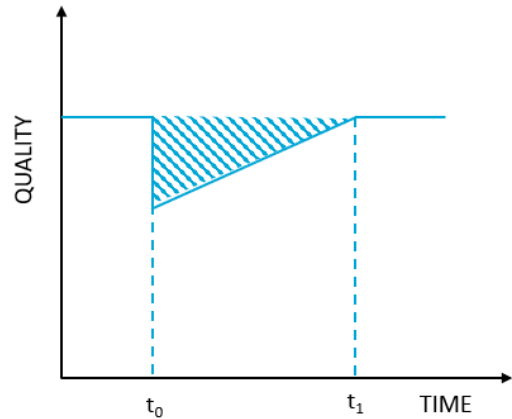


Figure 9: The resilience triangle

$$RL = \int_{t_0}^{t_1} [100 - Q(t)] dt \quad (1)$$

In Equation 1 Q represents the quality of the system, this is the vertical axis in Figure 9. RL is visualized by the shaded area.

Henry & Ramirez-Marquez (2012) propose a more detailed form of the graph which includes different states of the system. The states are shown above the graph line in Figure 10.

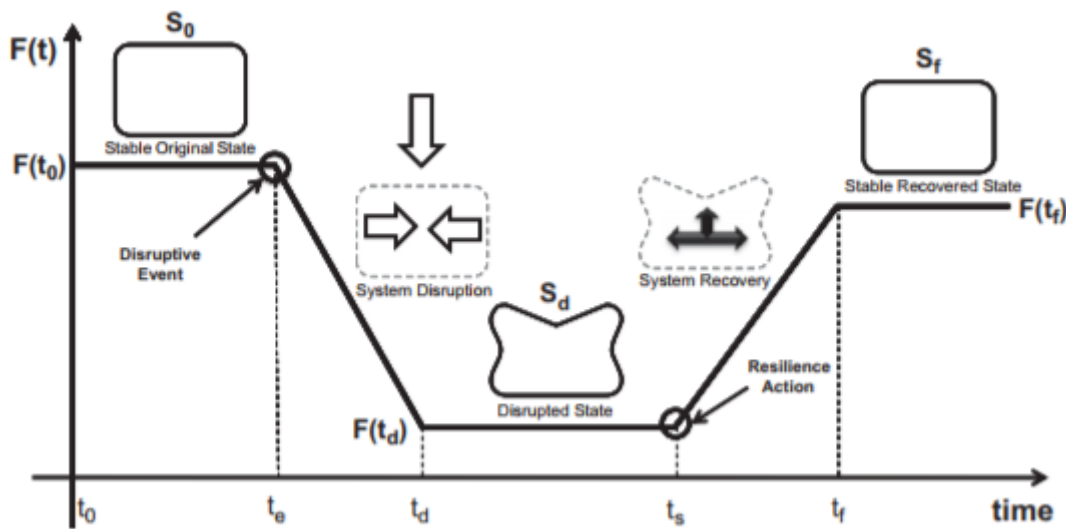


Figure 10: Performance function transition in resilience (Henry & Ramirez-Marquez, 2012)

The resilience metric they propose is time dependent and represents resiliency as the proportion of the function that has been recovered from the disruption. In other words: the ratio of recovery to loss. Several states and their timesteps are of importance for quantifying resilience: the stable original state, the disrupted state and the stable recovered state. Figure 10 also indirectly shows the dimensions of resiliency:

- Reliability, by which the authors mean the ability of a system to function in a good way prior to a disturbance $[0, t_e]$.
- Vulnerability, which stands for the ability of a system to limit the consequences of a disturbance on the functioning $[t_e, t_d]$.

- Recoverability, or the time it takes the system to recover from the disturbance $[t_s, t_f]$. The time dependent resilient metric can be calculated by Equation 2 under the condition that the system performance measure F is also quantifiable.

$$R_F(t_r|e_j) = \frac{F(t_r|e_j) - F(t_d|e_j)}{F(t_0) - F(t_d|e_j)} \quad (2)$$

The numerator stands for the recovery up until time t , the denominator stands for the total loss caused by disruption e_j . The minimum value of $R_F(t_r|e_j)$ is equal to zero which is the case when $F(t_r|e_j) = F(t_d|e_j)$, meaning the system has not recovered at all from the disrupted state. This can either mean no resilience related action has been taken, or that the actions had no effect. $R_F(t_r|e_j)$ equals 1 when $F(t_r|e_j) = F(t_0)$. This means the system has recovered from the disrupted state to the original functional state. Higher values than 1 can be achieved when the recovered state performs better than the original state.

Ip & Wang (2011) developed a method to quantitatively determine the resilience of a transportation network. Their way of calculating the network resilience is based on the number of reliable passageways between points weighted with the population of those points. They define the resilience of a node (or point) as *“the weighted sum of the numbers of reliable passageways of all other nodes in the network”*. Their definition of the resilience of a transport network is as follows: *“The resilience of a transportation network presented by graph G , $R(G)$ is defined as the weighted sum of the resilience of all nodes.”* After they have evaluated the resilience of the nodes and the whole network, they introduce the concept of friability for nodes which is defined as the reduction of network resilience resulting from its removal from the network. The friability (the influence of a disaster on the network) of the entire network is then a weighted sum of the friability of all the nodes. Omer, Mostashari, & Lindemann (2014) look at resiliency in a similar (node-based) way. They calculate resilience as the ratio of the closeness centrality of a network prior and after a disturbance. This centrality is dependent on the accessibility of a node to the other parts of the network.

4.2.2.3 Probabilistic approaches

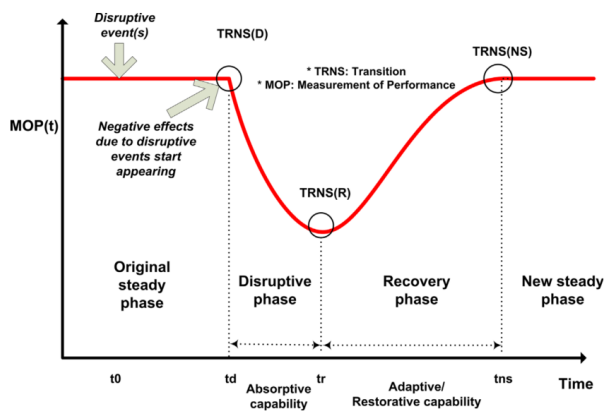
These approaches include the stochasticity that is associated with the behavior of the system under study. According to Murray-Tuite (2006), transport resilience is viewed as a network characteristic that indicates how well the traffic network performs after disturbances. Resilience has ten different dimensions (redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly). The last four dimensions are given values by means of simulation.

Structural based models

The structural based approach assesses the influence of the structure of a system on the resilience of that system. System characteristics and behavior are included in this approach. There are three different types of models that can be used; optimization, simulation and fuzzy logic models.

In optimization models the goal is to maximize the resilience of network while certain constraints are in place. Examples can be found in (Faturechi & Miller-hooks, 2014; Jin, Tang, Sun, & Lee, 2014; Vugrin, Turnquist, & Brown, 2014).

Nan & Sansavini (2017) developed a method to quantify resilience and propose a model that is able to simulate it. Four phases are of importance, the original steady phase, the disruptive phase, the recovery phase and the new steady phase. Resilience is measured during the different phases by the absorptive, adaptive and restoratives capabilities that were defined in Francis & Bekera (2014).



Summary of different resilience phases.

Phases	Time scope	Transition point	Capabilities (features)	Measurements
Original steady phase	$t < t_D$		Susceptibility	Susceptibility
Disruptive phase	$t_D \leq t < t_R$	TRNS(D)	Absorptive capability	R RAPI _{DP} PL _{DP}
Recovery phase	$t_R \leq t < t_{NS}$	TRNS(R)	Adaptive capability Restorative capability	RAPI _{RP} PL _{RP}
New steady phase	$t \geq t_{NS}$	TRNS(NS)	Recovery capability	RA

R: robustness; RAPI_{DP}: rapidity in disruptive phase; PL_{DP}: performance Loss in disruptive phase; RAPI_{RP}: rapidity in recovery phase; PL_{RP}: performance Loss in recovery phase; RA: recovery ability.

Figure 11: Resilience curve and corresponding measurements per phase (Nan & Sansavini, 2017)

Nan & Sansavini (2017) make use of a curve representing the measurement of performance of a system. They give formulas for each of the four phases to quantitatively assess the resilience of a system. Examples are the calculating of robustness and rapidity, see Figure 11. Robustness refers to the minimum value of the measure of performance (MOP) between the time of the disruption and the time of the new steady state. Rapidity refers to the average slope of the MOP function during the disruption phase.

All the separate measurements are combined into a single integrated resilience metric. This metric assumes equal importance of the different contributing factors. Robustness, recovery speed and recovery ability are assumed to have a positive effect and performance loss and loss speed have a negative effect on resilience. Up to this part, the formulas are not domain or model specific. However, the authors take the next step as well and propose a modelling framework for the measuring of the resilience of an electricity network.

The final structural based model is a fuzzy logic model. Fuzzy logic is a method to formalize the human capacity of imprecise or approximate reasoning. This model is able to encapsulate partial truths (Ross, 2016).

4.3 Discussion of literature: implications for assessment method

The literature review provided an overview of the existing research on the resilience of systems. These systems are diverse; research exists on social systems as well as on telecommunication networks. Some research on transportation resilience also exists. As diverse as the research may be, there is some clear overlap. Resiliency consists of different properties, depending on the system of study. All literature on conceptual frameworks started with properties defining the resiliency of the system. In most cases this lead to an overview of indicators, sometimes together with a range. Such an overview for tsunami resiliency of transport systems – which is currently lacking - would be a good first step for the eventual assessment.

Another point of consensus in the analyzed system resilience literature is that there is a system which has to deal with a disturbance. The impact of this disturbance combined with the manner of recovery say something about the resilience of a system. This is explained in a simplified manner by means of the resilience triangle or curve. This representation makes it relatively easy to interpret resilience but some remarks must be made on the defining of resilience by means of the resilience triangle.

Firstly, such a graph can only capture basic behavior. It is highly unlikely that the performance of the system immediately drops to a point and starts recovering from there. It is more likely that the performance will continually go down until the lowest point is reached. Secondly, it may take a while before the system's performance will start to increase again. After a disturbance it can be expected that the performance remains on approximately the same low level before recovery activities will increase the performance. Thirdly, the triangle shows straight lines, it could be the case the performance starts to increase but has a small decrease at a later point in time. A final remark is the measure of performance. A suitable measure of performance is needed, or possibly multiple that can be used to describe the performance of a system during the different disaster phases. Bruneau et al. (2003) defined the technical resilience of a system as the ability of a physical system to perform on an acceptable level when subjected to a disturbance. So in the case of a transport system, an acceptable level of performance can mean that emergency services can access the area while people living in the area cannot make use of the transport system. This is difficult to capture in a measure of performance. A positive side of using this definition is that because of its generality, it is applicable for many different systems and is easy to interpret and communicate.

When taken these points into account and assuming performance drops more gradually, graphs such as in Figure 12 could be a result. Imagine three different systems which suffer from the same disturbance. The performance of the system on the left drops to a lower level than that of the two other systems. However, the left system reaches the original performance level faster than the systems on the right. Which of the systems is the more resilient one? Or, in case they have the same level of resiliency, which system should be designed? And, how can the performance and thus resilience of the system be influenced?

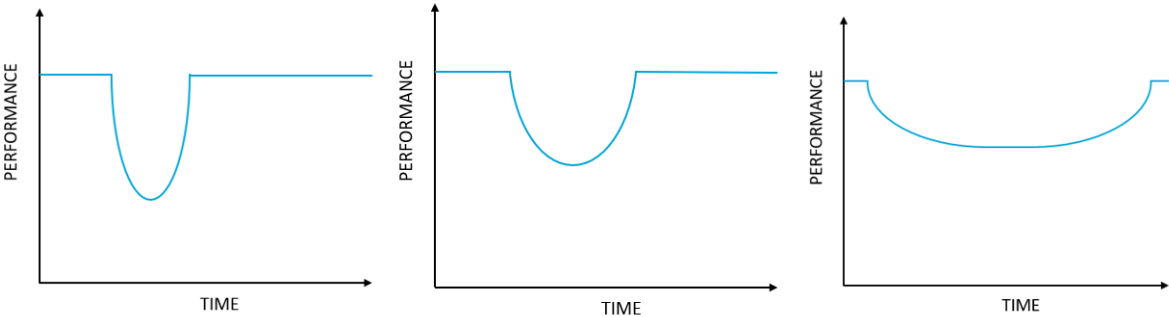


Figure 12: Adaptation on the resilience triangle.

4.4 Conclusion

In this chapter an overview of existing resilience research is given along with possibilities to assess resiliency of different systems. It remains unknown what exactly comprises the tsunami resiliency of a transport system. It is not known what the measure of performance is and what factors might have an influence. On top of that, the question which of thy systems in Figure 12 is most resilient cannot be answered. It must be analyzed what factors have an effect on the impact and the recovery phases and thus on the resiliency of transport systems. Ideally, the different factors can be weighed compared to each other and thus allow a more quantitative approach. The aim of this research is to develop the basis for this. The factors contributing to the tsunami resiliency of transport systems will be derived in the next chapter.

5. Design of the assessment method

This chapter will describe the design of a tsunami resiliency assessment method and its use. The previous chapter gave a literature analysis on systems resilience and existing assessment methods. This chapter will use insights obtained in the previous chapter as input. It will be more specific; the system of research is a transport system and will not be assessed on general resiliency, but on tsunami resiliency.

The aim of the method is to qualitatively assess the tsunami resiliency of a transport system. In order to do so, firstly an understanding is needed on what comprises tsunami resiliency. The first section of this chapter will start with the concept “tsunami resiliency” and decompose that into different subjects related to a transport system that matter for the tsunami resiliency. The second section will then elaborate further on these subjects, explaining if and how they can be measured along with an indication of what outcomes would be desirable. When all of the smaller subjects can be assessed, it becomes possible to assess the tsunami resiliency of the transport system as a whole, this will be described in the third and final section. The next chapter will demonstrate the assessment method by means of an example assessment for Oahu.

5.1 Decomposing tsunami resiliency for transport systems

A tsunami resilient transport system is a difficult concept to fully grasp. This section specifies the term and shows what subjects are relevant in order to determine the tsunami resiliency of a transport system. This will be done by means of a hierarchical structure with tsunami resiliency at the top. The further down in the decomposition, the more detailed and tangible the subjects will become. The subjects at the bottom of the hierarchy should be usable for the assessing of tsunami resiliency. This approach is similar to the first step of making a composite indicator model. The model structures characteristics or factors in a transparent way and enables a relative scoring of a system based on these factors. The factors can be qualitatively or quantitatively measured and are derived from observations of the system of interest. They should be precise, clear, interpretable and understandable (Merz et al., 2013).

5.1.1 Temporal dimensions; disaster phases

The literature review in the previous chapter mentioned several assessment methods and approaches for system resiliency research. Four contributing factors to resiliency that are recurring in literature are the 4 R's as explained in chapter 4. According to Bruneau et al. (2003), a system is more resilient when it is robust, has redundancy, has access to resources and has a high rapidity when recovering. Redundancy and resources are means to achieve robustness and rapidity, which in turn lead to resiliency.

Other literature explained resiliency by using the resiliency triangle or curve (see also Chapter 4). In such depictions the performance of a system is measured by means of one or multiple measures which depend on the system of interest. The resilience curve uses different phases; normal functioning, impact and recovery, this can be seen in Figure 13, where the impact (I) and recovery (R) are visualized. The left side of the curve is the performance level of the system under normal circumstances, then the system is impacted and the performance level decreases until further decrease stops. This is the impact phase. This phase is characterized by chaos, people are panicking and there is a lack of information because systems (transport, communication, energy but also social systems) are not functioning or no longer existing (Harrison & Williams, 2016). It is difficult to know the functionality of parts of the system while the system is still impacted by a disaster and means of sharing information are damaged. The impact phase is followed by the recovery phase, during which efforts are made to repair damages in order to increase the performance level of the system on the long term. Both the impact and the

recovery phase are related to the decrease or increase of the performance level of the system. The 4 R's of Bruneau et al. (2003) can also be linked to these disaster phases. When a system has a high level of redundancy and robustness, the impact of a disaster is likely to be smaller. When there are plenty of resources and the system recovers rapidly, the recovery phase will likely be shorter.

The first step in the decomposition of tsunami resiliency for a transport system is a temporal decomposition based on the disaster phases. A transport system can be tested towards its resilience in relation to different time intervals surrounding a tsunami. When system A and system B are both impacted by a tsunami, and system A has a lower drop of performance and recovers faster it is more resilient than system B. The next step is to determine which components contribute to the drop and increase of performance in their respective phase.

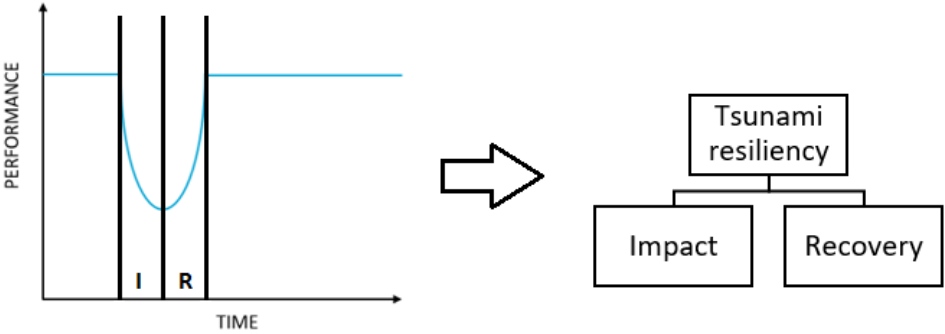


Figure 13: Decomposition based on disaster phases

5.1.2 Factors affecting the disaster phases

The decomposition to the lower level indicates the two complementary factors that jointly determine the extent of the impact and the two factors that jointly determine the course of recovery. When the same system is impacted by a disaster, the severity of the impact depends on the severity of the disaster itself (disaster is visualized in the red block). On the other hand, if exactly the same disaster were to impact two different systems, the system that was designed for that disaster will likely suffer less damage than a system that was not designed for it; it has a higher ability to cope with that disaster (visible in the blue block). Take for example a rail system, in Japan they are designed to endure severe earthquakes, in other countries no examples were found for such designs (Ashiya, 2004). It is likely that the rail system in Japan suffers a smaller drop in performance than the system in another country after an earthquake.

The course of recovery is also dependent on two factors. Resources and the recovering ability of the transport system. When system A and B have suffered exactly the same impact, but system A has more resources (visible in the yellow block) it is likely that system A will recover faster than system B. On the other hand, if the amount of resources is the same, but system A is designed in such a way that it enables easy repairs and system B is not designed with a possible reconstruction kept in mind, system A has a higher ability to recover (visible in the green block) and is likely to recover faster than system B.

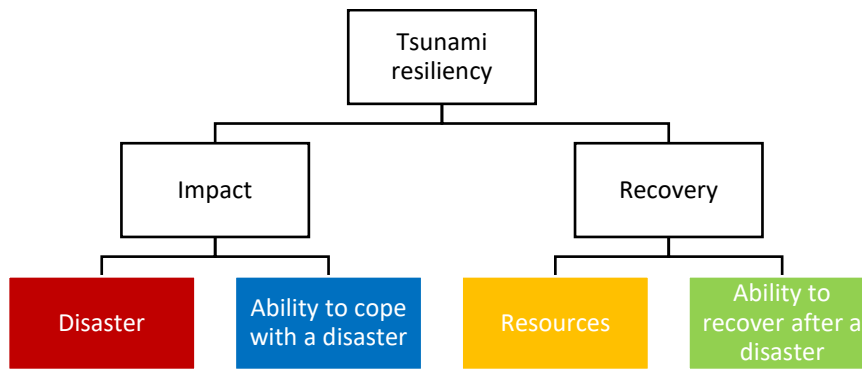


Figure 14: Four factors determining the disaster phases

The following decomposition will be based on the four colored blocks; disaster, ability to cope with a disaster, resources and ability to recover after a disaster. The decomposition is summarized in Figure 14.

5.1.2.1 Impact phase: decomposition of the “disaster” block

Tsunamis are caused by earthquakes most of the time and can travel across oceans. Regions can be hit by a tsunami caused by an earthquake on the other side of the earth. While looking at the disaster in case of tsunami resiliency this therefore is a tsunami, or a tsunami combined with an earthquake. The first step in the disaster decomposition is the distinction between a tsunami and an earthquake. Both are natural disasters with a potentially large impact, but their characteristics and effect on the transport system are different. In this research the disaster is either an earthquake combined with a tsunami, or only a tsunami. Earthquakes are not taken into account separately.

When a tsunami impacts a region, there are three relevant factors for the transport system. The first one is the force of the water. A tsunami can cause structural damage to the transport system itself, causing parts of it to be (partly) unusable. The second subject is warning time. When a tsunami is formed, it takes time to reach the shore. As soon as people become aware that a tsunami is coming and they are in a dangerous area, they will want to reach a safer area. This has a relation with the transport system. Regular travel patterns are replaced by evacuation, causing many people to move in the same direction behaving differently, possibly creating congestion. The amount of warning time is of importance and can vary between a few minutes when the epicenter of the earthquake that caused the tsunami is close by to multiple hours when the epicenter is on the other side of the ocean. When the warning time is multiple hours, the demand can be more evenly spread compared to a warning time of a few minutes. The last subject of importance for the transport system is the inundated area. On the one hand this affects the number of evacuees which will have to use the transport system to leave. On the other hand, it directly affects the functioning of the transport system. When parts of the system are below the water, they will no longer be usable. The larger the inundated area, the larger the impact on the transport system.

When an earthquake impacts a region, two subjects are relevant for the impact on the transport system. The first subject is the force of the earthquake. Earthquakes cause structural damage to the transport system, causing parts of it to be (partly and temporarily) unusable. The earthquake force is location specific; as the distances to the epicenter increases, the earthquake force weakens. The second subject is warning time. Prior to the damaging earthquake wave (the S-wave) a P-wave propagates from the earthquake epicenter. This P-wave travels faster and can be detected by earthquake sensors which ‘warns’ for the follow up S-wave. The warning time for an earthquake is the

time between the detection of the P-wave and the arrival of the S-wave (USGS, n.d.-a). This time is too short to be of relevance for the evacuation of people. However, for the limiting of damage to the transport system itself it can be of use. The Japanese railway companies for example stop their trains when seismometers sense seismic motion, decreasing the chance of derailment (Yamamoto & Tomori, 2013).

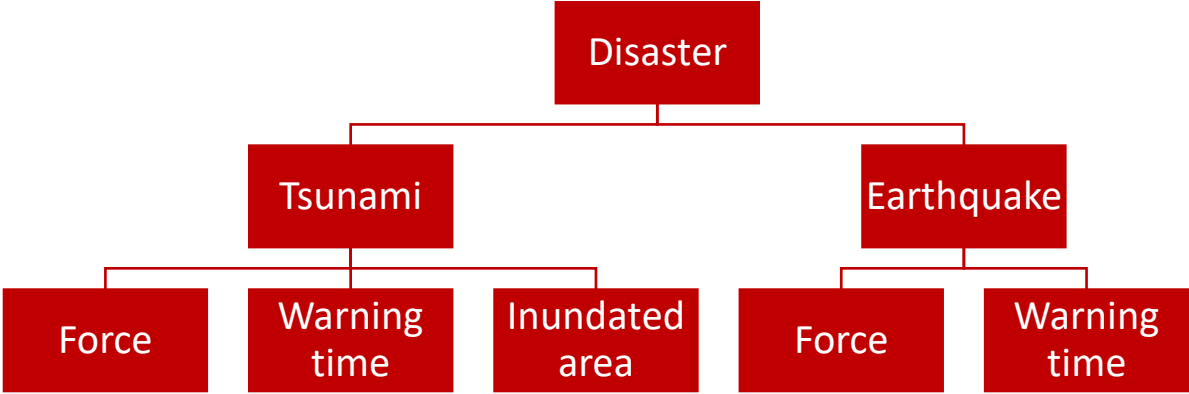


Figure 15: Disaster block decomposition

5.1.2.2 Impact phase: decomposition of the “ability to cope with a disaster” block

The ability to cope with a disaster consists of two subjects. Before explaining about them, it is important to shortly mention the difference between a transport system under normal functioning and a transport system that is impacted by a tsunami. To explain this in a simplified manner, the example of a high office building is used. The building consists of several floors that accommodate a number of people. In order to get all these people to their floors, a transport system is used: a system consisting of elevators and staircases. During an average workday, people arrive in the morning and leave in the afternoon, causing the highest peaks in demand. The elevator is the most attractive option for most people to reach their floor. Indicators that tell something about the functioning of the transport system are waiting times, travel time, comfort, safety, reliability and so on. When a disaster occurs, the impact phase of the building’s transport system ‘begins’. There is an increased demand (everyone wants to leave at the same time) and a decrease in supply (elevators are out of use or not allowed to be used). Suddenly indicators such as comfort and waiting time for elevators are useless, the thing that matters is to be able to reach safety. How the transport system accommodates that, tells something about the ability to cope with disasters. There are two possible strategies, one focusing on managing demand and the other focusing on managing supply. In this case this comes down to creating capacity in case of a disaster by means of staircases and possibly managing how and when people use them by means of evacuation plans.

When translating the example of the office building to a transport system in a region, the two strategies are focusing on the supply and demand. Within this decomposition supply is named “network characteristics” and demand is named “control measures”. The network influences the coping ability. A robust and redundant network will increase the coping ability. When the transport system is impacted and damaged, control measures can mitigate the severity of the impact by managing the demand. The basis of the ability of a transport system to cope with a disaster is the demand and supply ratio, this ratio can start to vary in the impact phase. The way the network is built and the way demand is controlled both affect the demand and supply ratio and thus determine the ability to cope with a disaster.

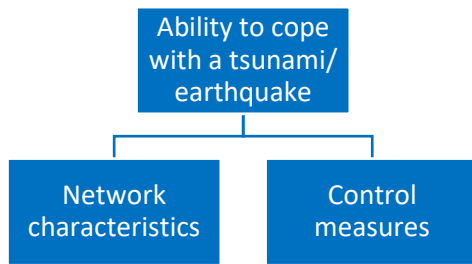


Figure 16: Decomposition of the "ability to cope with a disaster" block

The first subject of influence on the ability of the transport system to cope with disaster is “network characteristics”. This subject is divided into the network as a whole (network structure) and the infrastructure components that build up the network. This division is used because the infrastructure components tell something about the structural integrity of the network, while the network structure focuses on the topology of the network.

Because of its broad definition, “Infrastructure components” is further divided into the properties “Location”, “Capacity” and “Fragility”. Each component is located somewhere, has a certain capacity and fragility. The location is of importance for the disaster impact. When a component is located higher, or surrounded by defensive structures, it is less likely to be inundated and damaged by water. The capacity determines the amount of people that can use that part of the infrastructure during a period of time and is relevant for the evacuation capability in case of a disaster. The fragility of a component gives the probability of failure for a component type subject to disaster forces and is determined by the type of component (for example a bridge or a tunnel), the modality that uses it (for example a train or a car), the quality of that component (for example a steel bridge that is maintained well) and the disaster forces (Department of Homeland Security and the Federal Emergency Management Agency, 2017b). The force of the disaster is already included in the “disaster tree” in Figure 15.

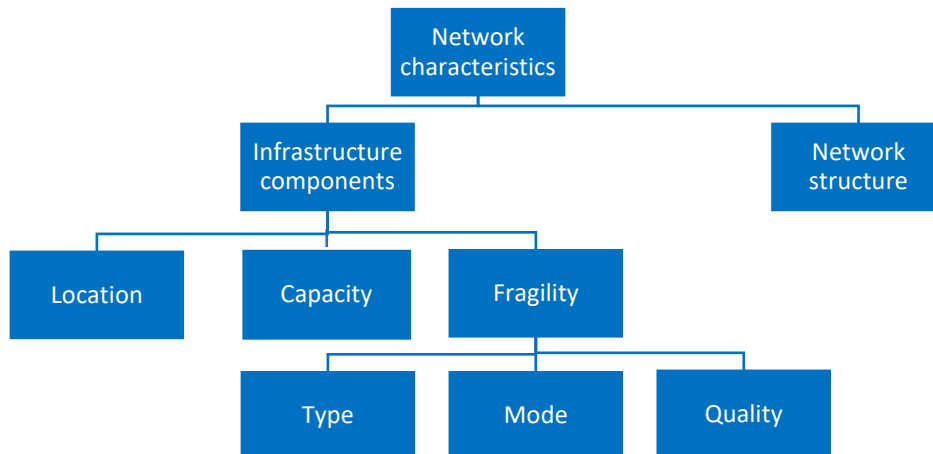


Figure 17: Decomposition of "Network characteristics"

The other subject that affects the ability to cope with a disaster is “control measures”. These are measures taken during the impact phase to manage the demand. During the impact phase there are two different flows: a flow out of the disaster area (outbound) and a flow into the disaster area (inbound). The outbound movement is the evacuation of people to safer areas. The inbound flow consists of emergency services.

Several subjects are of influence on the manner of evacuation. Firstly, the proximity to evacuation locations. Do people need to travel inland, and if so what are the distances, or are there safe locations close by? The second subject is the location of people. Depending on how many people are located where, evacuation can be planned for. If there are no people at the tsunami risky areas there is less to plan than in case it is densely populated. The final subject affecting the evacuation is the travel behavior of people. When planning for evacuation, knowing how many people will have to go from where to where is important, but in reality people behave differently than initially expected and often far from desirable. A painful example is what happened at Okawa primary school during the Great East Japan Earthquake. Teachers misjudged the disaster and decided not to evacuate to higher ground, but to an open area, following the procedure for an earthquake. This caused the death of most teachers and pupils because the open area inundated (The Economist, 2017). According to van den Berg (2016) the travel behavior of people during an evacuation is dependent on three subjects; information, personal context and the choice options that are available to people. Information means: do people know what is going on? Do they know there is a warning and they should evacuate? Do they know where to evacuate to? Personal context encompasses socio-economic data such as gender, education level and income but also the personal experience of people with disasters. People who have experienced a tsunami before are likely to evacuate sooner than people who have not (Charnkol & Tanaboriboon, 2006). The final aspect is called choice options and consists of the possibilities for people to evacuate. This includes possible routes, which can be different than usual due to damages from the earthquake, and modes the person has access to.

The inbound flow during the disaster phase consists of emergency services trying to help people in the impacted area, either by providing medical aid or by helping them evacuate the area. There are three subjects of influence on the functioning of emergency services. The first is the location of emergency services; where are they located and how are they spread through the area of study? The second is the proximity to the disaster area; how far do the emergency services need to travel before they have accessed the area where they are needed? The last subject is the accessibility of the area. When an area has been impacted by a disaster the area will be covered in debris making it more difficult for emergency services to reach the area.

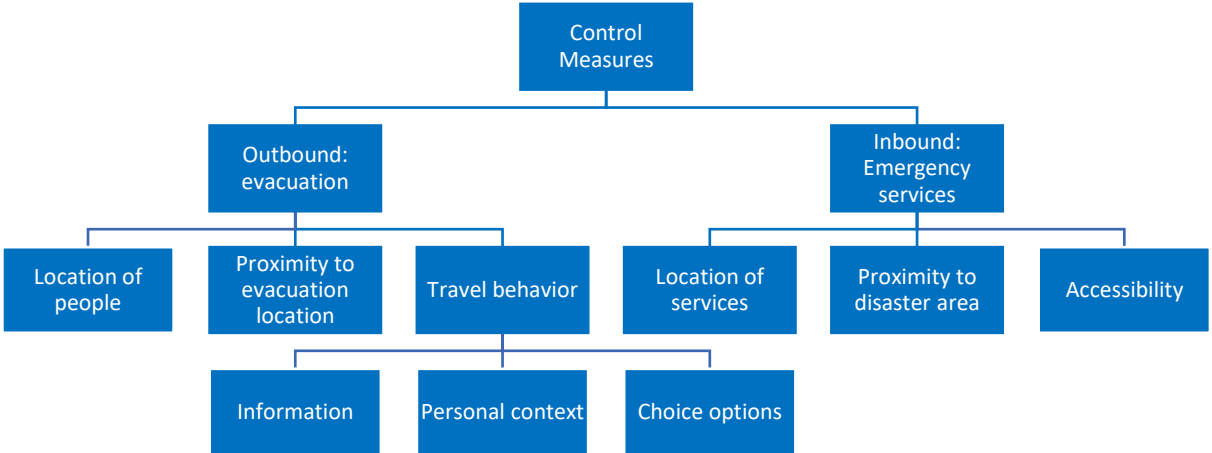


Figure 18: Decomposition of "control measures"

5.1.2.3 Recovery phase: decomposition of the "resources" block

When the disaster has happened and the degradation of performance has stopped, the recovery phase starts. The rapidity of recovery depends on two factors: resources and the ability to recover from a disaster. Without resources it is not possible to repair damages, even when the system itself is easy to

repair. When there are resources but the system itself is difficult or impossible to recover, there is also no recovery.

Resources are divided into people and materials. A combination of the two is necessary to allow for recovery. For people three different subjects are of importance. The first is the location of people, from where to where do they need to go? Can they access the area they need to go to? The second subject is the number of people. Although there may be an optimum for the number of people required during the recovery phase, in general it is to be expected that with more people it becomes easier to recover. The third subject is the level of skill of the people. Depending on the recovery efforts and tasks to be performed, people need to have a certain set of skills. Not everyone is able to repair a bridge, but most people are able to help clear debris.

Materials are divided largely into the same subjects as people, with the same argumentation. The only difference is “properties of material”. It could be that there is plenty of material available of a lesser quality than ideal. Then a tradeoff must be made, is it worth to wait for the higher quality material? Or can recovery start with the initially available materials and increase the quality later?

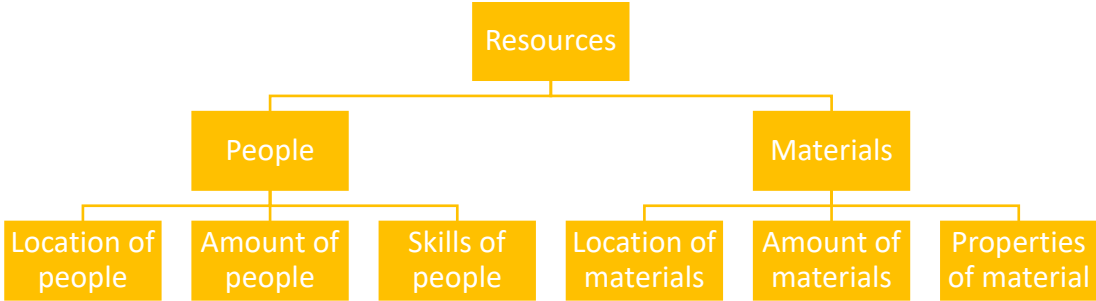


Figure 19: Decomposition of "Resources"

5.1.2.4 Recovery phase: decomposition of the “ability to recover after a disaster” block

The final block is the ability to recover after a disaster. Together with the resources it determines the course of recovery for the impacted transport system. The ability to recover is divided into two recovery types; the short and the long term. While the long-term recovery focusses on restoring the original level of functioning of the transport system over a long period of time (months or even years), the short-term recovery focusses on recovery efforts for a shorter period of time (weeks) that help to increase the functioning of the system until recovery efforts on the long term can start. Short term recovery also includes supplying the disaster area with relief goods. So short term recovery consists of the supply of relief goods and a factor called “preparedness”. Prepared means that in case an earthquake or tsunami occurs, it is known who is responsible for what. In case of a disaster, transferring more authority to lower level governments is a means to speed up recovery (UNISDR, 2017). The long-term recovery consists of resource allocation, governance and restorative ability. Resource allocation means the allocating of resources (materials and people) to the right place at the right time, aiming to minimize the recovery time. Governance means the governmental structure of the area of study. For example, Japan has a reconstruction agency focused on the recovery of the Tohoku region (Reconstruction Agency, n.d.). However, bureaucratic practices caused difficulties for municipalities applying for funding for recovery (see Appendix A). The restorative ability means how fast infrastructure components can recover from damages. Some infrastructure components can be repaired faster than others.

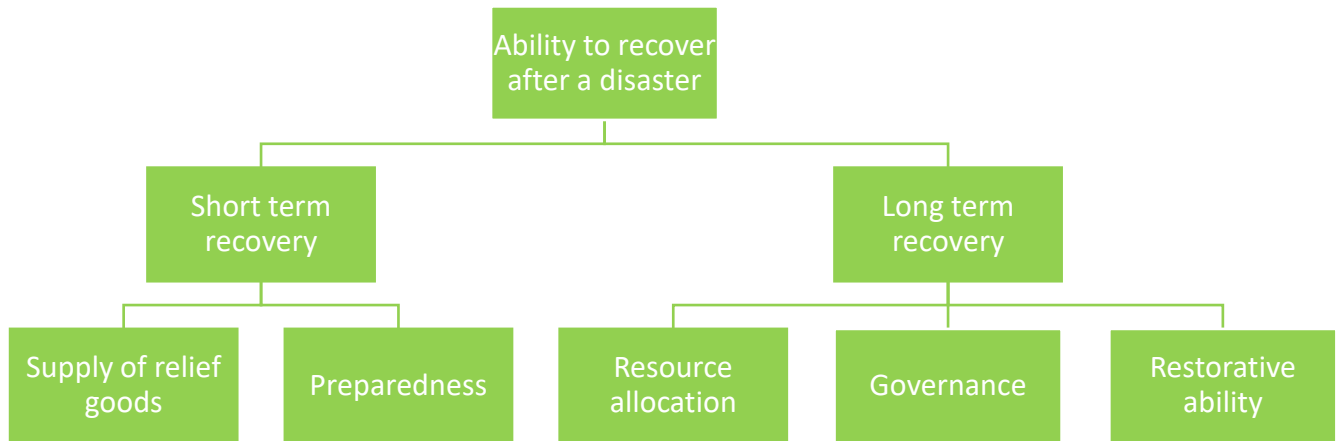


Figure 20: Decomposition of "ability to recover after a disaster"

5.2 Measuring tsunami resiliency factors

The previous section led to an overview of factors related to the tsunami resiliency of a transport system. This section will use those factors as a starting point and explain how they can be assessed and what would be desirable outcomes per factor. This will be done in the same order as the previous section; starting with the impact phase, followed by the recovery phase. Each subsection will start with an overview of the relevant factors summarized in a table. This is followed by a more detailed explanation about the measuring of that factor and what will lead to the highest and lowest score for that factor. Each subsection will conclude with checklists consisting of questions to answer and actions to follow to be able to score the factors.

5.2.1 Impact related factors

5.2.1.1 Disaster – factors

Table 2 gives an overview of the factors derived by the decomposition in the previous section. The factors are listed together with their meaning and a measurement.

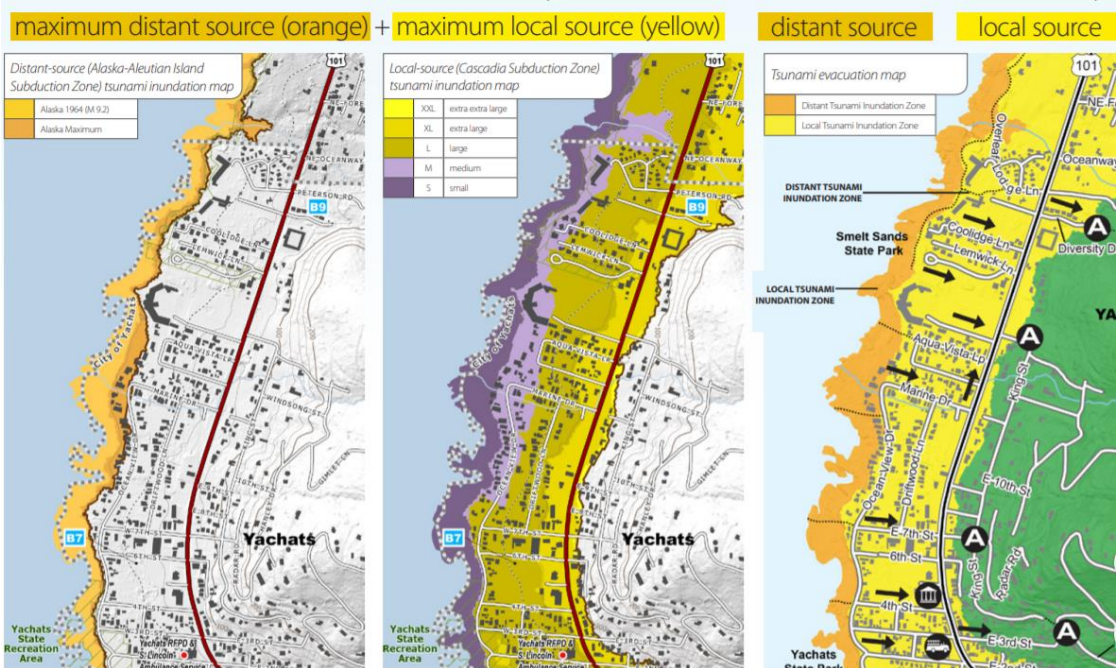
Table 2: Disaster related factors

Factor	Meaning	Measurement
Tsunami force	The force of the water that impacts the area.	Flow speed, hydrodynamic force.
Tsunami warning time	Time between sensing the tsunami and the impact of the tsunami.	Time in minutes or hours.
Inundated area	The area that is inundated after a tsunami.	Static map of the area showing inundation areas.
Earthquake force	The force of the earthquake that impacts the area.	Peak Ground Acceleration, Peak Ground Deformation, Peak Ground Displacement, Spectral Acceleration.
Earthquake warning time	Time between sensing the earthquake and the impact of the earthquake.	Time in seconds between sensing the P-wave and S-wave.

The tsunami and earthquake forces are relevant because of its impact on the physical transport system. The force of the wave can destroy the built environment. This will be explained further on page 33. The tsunami and earthquake forces and inundated area are not directly needed to assess the tsunami resiliency of transport systems. The forces are relevant in the determining of the fragility, but on their own say nothing about resiliency of a transport system. The inundated area itself also says nothing about the resiliency of the transport system, but it provides the information to determine whether the transport system suffers from inundation. The forces and inundated area are therefore not needed to score separately.

Warnings for tsunamis and earthquakes help to decrease the impact of the disasters. They are generated by warning systems that consist of sensors and a communication system to distribute the warning (Yamamoto & Tomori, 2013). When a tsunami warning is issued, it enables people to evacuate the area. In case of an earthquake warning, evacuation is not possible, but it enables to stop trains to avoid derailments and thus damages and loss of life. The sooner a warning is given the better because it gives more time to evacuate or take other actions.

The inundated area (partly) determines the impact on the transport system in the sense that if infrastructure components are inundated, they are not usable. Inundation maps can be created by combining characteristics of the area with tsunami scenarios. In the example in Figure 21, two inundation maps are combined into an evacuation map for Cannon Beach, Oregon. The map on the left shows two different scenarios, the first being based upon the actual tsunami that occurred in Alaska in 1964 and the second one based on the worst case scenario. The orange areas show what areas would be inundated in those scenarios. The map in the middle shows five different tsunami scenarios with a source close to Oregon. The S-M-L-XL-XXL classification is based on the magnitude of the earthquake causing the tsunami and the life cycle of such an earthquake, an S classification meaning a tsunami caused by an earthquake with a recurrence rate of about 300 years of ~8.7 Mw and an XXL classification meaning an earthquake with a recurrence rate of about 1200 years of ~9.1 Mw (State of Oregon, 2013).



5.2.1.2 Ability to cope with a disaster – factors

This subsection will describe the measuring of the related factors for the ability cope with a disaster.

Infrastructure components

Table 3 gives an overview of the factors related to the infrastructure components.

Table 3: Infrastructure component related factors

Factor	Meaning	Measurement
Location	Location of an infrastructure component. Tells something about the height of the component compared to the expected inundation depth.	Height above inundation depth.
Capacity	Capacity of the infrastructure. How many people can make use of that part during a time period.	People or vehicles per hour.
Fragility	Fragility of an infrastructure component. Shows the probability of failure when subjected to a range of forces.	Probability of structural failure for a given force.

The location of the infrastructure, combined with the inundation maps provide information about inundation of the component. When the infrastructure is located on higher ground or is protected by defensive structures, it is less likely to be inundated. By putting a map which depicts the transport system on the inundation map, it can be derived what components will be inundated and which will not. The best score is in the case no infrastructure components will be inundated, the worst score is the scenario where all infrastructure is inundated in case of a tsunami.

The capacity of the infrastructure gives the supply. The capacity of an infrastructure component can change due to the disaster. For instance a road can be damaged in such a way that only a quarter of the capacity can be reached compared with the capacity before the disaster. This capacity measure is about the capacity prior to the disaster in order to analyze whether the capacity of the existing infrastructure is sufficient to accommodate for evacuation. It should be kept in mind that the capacity can be influenced because of the disaster. Take for example a bridge, this bridge can have enough capacity to accommodate for a large amount of people, but when the bridge collapses suddenly the capacity becomes zero causing difficulties for evacuees. The best case would be sufficient capacity that allows evacuation within the time between the tsunami warning and the arrival of the tsunami, the worst case would be insufficient capacity during day to day use.

Every infrastructure component has a certain fragility towards disasters. In risk and hazard analyses fragility functions or curves are used to predict the damage of a natural hazard on the built environment. These curves are graphs which give the probability of sustaining or exceeding a certain level of damage in a structure (Koutsourelakis, 2010). An illustration to explain the fragility function is given in Figure 22. The horizontal axis represents an earthquake measure, in this case “weak”, “medium” or “strong” shaking. The vertical axis shows the probability that the building type will reach a certain damage state. So with weak shaking the chance is very high that there will be slight damage and an extremely low probability of moderate damage. Such curves exist for seismic forces and the force of tsunami water. Obviously the fragility function is dependent on the definition of damage states and the way the building is designed and constructed (Department of Homeland Security and the

Federal Emergency Management Agency, 2017b). It is not necessary to be able to make these curves in order to use the tsunami resiliency assessment method. Fragility curves can be used to assess the impact of a disaster on the structural integrity of the transport system. For more detailed information about the developing of such curves, see (Shinozuka, Member, Lee, & Naganuma, 2000).

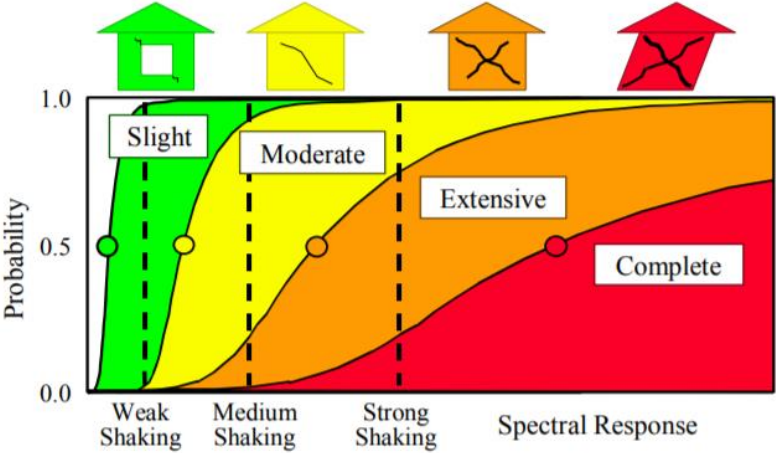


Figure 22: Explanation of a fragility function. Source: (Department of Homeland Security and the Federal Emergency Management Agency, 2017a)

An example of what the fragility functions can lead to is given in Table 4. It shows what damage can be expected for buildings and boats with a tsunami of different intensities.

Table 4: Damage scale of buildings and boats subjected to a tsunami. (Koshimura, Namegaya, & Yanagisawa, 2009)

Tsunami intensity	0	1	2	3	4	5
Tsunami height (m)	1	2	4	8	16	32
Damage : wooden house	partly damaged	completely destroyed				
Damage : masonry house	withstand		no data	completely destroyed		
Damage : reinforced concrete building	withstand			no data		completely destroyed
Damage : fishing boats		damage	50% damage	completely damaged		

Such an overview can be made for transport system components specifically and should consists of all the different components (per mode and type, for instance “railway bridge”) that exist in the transport system of study. The best case would be a small chance (10% maximum) on minor damages with the expected seismic forces. The worst case would be a high chance (75% or higher) on severe or complete damage with the expected seismic forces for the area.

Network structure

Besides the infrastructure, the network itself also affects the resiliency of the transport system.

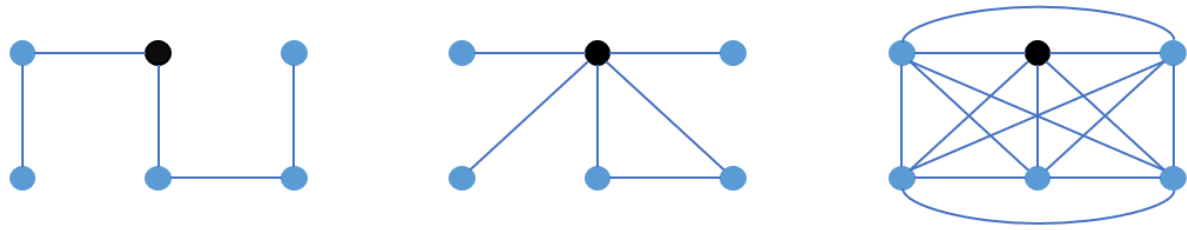


Figure 23: Three different network structures

When looking at the example networks above in Figure 23, the network on the left has the highest average path and the lowest average node degree. The network in the middle has a slightly lower average path and higher node degree. The network on the right is fully connected and has the lowest shortest path and the highest average node degree. When in all cases the black node becomes unusable this means that it is no longer possible to travel through this node. The left and middle network are split; it becomes impossible to travel from for example the node on the bottom left to the top right. The network on the right suffers less from the unusable node; it is still possible to travel from every node to every other node except the destroyed one. The network on the right is more resilient than the two other ones. Analyzing the effect of a broken link on the total structure is also possible. The network on the left is broken in two as soon as one link is unusable. The network in the middle can suffer a larger impact, if one link is destroyed one node can become isolated, but the rest of the network is still well usable. The network on the right suffers almost no impact since every node can still access all the other ones by using a different route. The best case situation would be a network as the network on the right, having a high level of redundancy. The worst case would be a linear network for the road and rail network and only one node for the air and water networks.

Evacuation

The factors contributing to the effectiveness of evacuation are listed in Table 5.

Table 5: Evacuation related factors

Factor	Meaning	Measurement
Location of people	Where are people located throughout the day?	OD-matrices.
Proximity to evacuation	Distance people need to travel when evacuating to a safe area.	Distance in (kilo)meters between the location of people at the moment of the evacuation warning and the location of the closest safe location.
Travel behavior	How people behave during an evacuation. Includes the decision to evacuate, when to evacuate, how to evacuate and where to.	Qualitative and based on the information available, personal context and choice options.

The first factor is the location of people. This factor determines the whereabouts of people throughout the day and is determined by the locations of residential and business areas. Precise numbers can be derived from OD matrices. A more general approach is by analyzing satellite pictures to determine which areas are residential or business areas. The best case would be that no residential or business

areas are located within the inundated area. The worst case would be that during the night and during the day people are located within the inundated areas.

The second factor is the proximity of people to an evacuation location. Together with the travel speed in theory this determines the time it takes for evacuation. If the evacuation time is shorter than the time between the tsunami warning and the tsunami impact it means that people have enough time to evacuate. Evacuation locations can be located further inland, but it is also possible to evacuate to designated tsunami evacuation buildings. In order to calculate the evacuation distance it is necessary to know what the starting point of the evacuation is (see the previous step) and to where they need to evacuate. The best case would be if people are able to evacuate to a safe area within 5 minutes. The worst case would be that safe locations are so far away that a safe locations cannot be accessed by car in time.

Not only distance and speed but also the behavior of people affects the evacuation time. This is a lot harder to assess. According to van den Berg (2016) different aspects influence the evacuation behavior; information, personal context and the choice options they have. These three aspects are included as factors contributing to the evacuation behavior. The best case for information is a good supply of information, giving people a warning telling them to evacuate, signs showing where to go and how to go there. The worst case would be if no information is available at all and people are surprised by the disaster and do not know what to do. The best case for personal context is to be a young person living alone (Okumura & Kim, 2018). The worst case would be an elder person or someone who is foreign to the area. The best case for choice options would be multiple routes available with more than one mode, the worst case is to have no evacuation routes available at all.

[Emergency services](#)

The factors contributing to the effectiveness of emergency services are listed in Table 6.

Table 6: Emergency services related factors

Factor	Meaning	Measurement
Location of emergency services	Place where emergency services are located and dispatch from in case of a disaster.	Location on map
Proximity to disaster area	Distance emergency services need to travel before reaching the impacted area.	Distance (km) between dispatch facility of emergency services and place they are needed.
Accessibility	Ease of access for emergency services to reach the impacted area.	Qualitative and based on the network that is left after the disaster impact.

The first factor affecting the effectiveness of emergency services is the place where they are located. If an emergency service location is at an inundated area in case of a tsunami, this will likely impact the functioning of the emergency services. The best case would be that all emergency services are located such that none of the locations will be inundated in case of a tsunami. The worst case would be that all emergency service locations will be inundated in case of a tsunami.

The proximity to the disaster area is the distance between the emergency service location and the disaster area. If the emergency services have to travel long distances before reaching the disaster area where they are needed, they are likely to function less effective than when the distance is shorter. The

best case would be if emergency services were located within the disaster area. The worst case would be if they are located far away from the disaster area.

The accessibility is the last factor determining the functioning of emergency services and says something about the ease of access for the services to reach the impacted area. In case an earthquake has destroyed several bridges necessary to reach the disaster area, the ease of access is compromised. The best case would be if the accessibility of the area between the emergency service and disaster location is not affected by the disaster and emergency services can easily reach the disaster area. The opposite case is the worst case; the routes between the emergency services and disaster location are unusable and the disaster location is inaccessible.

5.2.2 Recovery related factors

This subsection describes the factors related to recovery.

5.2.2.1 Resources – factors

The factors determining the resource block are listed in Table 7.

Table 7: Resource related factors

Factor	Meaning	Measurement
Location of resources	Where resources are located, and how far that is from the impact area.	Distance (km) between storage and place they are needed.
Amount of resources	Number of people and amount of materials.	Number of people Kg or number of materials
Skills of people	Skills can vary from planning to clearing debris and building highways.	Qualitative
Properties of material	Type of material	Qualitative

The first factor is the location of resources. This factor tells where recovery related materials and people need to come from. When repairs need to be made raw materials are needed, where do they usually come from? Would it be possible to perform major repairs with the resources from this location or are other locations needed as well? The second factor is the amount of resources, so the number of people and amount of materials available. The third factor is the skill of the available people, besides manpower there is also a need for planners and technical people who know how to rebuild a bridge for example. The last factor is ‘properties of material’ which says something about the quality and type of material. There can be a shortage on asphalt for example, but there are wooden plates available that might serve as a substitute for a short time. The combination of the location, amount and properties/skills of resources determines how well this factor scores. The best score is given to sufficient people or materials, with the right properties or skills, on the right location. The worst score is given when no people or materials are available not matter their properties or skills.

5.2.2.2 Ability to recover – factors

The factors determining the ability to recover are listed in Table 8.

Table 8: Ability to recover related factors

Factor	Meaning	Measurement
Supply of relief goods	How easy and fast relief goods can be gathered and reach the	Accessibility

	disaster area, and be distributed in the disaster area.	
Preparedness	A short term disaster plan.	Qualitative
Resource allocation	The allocating of materials and people to recovery efforts.	Optimization
Governance	The political structure of an area. Partly overlaps with preparedness, but looks at the long term.	Qualitative
Restorative ability	Ability of an infrastructure component to recover to full functioning after suffering damage.	Restoration curves/functions

The first factor is the supply of relief goods. Directly after the impact phase, the most important function for the transport system to fulfill is to supply people in the disaster area with medicine, water, food and any other supplies they are in need of. This factor can be assessed by determining the damage to the transport system to see if the disaster area is still accessible and how easily goods can be distributed after reaching the disaster area. If the accessibility of the area (to the area and within the area) is not decreased, the highest score is given. In case the area cannot be accessed anymore, the lowest score is given.

The preparedness factor means whether there is a short term disaster plan, so that in case of a disaster the relevant governments know who is in charge of what and can immediately take action. During the GEJE for example, within 30 minutes after the first shock, the 'Extreme disaster management headquarters' was established coordinating emergency operations on different governmental levels (Suzuki & Kaneko, 2013). The lowest score is given when no disaster is considered at all. The highest score is given when an area has prepared for a disaster and has well thought out plans for multiple disaster scenarios.

The resource allocation is related to the resources but is not about the physical resources, but the planning of those resources. An example of efficient allocation can be that with the available resources in the disaster area the access point of the area such as an airport are repaired first in order to bring in more resources.

The governance of an area is only possible to assess qualitatively and generally in this research. It says something about the governmental structure of an area in general and in disaster periods. Governments react differently on disasters and this has an effect on the recovery (Johnson & Olshansky, 2016). The worst case scenario would be when the governance actively prevents recovering of the transport system, the best case would be when the governance allows for efficient recovery of the transport system.

The restorative ability is a factor that gives the recovering time per infrastructure components. Some components recover faster than other because they are simpler to repair, or easier to access. The recovery time per infrastructure component is predicted in the Hazus tool from FEMA by means of restoration curves or functions (Department of Homeland Security and the Federal Emergency Management Agency, 2017b). Empirical data of recovery of infrastructure components after past natural disasters is used to estimate the time it takes for specific infrastructure components to be fully functional again (Department of Homeland Security and the Federal Emergency Management Agency, 2017b; Okumura & Kim, 2018). The highest score is given in case all infrastructure components are

fully functional within one week. The lowest score is given when it takes longer than three months for all infrastructure components to be fully functional again.

5.3 Assessing tsunami resiliency factors

This section will give the overview of the tsunami resiliency factors and a qualitative range to score the factors on. The previous section already gave the best and worst case example for each factor. These opposites will be used for the score of 1 (worst case) and 5 (best case), this section will describe what corresponds to the scores of 2, 3 and 4 by means of four matrices matching the four main themes as described in the first section of this chapter: disaster, ability to cope with a disaster, resources and the ability to recover after a disaster.

5.3.1 Assessing disaster related factors

The decomposition of the disaster into smaller factors lead to five different tsunami or earthquake related factors: tsunami force, tsunami warning time, inundated area, earthquake force and earthquake warning time. As explained in the previous section in this chapter, the forces and inundated area are of importance to know, but do not need to be assessed in this part. They will be used as input to assess the ability to cope with a disaster in the next section. The two factors that remain are the tsunami warning time and the earthquake warning time. Tsunami and earthquake warning time can be scored based on whether there is a warning system and whether it functions properly. Questions to answer in order to fill in Table 9 and Table 12 are summarized in a checklist format, seen in Figure 24.

Checklist for disaster

- What is the tsunami force that can be expected in the area of study?
- Is there a warning system for tsunamis?
- How much warning time is there in which scenario?
- How long does it take for the warning to reach people that need to evacuate?
- Does the warning system function properly? (Look into past warnings)
- What area is inundated in which scenario?
- Is there a warning system for earthquakes?
- Is it linked to the transport system?
- What is the earthquake force that can be expected in the area of study?

Figure 24: Checklist for assessing disaster factors

Table 9: Assessment matrix for 'disaster'

	1	2	3	4	5
Tsunami warning time	No warning system in place.	Malfunctioning warning system. System sometimes sends warnings in case there is no tsunami.	Functioning sensing system in place that is capable of sensing a tsunami but is slow in the communication of the danger.	Functioning sensing system in place that does not immediately recognizes tsunami danger, but is capable of communicating the warning as soon as the danger is recognized.	Functioning sensing system in place, capable of sensing a tsunami and communicating the warning
Earthquake warning time	No warning system in place.	Warning system in place that has a low reliability of passing the warning.	Warning system in place but not connected to transport control.	Warning system in place, that can sense seismic activity but the communication to transport control takes a long time.	Well-functioning warning system in place that can sense seismic activity and communicate the warning to transport control.

5.3.2 Assessing 'ability to cope with a disaster' factors

The decomposition of the ability to cope with a disaster block led to several factors which are explained in the previous section of this chapter. The assessment matrix for this building block is split up in order to clarify it. Again, a checklist precedes the matrix that needs to be filled in. The actions to take in order to fill in Table 10 are summarized in a checklist format, seen in Figure 25.

Checklist infrastructure location

- Make a map showing the infrastructure, if possible with all modalities on one map
- Combine with the inundation maps
- Determine what parts of the transport system become inundated in case of a tsunami
- Make an update of the transport system which excludes unusable parts

Figure 25: Checklist for assessing the factor 'infrastructure location'

Table 10: Assessment matrix for 'location'

	1	2	3	4	5
Location	All infrastructure components will be inundated.	75% of infrastructural components are inundated	50% of infrastructural components are inundated	25% of infrastructure components are inundated	No infrastructure will be inundated in case of a tsunami.

The questions to answer in order to fill in Table 11 are summarized in a checklist format, seen in Figure 26.

Checklist infrastructure capacity

- Which components are most likely to be used during an evacuation?
- Is the capacity sufficient under normal circumstances?
- What problems arise in case of damage or destruction?

Figure 26: Checklist for assessing the factor 'infrastructure capacity'

Table 11: Assessment matrix for 'capacity'

	1	2	3	4	5
Capacity	Capacity of the infrastructure is insufficient in normal use	Capacity of the infrastructure is mostly sufficient for normal use, there are some small exceptions	Capacity of the infrastructure is sufficient for normal use. Some bottlenecks may lead to major crowding in case of evacuation.	Capacity of the infrastructure is sufficient for normal use, but there are some bottlenecks leading to crowding in case of evacuation	Capacity of the infrastructure is sufficient in case of a disaster as well.

The questions to answer and actions to take in order to fill in Table 12 are summarized in a checklist format, seen in Figure 27.

Checklist infrastructure fragility

- What infrastructure components are part of the transport system?
- Determine the range applicable in the fragility curve
- Determine the components with the highest probability to suffer damages
- Look back at the capacity checklist, are there components crucial for evacuation that have a high probability of suffering damage?

Figure 27: Checklist for assessing the factor 'infrastructure fragility'

Table 12: Assessment matrix for 'fragility'

	1	2	3	4	5
Fragility	Infrastructure components have a probability of major damage higher than 75%	Infrastructure components have a probability of major damage between 50 and 75%	Infrastructure components have a probability of minor damages higher than 50%	Infrastructure components have a probability of minor damages between 10 and 30%	Infrastructure components have a probability of minor damages of less than 10%

The actions to take in order to fill in Table 13 are summarized in a checklist format, seen in Figure 28.

Network structure checklist

- Determine the network structure of the transport system
- Determine the vital nodes or links (have a high effect on the connectivity of the network)
- Look up vital nodes and links in the previously made fragility classification

Figure 28: Checklist for assessing the factor 'network structure'

Table 13: Assessment matrix for 'network structure'

	1	2	3	4	5
Network structure	less than 2 of the following: road and rail: Linear network air: only 1 airport water: only 1 port	Road and rail: linear network air: only 1 airport water: only 1 port	road and rail: linear network with some extra connections air: 1 airport water: 1 port	road and rail: medium connected network (multiple routes available between two points) air: 2 airports water: 2 ports	Road and rail: Highly connected network, high node degree. Air: 2 or more airports or helipads water: 2 or more ports

The questions to answer and actions to take in order to fill in Table 14 are summarized in a checklist format, seen in Figure 29. The personal context factor turned out to be impossible to develop a logical scoring range for. The best and worst cases could be found in literature, but which aspect had the largest impact on evacuation behavior was not found in literature. Therefore only the best and worst case values are given. The consequences of this will be elaborated on further in chapter X.

Checklist evacuation

- Determine the whereabouts of people during the day
- Determine age distribution
- Locate evacuation locations by means of height maps or evacuation plans
- Determine (static) evacuation time
- What information do people have?
 - Is there a warning system and do people know about it?
 - Is there a clear evacuation plan? (for instance road signs)
- Do people have experience with tsunamis?

Figure 29: Checklist for assessing the factors related to evacuation

Table 14: Assessment matrix for 'evacuation'

	1	2	3	4	5
Proximity to evacuation location	So far away that even when evacuating by car, safe location cannot be reached in time.	So far that evacuation by car is possible when there is no congestion	Allows evacuation on foot in less than 30 minutes	Close enough to allow evacuation on foot between 5 and 10 minutes.	Close enough to allow evacuation on foot in less than 5 minutes.

Location of people	Large number of people located in tsunami dangerous area at night and during the day.	Large number of people are in tsunami dangerous area during the day, small number of people located in tsunami dangerous area at night.	Large number of people are in tsunami dangerous areas (business area overlaps with tsunami dangerous area)	Small number of people are in tsunami dangerous areas during the day (for instance recreational areas, but no offices are located in tsunami dangerous areas)	No people are ever in the tsunami dangerous area.
Information	No means to know whether an area is safe or not. No signs. No maps. No warning.	No means to know whether an area is safe, no signs or maps, but a warning is given in case of a tsunami.	People know if they are in a risk area, but not where they should go in case of a warning.	Most information can be provided. There is a warning, people know if they are in a dangerous area and where to evacuate to. But they don't know how.	All information can be provided. A warning is given, people know if they have to evacuate and if so where to and how.
Personal context	Elderly, multiple person households, low income, ethnic minority, no experience with tsunamis				Young, single person households, high income and education, experienced with tsunamis
Choice options	No routes available	One route available, but no transportation means	More than one route available, but no transportation means	More than one route available, transportation means available	Multiple routes are available and multiple choices for mode

The questions to answer and actions to take in order to fill in Table 15 are summarized in a checklist format, seen in Figure 30.

Checklist emergency services

- Where do emergency services dispatch?
- How far away is the disaster area?
- Is the disaster area accessible by emergency services?
- Compare location of services with the impacted network structure that is previously made.

Figure 30: Checklist for assessing the emergency services related factors

Table 15: Assessment matrix for 'emergency services'

	1	2	3	4	5
Location of emergency services	Emergency services are all located in areas likely to inundate	75% of the locations will be inundated	50% of the locations will be inundated	no more than 25% of the locations will be inundated	Emergency services are spread over the area and none will be inundated.
Proximity to disaster area	Emergency services are not located within 10 km	Emergency services are located between 1 and 10 km of the disaster area.	Emergency services are located within 1 km of the disaster area.	Most emergency services are located throughout the disaster area, one	Emergency services are located throughout the disaster area

	of the disaster area.			type is located further away.	
Accessibility of the disaster area	Earthquake and tsunami have destroyed all access to the disaster area.	Only possible to access the disaster area via air.	Possible to access the disaster area via roads, but with access is very difficult due to large damages.	Possible to access the disaster area via roads, but with increased travel times due to damages and decreased capacity on the roads	Disaster had no impact on the accessibility between the emergency dispatch and the disaster area.

5.3.3 Assessing 'resources' factors

The decomposition of the resources block led to several factors which are explained in section 5.1. Again, a checklist precedes the matrix that needs to be filled in. The questions to answer in order to fill in Table 16 are summarized in a checklist format, seen in Figure 31.

Checklist resources

- Is the area of study dependent on other areas for their resources?
- In case resources are imported, from where?
- What amount of resources can be imported in what amount of time?
- What quality do the 'quickly available' resources have? Can they be used for initial repairs?
- What type of people live in the area of study? Are they sufficient for recovery efforts or are extra people needed?
- What is the economic situation of the area of study?

Figure 31: Checklist for assessing the resource factors

Table 16: Assessment matrix for 'resources'

	1	2	3	4	5
Location, amount and skills of people	No people available for recovery.	People are available, but they lack the proper skills for rebuilding.	Sufficient number of people are available but a limited number of skillful people available	Insufficient number of people directly available.	Sufficient number of people directly available.
Location, amount and properties of materials	No materials available with any recovering properties.	insufficient amount of materials available and of a lesser quality than ideal.	Materials are available, but of a lesser quality than ideal.	Insufficient amount of materials available with the right properties	Sufficient amount of materials available with the right properties.

5.3.4 Assessing 'ability to recover from a disaster' factors

The decomposition of the 'ability to recover from a disaster' block led to several factors which are explained in section 5.1. Again, a checklist precedes the matrix that needs to be filled in, visible in Figure 32. Three factors are missing the 5-step scoring range and only have the value of 1 and 5

represented. These factors proved to be impossible to develop a logical and consistent scale for within this thesis. This is elaborated on further in chapter 7 and 8.

Checklist ability to recover

- Is the disaster area still accessible after a tsunami and earthquake?
- Is it possible to distribute relief goods within the disaster area?
- Is there a disaster plan including who is responsible for what in case of a disaster?
- How can resources be allocated most efficiently? (think about access point within the area and accessibility within the area itself)
- What is the political structure of the area? Very bureaucratic? Efficient? Clear?
- Look up the recovery times of infrastructure components in the restoration functions.

Figure 32: Checklist for assessing the ability to recover factors

Table 17: Assessment matrix for 'ability to recover after a disaster'

	1	2	3	4	5
Supply of relief goods	Not possible to supply the disaster area with relief goods due to damaged access points ((air)ports, roads)	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods within the disaster area is not possible because of damaged roads.	Possible to supply the disaster area with sufficient relief goods. Access points are usable, but distributing is difficult due to damaged roads.	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods is possible because the roads are usable.	Possible to supply the disaster area with sufficient relief goods. Access points are still usable, from there relief goods can be distributed relatively easily within the disaster area.
Preparedness	Tsunami or earthquake is never considered, and no disaster plans exist.				Tsunamis or earthquakes are planned for. Disaster plan is thought through, consists of multiple scenarios so in case of a disaster no time has to be wasted on who has to do what.
Resource allocation	No planning is used at all. Resources are allocated randomly.				Based on damage overviews and resources available, recovery time is minimized.
Governance	Governance prevents recovering activities.				Governance enables recovering activities.

5.3.5 Using the assessment method

The previous subsections provided checklists and assessment matrices that enable the assessing of the tsunami resiliency of a transport system. Depending on the amount of time and resources available, the assessment method can be slightly adjusted in use.

The general recommendation for the use of the assessment is to start with a rough analysis such as the one performed in the next chapter. When collecting the required data for filling in the assessment matrix it will become clear if factors require a more in depth analysis before being able to score it. All necessary data could already be available, if this is not the case a trade off must be made. The factors that can be filled in with the data available could be sufficient for the purpose of the assessment. When an in depth analysis is wanted, the choice can be made to divide the matrices based per theme – or even per factor - to let an expert or expert team assess them.

When the assessment matrix is filled in, this provides an overview of factors and their scoring. However it is good to keep in mind that this does not directly lead to a plan for improvements. The assessment method as it is now is still simplistic. For example, it does not take weights for factors into account and the costs of increasing the score of a factor are not known. It is therefore not possible to determine whether a score of 4 on one factor is better than a score of 3 on another, which factor should be increased in score to have the biggest impact on the tsunami resiliency or what would be the most cost effective plan to increase tsunami resiliency.

5.4 Conclusion

This chapter derived the factors having an effect on the tsunami resiliency of transport systems. The overview of all tsunami resiliency related factors for transport systems is given in Appendix B together with how they can be measured and what the best and worst case scenarios for this factor would be. These best and worst case examples are used as the extreme values for the assessment matrix. All factors are included and given a 5-step scale in order to score the factors. A checklist precedes the assessment matrix per theme and provides the actions to take and questions to answer to be able to fill in the matrix.

6. Demonstrate the assessment method: case study Oahu

The previous chapter gave a set of factors that have an effect on the tsunami resiliency of a transport system along with a scoring range in order to assess them. This chapter will demonstrate how the assessment method is used on the island of Oahu. The choice for this island is made because it has experienced tsunamis before, has different modalities, is clear to scope and an initial search provided enough data to be able to perform at least a rough analysis. The sections are based on the four blocks from the previous chapter: disaster, ability to cope, resources and ability to recover. Each section will start with the factors relevant for that block, followed by the relevant analysis or information to score the factor. The scores of the factors, along with the argumentation, are visible in Appendix D.

6.1 Disaster

The factors determining the intensity of the disaster that are related to the disaster are;

- Tsunami force
- Tsunami warning time
- Earthquake force
- Earthquake warning time
- Inundated area

The choice is made to develop only one scenario due to the limited amount of data and the available time. To make sure the transport system is impacted and has to recover, the choice is made to develop a “worst case” scenario for Oahu.

Hawaii is known for its seismic activity because of its volcanoes. Oahu has also experienced earthquakes, but the most intense shaking usually occurs at Hawaii island itself (Cox, 1986). The intensity usually decreases as the earthquake propagates towards the other islands (Klein, Frankel, Mueller, Wesson, & Okubo, 2001). However, according to FEMA (n.d.) the island of Oahu can experience severe shaking causing damage to the built environment.

The disaster characteristics of the worst case scenario are listed in Table 18 below.

Table 18: Worst case disaster characteristics

Factor	Worst case scenario
Tsunami force	Large
Tsunami warning time	Several minutes
Earthquake force	Medium
Earthquake warning time	Several seconds
Inundated area	Major

Earthquake force is estimated in a PGA value by Klein et al. (2001) for the different regions of Hawaii. They estimated the 2% probability of exceedance in 50 years to be $2,65 \text{ m/s}^2$ for Oahu. The spectral acceleration at 1.0 second with a 2% probability of exceedance in 50 years is approximately 0.3 m/s^2 (USGS, n.d.). Estimates for peak ground deformation are not found. The inundated area for the two scenarios is estimated and displayed on an evacuation map visible in Figure 33. These evacuation maps show two zones which should be evacuated; one in case of a distant source tsunami causing minor inundation (red area) the other in case of a closer source tsunami causing a larger inundated area (yellow) and possibly damages due to the earthquake causing the tsunami. This scenario assumes the inundated area encompasses the entire red and yellow area.

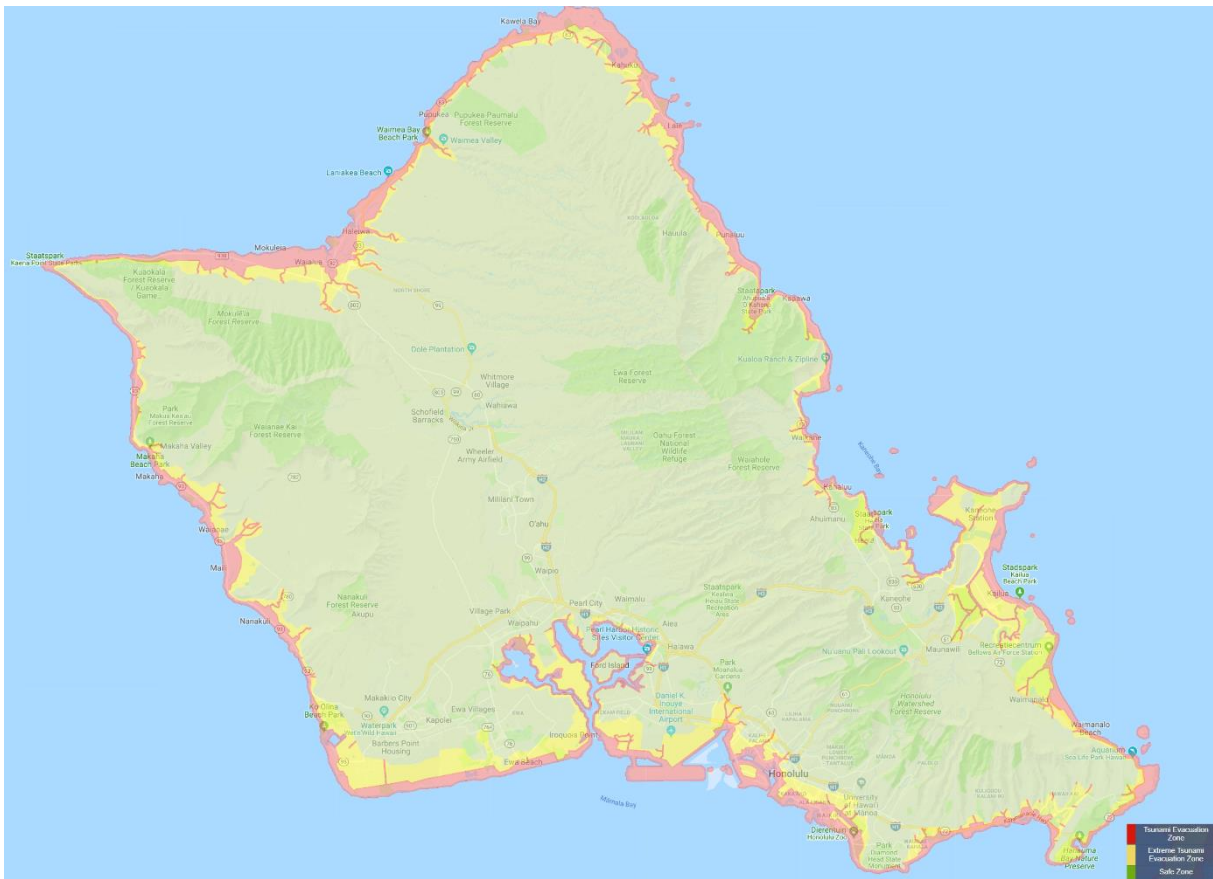


Figure 33: Tsunami evacuation map for Oahu Hawai'i. (NOAA Office for Coastal Management, 2015)

6.2 Ability to cope – Infrastructure components

6.2.1 Location

In order to perform an analysis on the different components of the infrastructure network and the network as a whole, the first step is to determine what networks there are and where they are located. A general overview is given in Figure 34. The roads marked in red are the highways, black indicates the smaller roads. The areas marked in bright blue (five in total) indicate airports, airfields or runways. Three can be found easily along the coast, one is located on the Kaneohe station (where the highway ends on the eastern side) and the last runway is located centrally on the island. Oahu has one major port, located east of the airport and one smaller port located on the west side and indicated by means of a yellow circle. There is no rail infrastructure on Oahu yet. The construction has started for a transit line connecting Honolulu to the airport, Pearl city, Waipahu and Ewa.



Figure 34: Overview of infrastructure network per mode

Road network

The road network of Oahu consists of highways and roads which is built up with roads itself, bridges and tunnels. The tunnels that are built, go through mountain ridges and have been bored and drilled and are located with a “T” on the map in Figure 34. No overview of the location of bridges was found, except for the ones clearly going over water. According to (Hawaii State Department of Transportation, 2016) there are 445 road bridges on Oahu of which bridges shorter than 20 feet and bridges that are not under the state jurisdiction are excluded. In 2015 5,3% of all bridges in the state of Hawaii (all the islands) were structurally deficient and 38,1% was functionally obsolete. Bridges are labeled structurally deficient in case light vehicles no longer are allowed to use them. Bridges are labeled functionally obsolete in case deck geometry, load carrying capacity, clearance or approach roadway alignment no longer meet the criteria for the system of which the bridge is a part (Hawaii State Department of Transportation, 2017).

Based on the location of cities and villages and the routes between them, a node/link network structure is created visible in Figure 35. To see the location of the nodes on the actual map of Oahu, see Figure 40 in Appendix C.

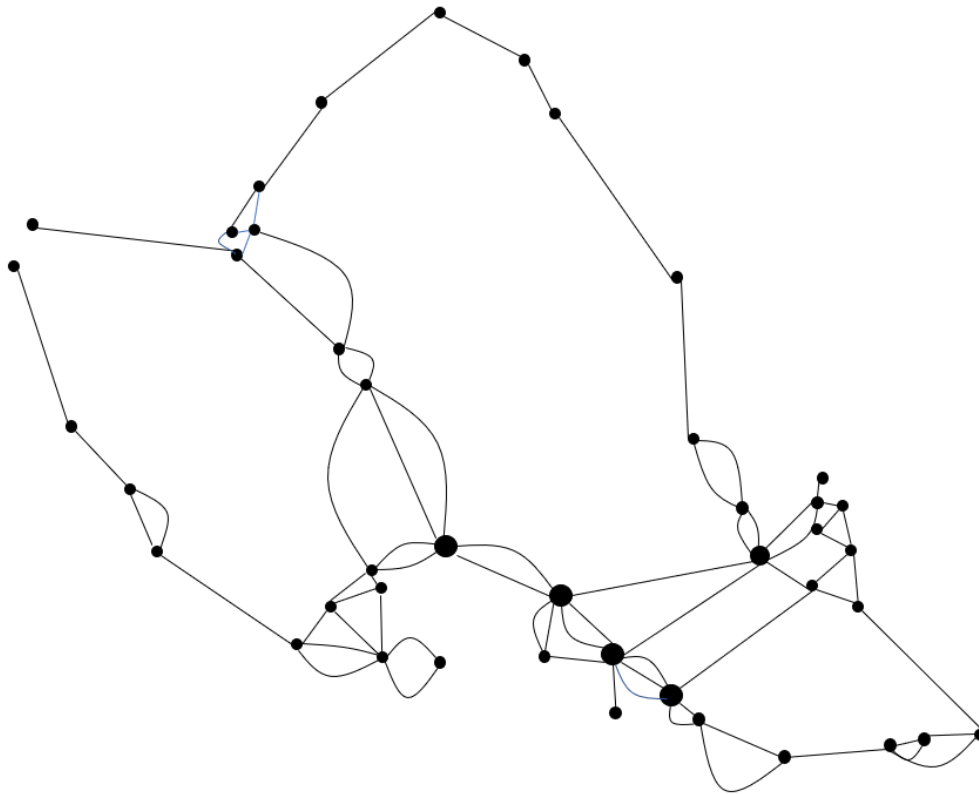


Figure 35: Road network structure Oahu

It can be seen that the network on the west/north/north east coast is linear and therefore there are less routes possible from the nodes in this area. The nodes located on the south coast have a higher node degree, enabling more route choices.

Air network

Oahu has five locations suitable for air transport. The largest location is Honolulu International Airport. In 2015 Honolulu International airport accommodated almost 20 million passengers and more than 400.000 tons of cargo (State of Hawaii Department of Transportation Airports Division, 2016).

Water network

Oahu has a port that accommodates for passenger and freight transportation. In 2016 over 6 billion kilograms of freight was imported and 837 million kilograms via water transport in Hawaii. No numbers were found on the import for Honolulu port, but it can be concluded that Oahu is dependent on water transport for imported freight (The State of Hawaii Databook, 2016).

6.2.2 Capacity

The capacity during regular functioning of Oahu's transport system is too few for the road network. Because of Oahu's geographical characteristics there are limited possibilities to build roads. The roads that form the road network do not have enough capacity to accommodate day to day traffic (Lohmann & Ngoc Nguyen, 2011). In case of an evacuation demand will be even higher leading to congestions in case of a car based evacuation.

This part of the analysis determines whether and where there are potential bottlenecks in case of an evacuation. Since there is no access to an evacuation model for the island of Oahu, there can be no precise predictions on the routes that people will take. Also no data was found on capacity for each

road section, so an alternative and more general analysis is performed to locate potentially risky areas. The following checklist is followed to determine whether an area is risky:

- Accommodates a large amount of people at any given time period (work/residential area)
- Area is inundated in case of a tsunami
- Limited number of routes available from the dangerous to a safe area

With these three criteria, six potentially risky areas are identified. A short explanation is given in the section below. The figures supporting the argument can be found in Appendix C.

- Sand Island is an island in front of the south coast connected with one bridge to the mainland of Oahu. The island is not residential but houses several business facilities such as a water treatment facility, a container terminal and car companies. The entire island must be evacuated in case of a close source tsunami, meaning if the tsunami happens during day time, all the people working at Sand Island have to evacuate to Oahu island. The distance from the central Sand Island to a safe area is almost four kilometers (approximately 40 minutes to walk and 8 minutes to drive). All evacuating traffic needs to use the only bridge of the island.
- Waikiki area is an area almost entirely surrounded by water. On one side there is the sea, on the other side a canal. The area consists of houses, hotels and businesses, meaning there will be people day and night. The entire Waikiki area has to evacuate in case of a close source tsunami. Evacuation can go in the eastern or western direction. When evacuating in the east direction, three bridges allow access in the direction of a safe area.
- Laie is a residential area and has a university. Evacuation distance can be around two kilometers without a clear road leading away from the dangerous area. In case people evacuate by car there is no clear place to evacuate to because the roads do not lead to a safe area.
- Iroquois point is a residential area consisting of many parallel roads connected by two perpendicular roads. This lay out can cause congestion in case of an evacuation.
- Kailua is a residential area surrounded by water, meaning it is only possible to leave the area by using bridges. In case some, or all, bridges are destroyed by an earthquake, it becomes impossible to leave the area or will cause capacity issues on the remaining bridges.
- Waimanalo beach is a residential area which is difficult to evacuate by car. There are only three points to leave the area on road. Evacuation on foot is possible because of its close location to higher area.

6.2.3 Seismic fragility of infrastructure components

As mentioned in the previous section, the road network of Oahu consists of roads and highways, bridges and tunnels. There are four large tunnels and 445 bridges. Of all Hawaiian bridges, 5% is structurally deficient and 38% is functionally obsolete. Generalizing those numbers for Oahu, this means 22 structurally deficient and 169 functionally obsolete bridges. These are more likely to suffer damage than bridges of higher quality. There was no quality data to be found for the tunnels.

The estimated PGA for Oahu was 2.65 m/s^2 (Klein et al., 2001). PGA is expressed in (g), meaning a value of $2.65/9.81 = 0.27(g)$. The estimated spectral acceleration for Oahu is 0.3 (g's) (USGS, n.d.-b). These values are used to read the fragility curves as estimated in the HAZUS technical manual (Department of Homeland Security and the Federal Emergency Management Agency, 2017b). These are used because Oahu is part of the United States and the curves are developed for estimating damages due to seismic activity in the United States.

Not all infrastructure components could be assessed on their fragility because there were no estimates for the peak ground deformation (PGD) on Oahu. PGD values are used to estimate the probability of

failure for ‘flat’ structures such as roads, runways and railway tracks. Therefore, the probability of failure for those infrastructures are missing in this section. The probabilities that were derived from the fragility functions (see Appendix C) are listed in Table 19 below.

Table 19: Damage probability for several infrastructural components

Component	Slight	Moderate	Extensive	Complete
Conventionally designed major bridges	0.3	0.2	0.1	0.05
Seismically designed major bridges	0.12	0.05	0.01	0
Bored/drilled tunnels	0.1	0.05	-	-
Stationary Cranes/cargo handling	0.45	0.2	-	0.05
Rail-mounted cranes/cargo handling	0.83	0.35	-	0.1

6.2.4 Effect of disaster on the network

Road network

The road network structure from Figure 35 is laid on top of the evacuation maps to determine which parts of the network are inundated. The assumption is made that in case of inundation, the road section is no longer usable and the link is removed. This results in the network visible in Figure 36.

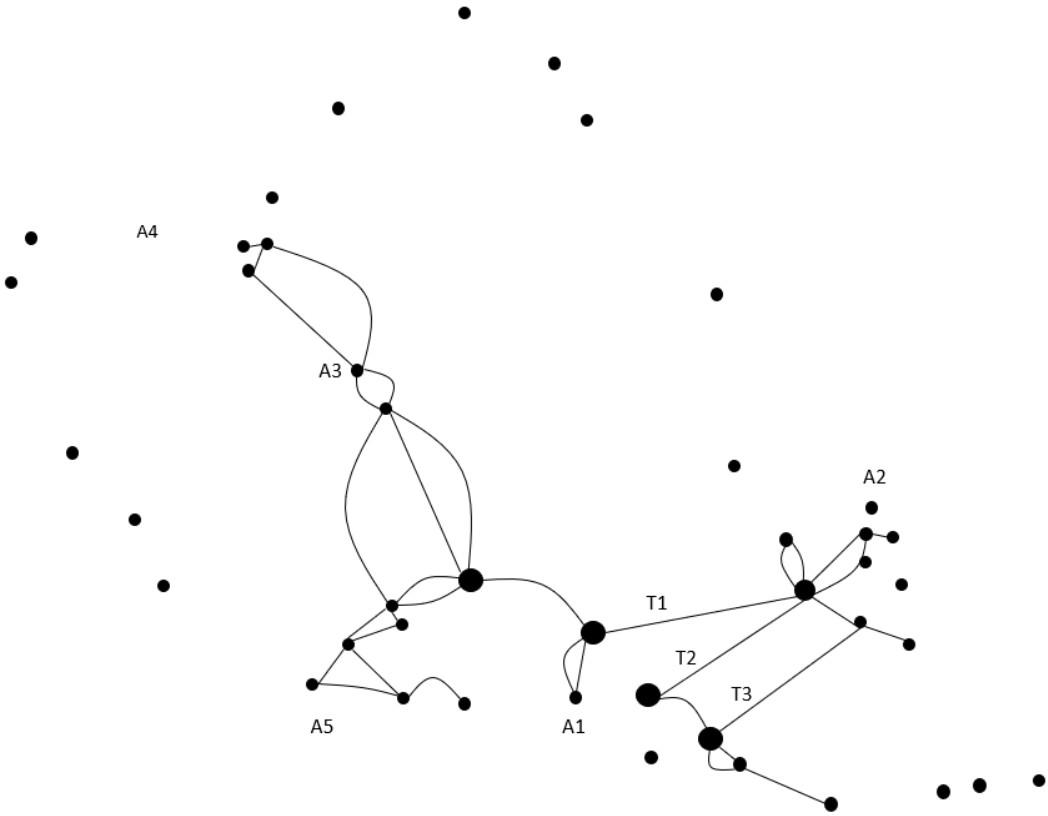


Figure 36: Usable links of the road network in case of a tsunami

Large parts of the island are no longer accessible by road. The roads further inland do not suffer damages from the tsunami, but can still suffer damage from the earthquake causing the tsunami, leading to an even further disconnected network. Since there are no estimates for the fragility of roads, it is not possible to determine the possible damage for roads due to an earthquake. It can be expected that the low quality bridges will suffer more damage from an earthquake than higher quality bridges. However, it is unknown where the bridges are located and thus it is unknown whether the road

network will be fragmented even further. The numbers 1, 2 and 3 after the “T’s” are links that include a tunnel. The probability for moderate damage for tunnels is 0.05 (see Table 19), which is not very high, but there can be such an amount of damage that a tunnel becomes unusable. In case tunnel 1 suffers moderate damage, the road network is cut in half. In case tunnel 2 or 3 suffers damage, the connectivity is decreased, but no extra parts of the network become isolated.

Air network

Oahu has five locations which could be used for aircraft take-off and landing (located with A1-A5). However, four of them are located so close to the coast that they will be inundated in case of both tsunami scenarios. The largest access point for the air network is Honolulu International Airport, since this access point becomes unusable due to inundation, the air network structure has a large impact and air traffic will be disrupted for several days. Airport A2 and A4 will not be accessible by roads due to the inundation. There are no estimates for the fragility of runways and other air infrastructure components, it is therefore not possible to determine whether the airport will suffer damages from an earthquake as well. So the assumption is that the airports will be unusable as long as they are inundated, and are likely to be usable once the water has receded and the airports can be accessed.

Water network

The ports are likely to be damaged by the tsunami because of their proximity to sea, causing the access/egress points for the water network to be unusable. There are probability of failure estimates for the cargo handling equipment. A quick scan using Google maps satellite view gave a mix of stationary and rail-mounted cargo handling equipment. Minor damage to the equipment can already cause it to be unusable, so after an earthquake at least a part of the equipment cannot be used until it is repaired with the high probabilities for minor damage (see Table 19). Besides the cargo handling equipment, the port itself will be unusable for docking as well. Hawaiian ports already suffered large damages following the 2011 tsunami and made it difficult for ships to dock (Roberts & Johnson, 2011).

6.2.5 Evacuation

The location of people is partly introduced in the capacity subsection. No OD matrices were found for Oahu, so a rough analysis based on a satellite picture of Oahu is performed. On the picture it is visible which areas contain homes and which contain businesses, so it can be roughly determined where there are people during the night and during the day and how densely an area is populated.

The proximity to evacuation can be determined by means of the evacuation maps. These clearly indicate what the dangerous areas and what the safe areas are. When comparing these areas on a map including a scale the distance can be determined. However, it is not known how many people are located at which location at what time, so it is not possible to calculate the static evacuation time. In the capacity section, an analysis has already been made on areas likely to experience difficulties in case of an evacuation. Averagely speaking for Oahu, there is an evacuation location on higher ground close by because of the mountains and hills on the island.

It is difficult to determine the travel behavior of people on Oahu; there is no model available simulating the behavior of this group. The choice is made to estimate the factor travel behavior based on the three influencing components as found in van den Berg (2016):

- Information
 - o Will people know that they have to evacuate? (based on a warning/alarm)
 - o Do people know where they have to go? (evacuation maps, road signs)
- Personal context
 - o What is the age distribution?
 - o What is the household composition?

- Are there vulnerable groups on Oahu?
- Are people experienced with tsunamis?
- Choice options
 - Are multiple modes available?
 - Are there multiple evacuation routes?

Oahu has a tsunami warning system that sounds an alarm in case of tsunami danger. People familiar with the sirens will know they are warned for tsunami danger. There are evacuation maps available, allowing people to check if their home is located within an area likely to inundate in case of tsunamis. However in case of a tsunami evacuation, there are little to no signs indicating when safe areas are reached or how to reach them. There currently are plans to increase the signage in the inundation prone areas (Hawaii Emergency Management Agency, 2017).

There are almost one million people living on Oahu, this includes the militaries stationed there. Approximately 200.000 are under 18 years and 165.000 are older than 65 years. No data was found on the composition of households. Oahu is a popular holiday destination, Honolulu International Airport had 9,5 million enplaned passengers in 2015 (The State of Hawaii Data Book, 2016b). People visiting the island are more vulnerable compared to its residents in case of a tsunami. Visitors are not familiar with the evacuation maps of Oahu and are not familiar with the tsunami alarm and will likely have more difficulties in case of an evacuation.

In case of an evacuation people can walk, bike or drive. No data was found on bicycle ownership, but vehicle ownership is high on Oahu (Lohmann & Ngoc Nguyen, 2011). The redundancy in evacuation routes is analyzed in the capacity section earlier. Some areas have only one or two main evacuation roads suitable for evacuation.

6.2.6 Emergency Services



Figure 37: Overview of fire stations, medical centers and police stations on Oahu

Figure 37 above shows three different types of emergency services, from left to right: fire departments, hospitals or medical centers and police stations. It can be seen that there are many locations. There is no information about the capacity of these locations. The fire departments are mostly located along the south coast, with some departments along the central road, one located on the north east coast and one on the north west coast. The southern west coast has no fire department. Some departments at the south coast are susceptible to flooding in case of a tsunami due to their proximity to the sea. In case of a tsunami, the locations at the south are mostly in the disaster area. The inundated area in case of a tsunami is not only on the south however, the west and east coast are hard to access by the fire department; there are almost no departments along these coasts and the only access is by a road which will be inundated as well.

The most hospitals are located in the densely populated areas along the south coast. One hospital is located centrally on Oahu. Two hospitals are located on the west coast, one at the north east coast and one close to the south east coast. The hospitals in the south are mostly located such that they do

not suffer from flooding in case of a tsunami. The hospitals located on the west coast are so close to the sea that they are likely to suffer from inundation or inundated surroundings.

The police stations are mainly located in the densely populated areas along the south coast. There are two stations located more centrally and three on the north east coast. Most of the locations are located so close to the coast that they will likely be impacted by a tsunami in case one occurs.

6.3 Resources

No data on the amount and type of resources on Oahu was found. However, based on import and export data the conclusion can be drawn that the Hawaiian islands are highly dependent on imported materials from Indonesia, Japan and Russia (The State of Hawaii Data Book, 2016a). Cargo is mainly imported through sea, the high valued and low weight materials are imported via air (The State of Hawaii Databook, 2016). Honolulu airport is the main airport for importing goods. This airport will be inundated in case of a tsunami, making it impossible for aircraft to use the runways and bring in resources. The port will also be damaged after a tsunami, making it more difficult for ships to dock. As can be seen in Table 19, cargo handling equipment has a high probability of minor damages, making it unusable handling resources.

6.4 Ability to recover

The ability to recover turned out to be impossible to assess fully. The first two points of the checklist regard the accessibility of the area after a disaster. Oahu is difficult to supply relief goods to because of the damaged (air) ports and damaged road network. In case the relief goods are supplied to those access points, the damaged road network will cause difficulties distributing the goods to the different towns and cities on Oahu.

The resource allocation factor cannot be assessed prior to a disaster. No specific disaster plan was found for Hawaii, so it is not possible to assess this factor. The political structure needs to be elaborated on further and could be assessed by studying the disaster management after the disaster at Puerto Rico to see how governance affected the recovery.

6.5 Conclusion per 'tsunami resiliency block'

The complete overview with scored factors including their motivation is summarized in Appendix D. Conclusions will be drawn based on the four main colored blocks: disaster, ability to cope with a disaster, resources and ability to recover. This subsection is concluded with an advice for Oahu.

6.5.1 Disaster

Oahu has a tsunami warning system, which could be improved by decreasing the chance of a false alarm. The defense structures at Oahu are minimal and consist of some seawalls, but in case of a close source tsunami, large areas will be inundated. There is no earthquake warning system connected to the transport system on Oahu. Since there is no rail network yet, the question is whether this necessarily is a bad thing. However, connecting a warning system to a rail system is a good measure to prevent deaths by derailment so this is something to consider for Oahu when building their rail system.

6.5.2 Ability to cope with a disaster

Due to geographical characteristics it is difficult to build roads on Oahu. The land close to the coast is the least mountainous and therefore many roads are built along the coast leading to inundation of the roads in case of a tsunami. Not only the roads, but the airports and naturally the ports are located close to or on the coast. Almost all runways of Oahu will be inundated in case of a close source tsunami. Protecting these runways with seawalls or other defensive structures would lead to an improvement of the ability to cope with a disaster.

The capacity of the transport system is insufficient for day to day use, large parts of the roads are filled with congestion throughout the day. This means that during a disaster the capacity is also likely to be insufficient.

The infrastructural components that build up the infrastructure network are analyzed on their seismic fragility, but not all data was available. It was not possible to determine the probability of damages for the road network. However, there were many bridges of insufficient quality under normal circumstances, meaning that in case of an earthquake these bridges are very likely to suffer at least minor damage. Especially the port components are vulnerable to earthquake damage and should be considered to design differently or made easier to repair.

The network structure of the road network could increase the ability to cope with disaster in case it is more redundant, this would be expensive due to the geographical characteristics of Oahu so it should be researched whether more redundancy is cost effective. The road network is fragmented after a tsunami and tunnels in the center of the island are crucial for keeping the rest of the network connected. There is redundancy in the air network, but the airports are inundated in case of a disaster. The advice is to either protect the existing airports better, or build a new runway further away from the coast.

Since large amounts of people are located within the tsunami dangerous area it is important to develop an evacuation plan that allows for car based evacuation on the locations where car based evacuation is necessary. Some locations of people are so far away from evacuation areas that evacuation by car is inevitable. With the information supply at this moment, this will lead to difficulties with evacuation. People know which areas to evacuate, but not via which route and in what way. Attention should be paid to the vulnerable groups of Oahu, including the elderly and tourists.

There are multiple locations for emergency services, including police stations, fire stations and medical centers. The locations along the south coast will suffer from inundation in case of a tsunami. The emergency services are spread over the island, but the less densely populated areas along the coast are relatively far away from emergency services. The accessibility of the disaster area is bad due to the inundation of airports and roads.

6.5.3 Resources

Oahu is highly dependent on materials from other areas. In case of a disaster Oahu will also be dependent on other areas for recovery. There are many people on Oahu, including a large amount of militaries that could provide help with the recovery.

6.5.4 Ability to recover

The supply of relief goods will be difficult due to the damaged (air)ports and fragmented road network. The ability to recover would increase when there would be a functioning (air)port with functioning access roads to bring in relief goods and distribute them further away from the (air)port onto the island.

The preparedness and governance turned out to be difficult to assess. Oahu has considered tsunamis, but their disaster plan could be more elaborate and also include more detailed car based evacuation plans for example.

The restorative ability of road, water and air components are relevant for Oahu. Normal road sections recover the fastest due to their ease of access. The port components and handlings equipment take the longest time to recover to fully because the expected damage is the highest.

6.5.5 Advice for Oahu's transport system

The advice for Oahu is summarized below:

- Ensure airport capacity by protecting existing runways with defensive structures, building a new airport/runway further inland or increasing the capacity of the existing runway in the center of Oahu.
- Increase the quality of bridges, decreasing the probability of damage due to earthquakes.
- Ensure the tunnels going through the center of the island can withstand earthquakes and remain usable.
- Decrease the existing capacity issues by either increasing the capacity of the transport system, or by demand management.
- Develop an evacuation plan that includes car based evacuation on the necessary locations and communicate it with residents and visitors of Oahu.
- Ensure emergency service locations are still usable when they are inundated.
- Create more emergency service locations on the west and north coast.
- Create an inventory which allows repairs that enable access to Oahu (runways, ports and the roads leading to them) in order to start with those repairs first and continue with newly brought in materials.

Although Oahu does not have a rail system yet, they are planning for one. Some considerations for the rail system should also be taken into account. When building the rail system, incorporate a seismic warning system that stops trains in case of an earthquake, decreasing the probability of derailment. The current route of the rail line will be going through areas that will be inundated in case of a tsunami. The inundation depth and the line's height should be compared and possibly adjusted in its design.

6.6 Conclusion

This chapter applied the developed tsunami resiliency assessment method on the island of Oahu. The assessment matrix is filled in and can be found in Appendix D. The disaster forces that are expected for Oahu are relatively small, but the impact of those small forces can be large. The impact phase could be assessed in more detail than the recovery phase due to the difficulties in scaling of the recovery factors. Problems that are expected to arise in case a tsunami and earthquake impact Oahu are the inundation of almost all airports, destruction of ports and inundation of the coastal roads. During evacuation problems are expected in some densely populated areas with limited possibilities to evacuate, which could be further decreased in case bridges collapse due to earthquake shaking. Oahu is dependent on other parts of the world for their supply. After a disaster, relief goods and recovery materials need to be brought in from elsewhere. There is a need for a good access point to supply the goods to, that remains usable after a disaster and provides options to distribute the goods on the island.

7. Evaluate

This chapter will evaluate both the tsunami resiliency assessment method and its application. The first part of this chapter will evaluate chapter 5 by means of an expert interview and a personal evaluation. The second part of this chapter will evaluate chapter 6 by means of a peer evaluation and a personal evaluation.

7.1 Expert validation

The expert validation serves as a method to check the validity of the proposed method and is performed by means of an interview with dr. Tina Comes, a resilience expert at the Delft University of Technology. During this interview chapter 5 and a rough draft of chapter 6 were discussed. After this interview, improvements were made by changing or adding sections. Some points are taken as suggestions for further research. The comments that were given and the actions taken afterwards are summarized in Table 20.

Table 20: Results of the expert validation

Comment	(Re)action
It would have been better to derive the factors for the assessment method not only from literature and personal insights, but also from experts.	The choice to interview experts (in this case being transport planners in tsunami risky areas) is not considered. It would have been better to have done this. This is recommend for further research.
The ability to recover can be more thoroughly assessed by looking into similar disaster cases. For example, Oahu's ability to recover can be derived by analyzing the recovery after the disaster at Puerto Rico.	Recommended for further research.
The method does not take interdependencies of infrastructures into account, while transportation strongly depends on electricity.	The choice was made to look at transportation as an isolated subject before taking other infrastructures into account as well. It would indeed prove valuable if the dependencies are analyzed and assessed as well. This is recommend for further research.
The case study considers only 1 scenario, the method would prove more useful as a decision making tool when multiple scenarios are considered.	True, the choice is made to only explore the worst case scenario because this is already usable for the testing of the assessment method. In order to make well thought through decisions for policy makers it is relevant to know the different impacts caused by different scenarios.
The assessment method (at the time of the interview) does not include a means of scoring the factors. The scoring is based on personal judgement and should be made more reproducible and transparent.	A scoring range is developed for the factors where possible, filled in for the Oahu case and then tested by letting six people with no background knowledge on the case fill in the assessment matrix.

In general, the method could be made more precise but provides a good first step in the analysis of transport systems dealing with tsunamis which could be further developed into a decision making tool supporting governments in making transport design choices in areas susceptible to tsunamis and maybe other water related disasters.

7.2 Personal evaluation on the design of the assessment method

The method that is developed is usable as a first exploration for the tsunami resiliency of transport systems but should be further developed in order to use it as a decision support tool. The analysis of the impact phase is more in depth than that of the recovery phase. The impact phase is divided into more factors that were relatively easy to measure and score. When some data was not available (for example OD matrices for Oahu) it was possible to adjust the plan slightly and still come up with a score for the factor.

The recovery phase was more difficult to assess. For example the resource allocation is highly dependent on the damage after a tsunami and earthquake and consists of many 'what ifs'. Also the decomposition of the recovery block itself might not be the best one. The decomposition seemed logical when it was made, but in the developing of the scoring ranges it turned out to be less logical. Another way to look at recovery is given by Rubin (2009). In that framework, recovery consists of personal leadership, the ability to act and the knowledge of what to do. Resources are then a factor contributing to the ability to act and thus to recover. This framework also provides the option to distinguish different types of knowledge. For the recovery of a transport system engineering knowledge is important, but also administrative knowledge is required. For the assessing of the recovery phase the decomposition used by the author is not detailed enough; the derived factors are still broad concepts and turned out to be difficult to develop scoring ranges for, and clarify what exact data is needed in order to score it.

The developed scoring ranges should also be researched and validated in more detail. The scoring ranges are made based on a best and worst case, and three situations 'in between'. However it is still useful to apply the developed method on transport systems just to see what could happen in case of a tsunami and earthquake.

The developed method could already be improved greatly by validating the factors and developing the scoring ranges by interviewing more experts in the transport or disaster management field. Also, the method could be developed further by following the methodology of the composite indicator model further. The factors will then all be weighed and tested on interdependencies leading to a more usable method suitable for decision making.

7.3 Case study validation

To test the ease of interpretation and the reproducibility of the method a peer validation is used. This will also show whether the factors are clear enough to score. The collected data for Oahu is given to six different students (p1-p6). They are asked to fill out the assessment matrix based on the provided data. In case they are hesitant about a score to give to a factor, they are asked to write down their reasoning. When comparing the filled out assessment matrices, the score is noted per factor and compared to the scores given by the author (visualized in yellow). The results are summarized in Figure 38.

Most factors and their scoring range and criterium were clear. Most factors are scored the same by the respondents and the author, with some small variations. "location of infrastructure component", "fragility of infrastructure component" and "network structure" are three factors that require a more detailed scoring based on modality. Both "proximity" factors require a scoring criterium because now it is not clear whether to score on average proximity or worst case proximity. The scoring for "resources: people", "personal context", "preparedness", "resource allocation" and "governance" was not possible because the range was ambiguous, unclear, or missing. These factors require further research. An evaluation on the possibilities for deviations on the scores is given in the next section.

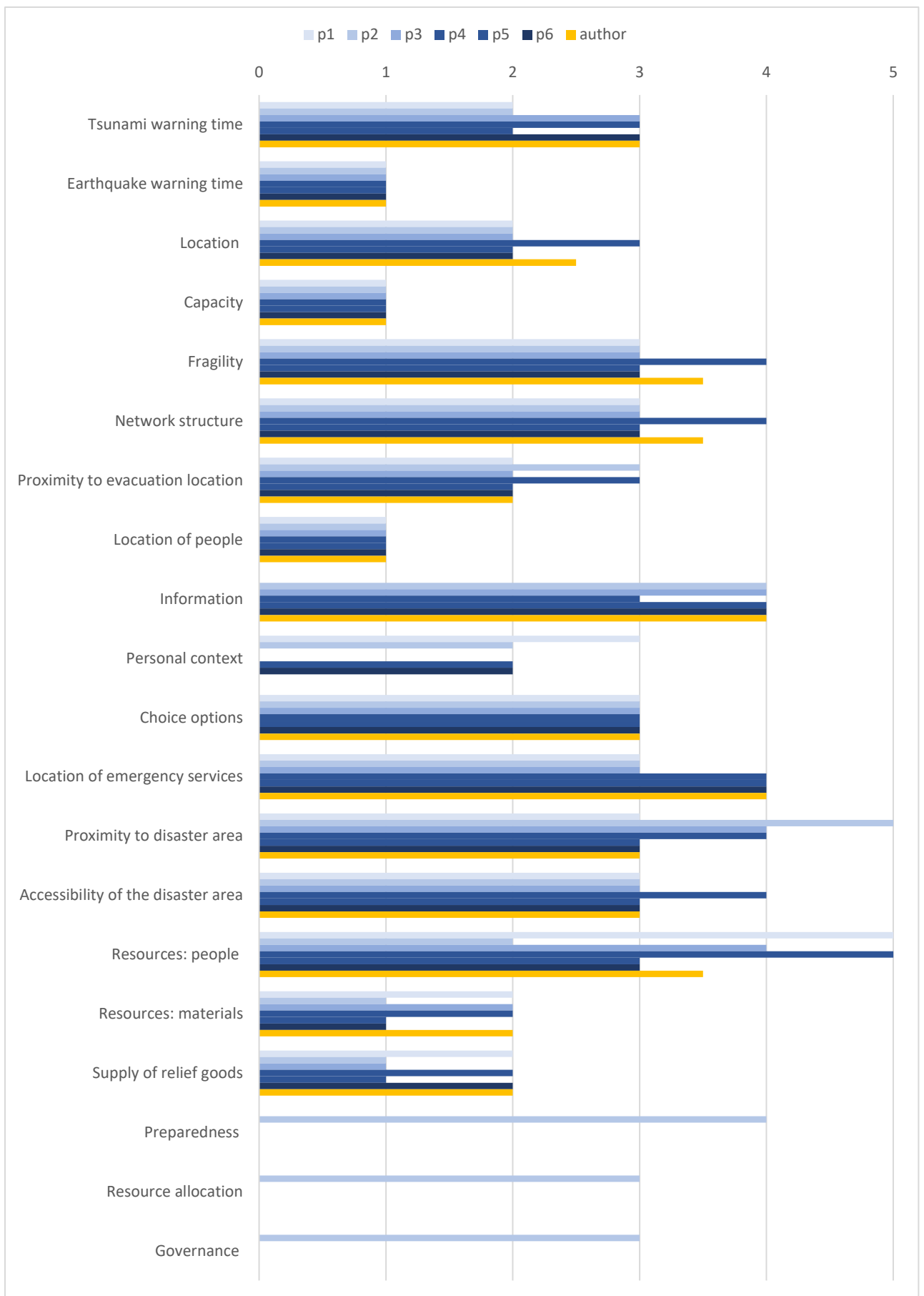


Figure 38: Overview of scoring by peers and author

7.4 Personal evaluation on the case study

This section will describe the application of the assessment method on the island Oahu and reflect on the deviation of scores given by the respondents and the author.

7.4.1 Using the assessment method on a test case

The first step in the case study was the data collection. This was done by following the checklists from chapter 5. Most data was available for the impact phase, but for example for the evacuation related factors, no OD matrices were found. Therefore another type of analysis was used where an estimation is made of the whereabouts of people using maps to identify residential and business areas. This will not give a detailed overview but will show whether there are people in tsunami dangerous areas and whether this is a 'large' or 'small' amount of people. The data itself (or lack of data) did not provide major difficulties for the assessment.

Filling in the assessment matrix itself proved more difficult. Some factors still consisted of more than one topic, for instance the location of infrastructure. Because there are different modalities, this factor should have been decomposed further in order to make it easier to score. Examples can be seen in the filled in matrix in Appendix D when a factor is given two scores.

The filled in assessment matrix provides an overview of factors having an effect on the tsunami resiliency of the transport system on Oahu. These factors are derived from the impact or the recovery phase. The impact phase has been decomposed to a higher level of detail. The measurements and scoring ranges were easier to interpret and thus the scoring was easier for this phase. For the impact phase some important factors that affected the tsunami resiliency were found to score very low (for example the locations of the airports and the capacity problems). The decomposition of the recovery phase was not very practical in use. As described in section 7.2, another way of decomposition might increase the usability for the assessment method. The 'ability to recover from a disaster' factors require more research. The scoring range as used in this research is not strongly founded in former research. Also, before being able to score these factors it is necessary to study similar disasters in similar countries for which there was not enough time. Therefore the only strong conclusion that can be made for the recovery phase is the lack of resources on the island itself for recovery and the difficulties that could arise when importing and distributing resource for recovery.

The assessment matrix provides an initial exploration and cannot be used as a decision making tool. It is not precise enough; only one scenario is considered and the different factors cannot be compared to each other. However it does provide an overview of factors to take into account when analyzing the transport system in relation to tsunamis and earthquakes. The developed method can be seen as a first step in the analysis of the tsunami resiliency of a transport system and could prove to be a useful decision making tool when developed further.

7.4.2 Reflection on the respondent scores

For tsunami warning time, the respondents either gave a score of 2, corresponding to a functioning sensing system but a slow communication system leading to a later warning or a score of 3 corresponding to 'malfunctioning system that sends warnings in case there is no tsunami'. An article in the data set that was given provided information about the malfunctioning of the warning system due to insects causing the sirens to warn for tsunamis when there was no tsunami, corresponding to a score of 3. There is no reason why some of the respondents chose a score of 2 instead of 3.

The location of infrastructure factor is scored between 2 and 3 by the author. The different modalities are differently impacted. The respondents either gave a score of 2 or 3. The score of 2 was given due to the location of the (air) ports. The score of 3 was given because of the location of the roads, which

will be inundated for about 50%. The author scored it 2-3 because large parts of the roads will not be inundated, but the (air)ports will be inundated. The respondents based their choice either on the best scoring modality or the worst scoring modality. The scoring of this factor could be improved by adding a subcategory that includes the inundation per modality and leads to an overall score for the 'location' factor. The same holds for the fragility of infrastructure components. Some components are more likely to suffer damage than others, making it difficult to assign one score by means of one scale. The scoring for this factor could also be improved by adding a subcategory that includes the fragility per modality and leads to an overall score. The network structure should also be assessed per mode first, leading to one score for the overall factor.

The proximity to evacuation location turned out to be difficult to score as it is not clear to score on the average proximity or the worst or best case that can be found. The respondents scored based on the average proximity which allows for evacuation on foot within 30 minutes. The author scored it based on the worst case. It should be made clearer what the scoring criterium is.

Personal context is a factor that turned out to be impossible to give a logical range within this research. The worst and best case for personal context are based on literature but even within the literature there were discrepancies. The author did not score the personal context for Oahu, but some of the respondents created their own meanings for scores and gave them a 2 and 3 respectively based on the mix of people on Oahu. They considered the many visitors on Oahu a vulnerable group because they have no 'tsunami knowledge' and will not know what to do in case of warnings. This factor is a factor that requires further research in order to assess it properly.

The location of emergency services is scored lower by some of the respondents than by the author. The images showing the emergency service locations were small and made it difficult to see which locations are within the inundated area.

The proximity to the disaster area was scored higher by some of the respondents. It turned out a scale was missing on the provided map, making it impossible to use the scoring range because it is based on the distance in kilometers. Another problem is the scoring criterion, it is not clear if the scoring is based on the average distance between locations and the disaster area, or the longest distance. This should be made clearer.

The resource factor "people" was difficult to score. The highest score of 5 was given because of the high number of militaries, the assumption was made that they would all have basic building knowledge. The lowest score of 2 was given due to the assumption that the militaries would not have any building skills. The developing of the scoring range on itself was difficult. The best and worst case were easy to determine, but the order of the steps in between caused difficulties. It was hard to determine whether it is better to have more people in total, but less who know what to do, or to have fewer people in total but they all know what to do. The same holds for the distance of people, how big is the effect on recovery when it is necessary to wait longer on people? This should be looked into further.

The scoring of the resource factor "materials" was easier because it was clear there was not enough, no matter the quality. However, this factor should also be looked into further to determine the proper range. It should be researched which combinations (of location, quality and amount) have what effect on the recovery of the system.

Preparedness, resource allocation and governance were three factors for which the author did not develop a range to score them on. One of the respondents did come with a score based on the fact that Oahu "wasn't bad, but also not too great on these three factors". The best and worst case were

already a challenge for the governance factor. Well thought of governance structures can seem great on paper, but do not work effectively in reality. More research is needed before being able to determine a proper scoring range for these factors.

7.5 Conclusion

This chapter evaluated the development and application of the tsunami resiliency assessment method. An expert interview is used to validate the design of the method. The case study is validated by means of a peer review. The method as it is can be used to determine the tsunami resiliency of a transport system up to a certain level. Especially the recovery phase needs further research before being able to assess it properly. The main contribution of this research is the decomposing of the broad concept 'tsunami resiliency' into a comprehensive set of factors to serve as a first step in the assessing of tsunami resiliency. The tsunami resiliency assessment method itself could be improved further, the outcomes of the evaluation will be used as input for the recommendations in the following chapter.

8. Conclusion and recommendations

This chapter will answer the main and sub research questions and give recommendations for further research.

8.1 Conclusion

This section will conclude this thesis research by answering the main research question and the sub questions as defined in Section 2. Firstly the sub questions will be answered, followed by an answer on the main research question.

How can the resiliency of systems be assessed?

This question is answered based on a literature review on the existing assessment techniques for resilience. Many ways of assessing resiliency have been found and categorized as either a qualitative or a quantitative approach. The qualitative approaches provide theoretical frameworks which are sometimes combined with indices to assess the resiliency in more detail. The quantitative approaches vary greatly depending on the definition of resilience in the research. No research existed on tsunami resiliency of transport systems, which is why the choice was made to firstly develop a theoretical framework determining what factors influence the tsunami resiliency of a transport system. The composite indicator model provided a matching methodology for the creating of a theoretical framework and the deriving of factors.

What are indicators for a tsunami resilient transport system?

The indicators for a tsunami resilient transport system are determined by the factors affecting tsunami resiliency. They are divided into two main categories; factors affecting the impact and factors affecting the recovery of the transport system. Impact is further divided into the disaster itself and the ability of the transport system to cope with that disaster. The recovery is divided into the resources and the ability of the system to recover after a disaster. This distinction is further divided into factors that are separately assessable. The complete overview of the factors and their origination is summarized in Figure 39. The most factors are defined for the ability of a transport system to cope with a disaster. The other blocks (resources and ability to recover) could be studied in more detail, but due to the limited amount of time available the focus was on the ability to cope.



Figure 39: Summary of tsunami resiliency factors and their origination

How can these tsunami resiliency factors be measured and what would be (un)desirable values?

The data that is needed for the measuring of the factors is summarized in Appendix B, together with the best and worst cases and values for that factor. While it was possible for every factor to determine their best and worst values, it proved difficult for the policy and socially related factors such as governance, preparedness and personal context to develop a range of values and score them. A scale of 1-5 is developed for the other factors. A score of 1 is the lowest value and corresponds to the worst scenario for the factor. The desirable values are values for the factors that lead to a small impact and a quick recovery. The entire overview of factors and their (un) desirable values is given in Appendix B.

How can a set of factors determine the tsunami resiliency of a transport system on a qualitative level?

The factors that are determined to have an effect on the tsunami resiliency of transport systems are mostly measurable and can be used to assess the tsunami resiliency of a transport system. Checklists are developed for transport authorities to use that provide the necessary answers to fill in the assessment matrix in Appendix D. The tsunami resiliency of a transport system is not assessed in one grading, but provides an overview and enables comparison between transport systems. The score on the different factors shows which aspects of the transport system are and are not contributing to the tsunami resiliency.

How to assess the tsunami resiliency of transport system?

In order to assess the tsunami resiliency of transport systems several steps are necessary. The first step was the deriving of factors that affect the tsunami resiliency of transport systems. The desired and undesired values of these factors are determined and lead to a scoring range between 1 and 5 for most factors, some factors require further research before the 1-5 scale can be determined. A checklist is created consisting of questions and actions. The information to fill in the assessment matrix is acquired by following the checklists. The next step is to fill in the assessment matrix by giving the tsunami resiliency factors a score between 1 and 5. This results in a color coded assessment matrix which at first glance gives an average idea about the tsunami resiliency, if all factors are graded with a green cell, the transport system is tsunami resilient. When all factors are graded with a red cell, the transport system is not tsunami resilient. The assessment matrix also allows the comparing of two transport systems and can determine on which factors one system scores better than the other.

8.2 Recommendations for further research and development

The developing of the tsunami resiliency assessment method was the aim of this research. An assessment method is developed that was usable for the assessment of the tsunami resiliency of Oahu. However, improvements could be made. The recommendations for further research, development and use are listed below.

The factors that are used to assess the tsunami resiliency of a transport system are derived based on literature and requirements as defined in chapter 3. The factors could be further validated by interviewing transport authorities and policy makers in tsunami risky areas. The assessment method itself could also be validated further by testing it with transport authorities and policy makers.

Some factors proved difficult to link to a range of scores. The best and worst case were possible to determine, but for example “governance” and “preparedness” are both as broad a concept as “tsunami resiliency”. It was clear from the site visit and literature that governance and preparedness have an effect on the recovery after disasters, but it is not clear how to define the range from worst to best. It is recommended to look into this further and for example look for natural disasters that occurred in a region with a similar governmental structure to determine how the area of study will handle disasters on a governmental level.

Other factors that require further research are personal context and the recovery phase related factors. Personal context consists of different characteristics. The best and worst characteristics of people that influence evacuation are known, but it is not known how they affect each other and what mix of social characteristics will lead to what evacuation behavior. The factors that were decomposed for the recovery phase should be looked into further. The decomposition that was used did not lead to a useful assessment. The framework of (Rubin, 2009) could be used to derive different factors which should then be tested to see if they are more useful for the assessing of the recovery phase.

When a transport system is assessed with the developed method, this gives an overview of the different factors and their score on tsunami resiliency. However, it is difficult to determine what actions should be taken. It is not known how big the effect of changing a factors’ score from 1 to 2 is going to be, or how costly. Policy makers need to be able to make tradeoffs to justify their choices. This should be researched further. A way to do this is by taking further steps of the composite indicator model methodology. These steps include:

- Multivariate analysis
- Normalization of indicators
- Weighing and aggregation

- Uncertainty and sensitivity analysis
- Regression analysis

The method is only applied to a single scenario; the worst case scenario where a close source tsunami is caused by an earthquake. The outcome of the method on this worst case scenario is a severely impacted transport system that will have difficulties recovering. The question is how likely this scenario is and how to determine what adjustments should be made on the transport system. When applying the method on two or three different scenarios, it will be more insightful. These scenarios can be made more realistic by deriving them from hydrological models. The scenario that was used assumed the worst possible inundation on all sides of the islands, while the inundation depth can vary depending on the direction and size of the tsunami.

The method could also be used in reverse to analyze up to what level of disaster the transport system can function in a certain way. When designing a completely new transport system the assessment matrix can be filled in with the desired scores for each factor and then used as input for the design.

Another recommendation is to include the dependency of the transport system on the energy system. Cars need fuel in order to move and traffic signs and trains need electricity in order to function. When the energy system suffers from a tsunami, the transport system will recover slower than in the case where the energy system still functions and only the transport system is damaged.

The last recommendation is to look into the possibilities to apply the developed method on other natural disasters. The factors are derived for tsunami resiliency, but tsunamis have similar characteristics to other natural disasters such as the damage to infrastructure, the outbound flow of evacuees and the inbound flow of emergency services and relief goods. The developed tsunami resiliency assessment could prove useful for resiliency assessments of transport systems for other types of disaster when it is adjusted to another type of disaster.

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Appendix A: Interviews

This appendix contains the two interviews that were held while visiting the Tohoku region.

Interview Anna Takayasu

Verified 4/12

Anna Takayasu is a transport master student who's currently researching the role of information propagation on evacuation. She helped me understand a bit more about the Japanese way of transport planning and management.

In Japan many transport services (such as road and railway infrastructure and services) are operated by private companies. For instance the highways are run by Nexco, and many public transport connections are operated by JR. Universities have played a role in the recovery and rebuilding of disaster affected areas. They do research and give advice to the local governments. There were also people of the university involved in the recovery process of Yuriage.

What trends are going on transport wise in Miyagi?

There are many many cars, there's very few public transport outside of the city center of Sendai. The usage of bus is decreasing. It's becoming more difficult for the elderly people living outside the center to access the center. In Tokyo this is different, the public transport is more extensive and dense and therefore more attractive for people to use.

Is there a relation between the level of innovation and the declining population? (when your population is declining you can expect fewer problems like congestion)

Well, this is only the case in the rural areas. There are no big congestion problems there. But the people leaving the rural areas are moving into the cities. So the cities are actually increasing in size, so it's still important to come with innovative solutions for problems that might occur in your cities due to the growing population there.

What caused the biggest damage after the GEJE?

The tsunami. The road network was already built in such a way that it was able to withstand earthquakes for the most part. There was some damage of course, but relatively little. The water that came in brought a lot of debris which caused blockages and made the road inaccessible. Also the fact that there was no overview of which roads were blocked where increased the difficulties of moving around the network.

What measures would make that better?

If you have one person in the region that receives information from people within that region. That leader will assess all the information and have the overview of which roads can be used and which can't. That person will then share that information with the people in the region again so that everybody is up to date on the state of the network and the chances of falsely spread information will decrease.

Why did people take so long to evacuate (or didn't evacuate at all?)

People didn't expect the situation to be so severe. They didn't feel the threat of the situation and felt secure.

What transport measures can be taken to increase the situation during and after a tsunami? (So if another tsunami would occur, what measures would help?)

Many people used cars for their evacuation, which felt like it made the most sense. With a car it is possible to stay ahead of a tsunami, when you bike or run the tsunami will catch up with you. Also for the areas close to the sea, there was nothing close to evacuate to. However, because so many decided to evacuate by car, people were caught in traffic jams. Because they didn't decide to change modes when they were stuck in traffic, many people died. This is an important problem and the government should make some rule for evacuation mode choice.

If you are the person to plan for 2050, what ideas would you like to see implemented?

Linear motors are being tested right now. I would like all train services to run on linear motors.

Interview Professor Makoto Okumura

Verified: 6/12

On the 10th of November I had an interview with professor Okumura. He is specialized in interregional transport and optimization models also in relation with disasters. He did a lot of research on the Great Eastern Japan Earthquake (GEJE). The first part of the interview consisted of professor Okumura explaining more about the disaster and the area. The second part consisted of more specific questions and answers.

Until the GEJE tsunami, the government had a ban on car evacuation, however experiencing the long distance invasion of inundated water from the coast then, they learned that some places in flat geography must rely on longer distance evacuation by car. Immediately after the GEJE, there was congestion between the location shelters. Due to the relatively large amount of people who drowned in their cars, the government strongly needs a method for safe evacuation planning permitting car use.

Natori/Yuriage/Sendai

Natori is a commuting town, people live there, but work in Sendai. It is very car based, there used to be a regular bus service by Sendai city before the GEJE to bring people to the city center and the shopping mall. The service was cancelled after a relatively short time. Yuriage is the nearest port in the area, people who live there either work in the fishing industry or also commute to Sendai. Traffic is also generated in the other direction by the fishing market in Yuriage. Natori was also damaged by the earthquake and tsunami. The reconstruction of this area focuses mainly on connecting Natori with Sendai. It is also possible to use different modes, Natori has a JR connection.

The increase in population in this area can be partially explained by the fact that people who were active in the fish, livestock and agriculture industries in Fukushima became jobless after the nuclear power plant disaster, because no one wanted to eat the fish and crops from around Fukushima. These people moved to Sendai to live for jobs, but didn't want to migrate to downtown Sendai, so they settled in Natori. The daily number of commuters increased as well, however congestion is not a problem since the roads were designed initially for larger numbers of people. The traffic mainly goes from north to south. The soil used for land elevation is coming from the west. The large and heavy vehicles are causing some traffic problems.

The Sendai area doesn't have a lot of heavy industries. The main industries are branch office jobs of nationwide companies, fishing and agriculture. In 2009 Toyota opened a new fabrication location north of Sendai. The local government promised good conditions and an expressway. They use the Sendai port for transport within Japan.

Impact of the disaster

The earthquake damage was limited, the railways were already strengthened based on the damage experiences of former large earthquakes, such as Kobe in 1995 and Niigata in 2004. The only problematic thing were the hanging over the rail tracks. This was difficult to repair because it was hard to reach and there was a shortage of construction vehicles. The impact is also larger, because you cannot operate the Rapid Railway network when part of the rail network is still destroyed. In Sendai Airport Access Railway Line, a railway station had their power supply and train control operation system on the ground level, they suffered damage from the tsunami water. Also a tunnel suffered damage either because of inundation, or because the tunnel blocks were slightly moved and had to be realigned. It took until the end of September before everything was up and running.

Due to the power outages and fires, it wasn't possible to process crude oil in order to make gasoline. Furthermore, those gasoline could not be transported by sea tankers, which caused a fuel shortage.

How long does it take to implement changes to the network/service structure?

It takes a long time, especially when they want to make new things. After the disaster the local offices had money from the national government for simple repairs. If a local office tried to use that money to build new things, it took a very long time for negotiations to finish. And before they were finished, the funds could already be used by another competing local government.

What is the relation between local and national governing and transport reconstruction?

Many small towns were affected by the tsunami. In these local governments not enough knowledge is available to plan all the reconstruction by themselves. Land use planning regulations/plans are made for a city scale, not for towns. The land re-adjustment plan was also used for towns. The Ministry of Land, Infrastructure and Transportation sent specialists to different towns to make a plan on a local level. Also, the National agency of reconstruction implemented a policy which led to a tax raise for the coming years of 2 percent to fund projects for the rebuilding.

Another phenomenon that can be seen is the merging of towns. This already happened before the disaster. This has to do with the shrinking populations. Towns need to have enough people living in there in order to receive enough taxes. Towns already started to prepare for the shrinking trend before the disaster happened but there's no specific or nationwide policy for this. The local policies are based on the myth of increasing demand. Local governments believe that if they make their village attractive enough, the people will soon come to live there. However this doesn't happen and each town competes with each other for funding for projects.

In the rebuilding process for transportation, is resiliency considered?

Yes, but with resiliency they mean: resilient for the next tsunami. They plan everything in such a way that it should be able to withstand the next incoming tsunami of similar scale. Other types of resiliency, such as social, economic, environmental resilience are not taken into account.

Is that the best way of planning in your opinion?

It's definitely not perfect but you cannot say you're against tsunami resiliency. However, the overall planning could be more efficient.

Do you think it would be possible to decrease the dependency on cars in the villages?

Yes it's possible, but it's extremely difficult. When the population density increases, it's easier but in reality the people in the villages live too widely spread. On top of that, the elevation differences in the land makes it difficult to plan certain transportation modes. In the past the local governments received subsidies in order to operate for instance a bus service, but this isn't the case anymore.

Do you think the overall mobility will decrease? (taking the reduced mobility of the elderly and the aging population into account?)

Yes. When planning for rail and bus services the access of the stations is often not taken into account. Elevation or simply the distance itself can be a problem for elderly. Automated driving vehicles could be a solution between station and home. But it could also run on the alignment of the former railway. AV is seen as a solution towards transport poverty.

Appendix B: Tsunami resiliency factors for transport systems, their measurement and extremes

Table 21: Overview of tsunami resiliency factors along with their best and worst cases

	Meaning	Measurement	Best Case	Worst Case
Tsunami Force	The force of the water that impacts the area.	Flow speed, hydrodynamic force	There is no noticeable tsunami force impacting the transport system. Example: Defensive structures stop the tsunami before reaching land.	The tsunami hits with full force on the transport system. Example: No defensive structures are in place to reduce or stop the tsunami impact.
Tsunami warning Time	Time between sensing the tsunami and the impact of the tsunami.	Time in minutes or hours.	There is a working warning system in place. As soon as a tsunami is sensed, a warning is issued to the mainland, informing everyone on the danger ahead. Example: GEJE 2011.	There is no working warning system in place. When a tsunami is travelling towards the land, the warning time will be when people see the tsunami coming. Example: 2004 tsunami Indonesia/Thailand
Inundated area	The area that is inundated after a tsunami.	Static map of the area showing inundated area.	The smaller the inundated area, the better. Example: The transport system is not inundated at all.	The inundated area includes large and vital nodes or links of the transport system. Example: the airport, large parts of the roads and a train station are inundated.
Earthquake force	The force of the earthquake that impacts the area.	Peak Ground Acceleration, Peak Ground Deformation, Spectral Acceleration	There is no noticeable earthquake force impacting the transport system.	The force is of such a size that it will have a big impact on the transport system.

Earthquake warning time	Time between sensing the earthquake and the impact of the earthquake.	Time in seconds.	There is a working warning system linked to control mechanisms decreasing the impact of an earthquake on the transport system. Example: Stopping trains, decreasing the derailment chance.	There is no warning system, or it is not linked to the transport system.
Location of Infrastructure Component	Location of an infrastructure component. Tells something about the height and the proximity to defensive structures.	Height above inundation depth.	The infrastructure component is located higher than the inundation depth. Example: elevated roads.	The infrastructure component is located lower than the inundation depth. Example: coastal road next to the sea without a seawall or embankment.
Capacity of infrastructure component	Capacity of the infrastructure. How many people can make use of that part during a time period.	People or vehicles per hour.	Capacity remains sufficient to evacuate people in case of a disaster. The capacity of the evacuation routes remains enough, despite being impacted by an earthquake. Example: evacuation routes are built earthquake proof and are not inundated in case of a tsunami.	Capacity is insufficient to evacuate people. This can be either because of insufficient capacity in the 'normal day' network, but the insufficient capacity can also be caused by damages because of the earthquake. Example: one bridge is needed for evacuation, and has barely enough capacity when it remains intact, but it collapses due to an earthquake, making it impossible to evacuate the area.

Fragility of infrastructure component	Fragility of an infrastructure component. Shows the probability of failure when subjected to a range of forces.	Probability of structural failure for a given force.	The entire built environment is designed and built in such a way that even in case of a severe earthquake and tsunami the probability of failure is small. Meaning the infrastructure itself remains whole, and the surrounding buildings have not collapsed, leaving the transport system usable.	The entire built environment is not designed with earthquakes or tsunamis taken into consideration. This will lead to damages to the transport system directly and by buildings collapsing onto the transport system.
Network structure	The topology of the network.	Connectivity.	The network is redundant. When one part of the network is damaged, it is still possible to access it through other routes or by means of other modes.	The network has a low connectivity. When one part is damaged there is a high impact on the connectivity.
Proximity to evacuation location	Distance people need to travel when evacuating to a safe area.	Distance in (kilo)meters between the location of people at the moment of the evacuation warning and the location of the closest safe location.	Evacuation locations close to activities (living, working, shopping etc.) Example: Different locations are suitable for evacuation, an office that is designed to withstand tsunamis, a safe area close to home.	The location to evacuate to is too far way or inaccessible. Example: people evacuating their homes have to walk 30 minutes before reaching higher land.
Location of people	Where are people located throughout the day?	OD-matrices. Maps indicating residential and work areas	No people are ever in the tsunami dangerous area.	Large number of people located in tsunami dangerous area at night and during the day.

Information during disaster	What information do people have in case of a tsunami/earthquake?	Flood risk maps, evacuation signs, evacuation plan, warnings, communication	All information can be provided. A warning is given, people know if they have to evacuate and if so where to and how.	No means to know whether an area is safe or not. No signs. No maps. No warning.
Personal context	Characteristics of people. Age, income, household, experience, social group	Socio-economic data	young, single person households, high income and education, experienced with tsunamis	Elderly, multiple person households, low income, ethnic minority, no experience with tsunamis
Choice options during disaster	Choices people have in case of an evacuation. Includes the routes and modes.	vehicle ownership data, available routes after disaster	multiple routes are available and multiple choices for mode	No routes to safe locations available at all.
Location of emergency services	Place where emergency services are located and dispatch from in case of a disaster.	Location on map, located in or outside inundated area	Emergency services are spread over the area (multiple locations) and will not be inundated.	Emergency services are all located in areas likely to inundate. Example: single story hospital on the coast
Proximity to disaster area	Distance emergency services need to travel before reaching the impacted area.	Distance (km) between dispatch facility of emergency services and place they are needed.	Emergency services are located throughout the disaster area	Emergency services are located far away (in distance or travel time) from the disaster area.
Accessibility of the disaster area	Ease of access for emergency services to reach the impacted area.	Network data	The area between dispatch of emergency services and the disaster area is accessible for the emergency services. Example: Roads are not covered in debris and not destroyed by ground displacement.	The area between dispatch of emergency services and the disaster area is inaccessible for emergency services due to the disaster impact. Example: Roads are destroyed and completely unusable. Emergency services cannot access the impacted area.

Location of resources	Where resources are located, and how far that is from the impact area.	Distance (km) between storage and place they are needed.	Resources that are needed for recovery are located close to the impacted area. Spare parts that are vital for the functioning for the transport system as a whole are already in the risk areas. Example: bulk building materials are located close by. A bridge that is vital for the access to an area can easily be replaced by a pontoon bridge.	Resources that are needed for recovery are located far from the impacted area. No thought has been given on spare parts vital for the functioning for the transport system as a whole. Example: Resources need to be imported from far away after a disaster. The replacing or repairing of vital parts takes longer because there is no back up.
Amount of resources	Number of people and amount of materials.	Number of people	The amount of resources available is higher than the amount of resources needed for recovery.	The amount of resources available is lower than the amount of resources needed for recovery.
Skills of people	Skills can vary from planning to clearing debris and building highways.	Qualitative	The people that are available to help are skilled. Example: the disaster plan of a country includes the training of 'normal' people to help in case of a disaster. When a tsunami occurs, part of the population acts as first aid providers, another part knows how to clear up debris, another part knows how to build a road etc.	The people that are available have no skills helpful for the recovery. Example: When a tsunami occurs in a part of the world where there are no construction workers available, recovery will take longer because they need to be hired elsewhere.

Properties of materials	Type of material.	Qualitative	The available materials have the right properties for rebuilding. Example: asphalt is required for the rebuilding of a road and is available.	There is no material available with usable properties. Example: asphalt is required and not available, no other materials could serve as substitutes for the asphalt.
Supply of relief goods	How easy and fast relief goods can be gathered and reach the disaster area, and be distributed in the disaster area.	Accessibility	Possible to supply the disaster area with sufficient relief goods. Access points are still usable, from there relief goods can be distributed relatively easily within the disaster area.	Not possible to supply the disaster area with relief goods due to damaged access points ((air)ports, roads).
Preparedness	A short term disaster plan.	Qualitative	Tsunamis or earthquakes are planned for. Disaster plan is thought through, consists of multiple scenarios so in case of a disaster no time has to be wasted on who has to do what.	Tsunami or earthquake is never considered, and no disaster plans exist.
Resource allocation	The allocating of materials and people to recovery efforts.	Optimization	Resources are allocated in such a way that the performance of the transport systems increases fastest. Example: A road section of ten kilometers is destroyed. The road consists of four lanes. When one lane is reconstructed until it is usable again, part of the road can already be used, enabling easier repairs for the other lanes.	Resources are not allocated in a way that benefits the increase of transport system performance. Example: The road section of 10 kilometers is destroyed. The road consists of four lanes, instead of recovering partial functioning, the road is rebuild four lanes at a time.

Governance	The political structure of an area. Partly overlaps with preparedness, but looks at the long term.	Qualitative	Governance enables recovering activities. Example: Japan disaster headquarters established within 30 minutes.	Governance prevents recovering activities. Example: Japanese towns competing with each other for funding; the town receiving the most funding is most likely to 'become the best' in the area.
Restorative ability of infrastructure	Ability of an infrastructure component to recover to full functioning after suffering damage.	Restoration curves/functions	The infrastructure recovers easily in case it is damaged. Example: roads are easy to repair in case there are small damages, the road is still accessible up to the damaged part.	The infrastructure is difficult to repair. Example: Railways were difficult to repair after the 2011 earthquake in Japan. The railways itself were still largely intact, but the power supply lines had to be replaced. They were more difficult to access.

Appendix C: Extra information used for the Oahu Case study

This appendix contains the additional maps that were used to perform the case study to Oahu's transport system and its tsunami resiliency.

Node/link road network mapped on Oahu



Figure 40: Developing of the road network structure of Oahu

Capacity/Evacuation analysis maps

The maps used in this section are all originating from NOAA Office for Coastal Management (2015).

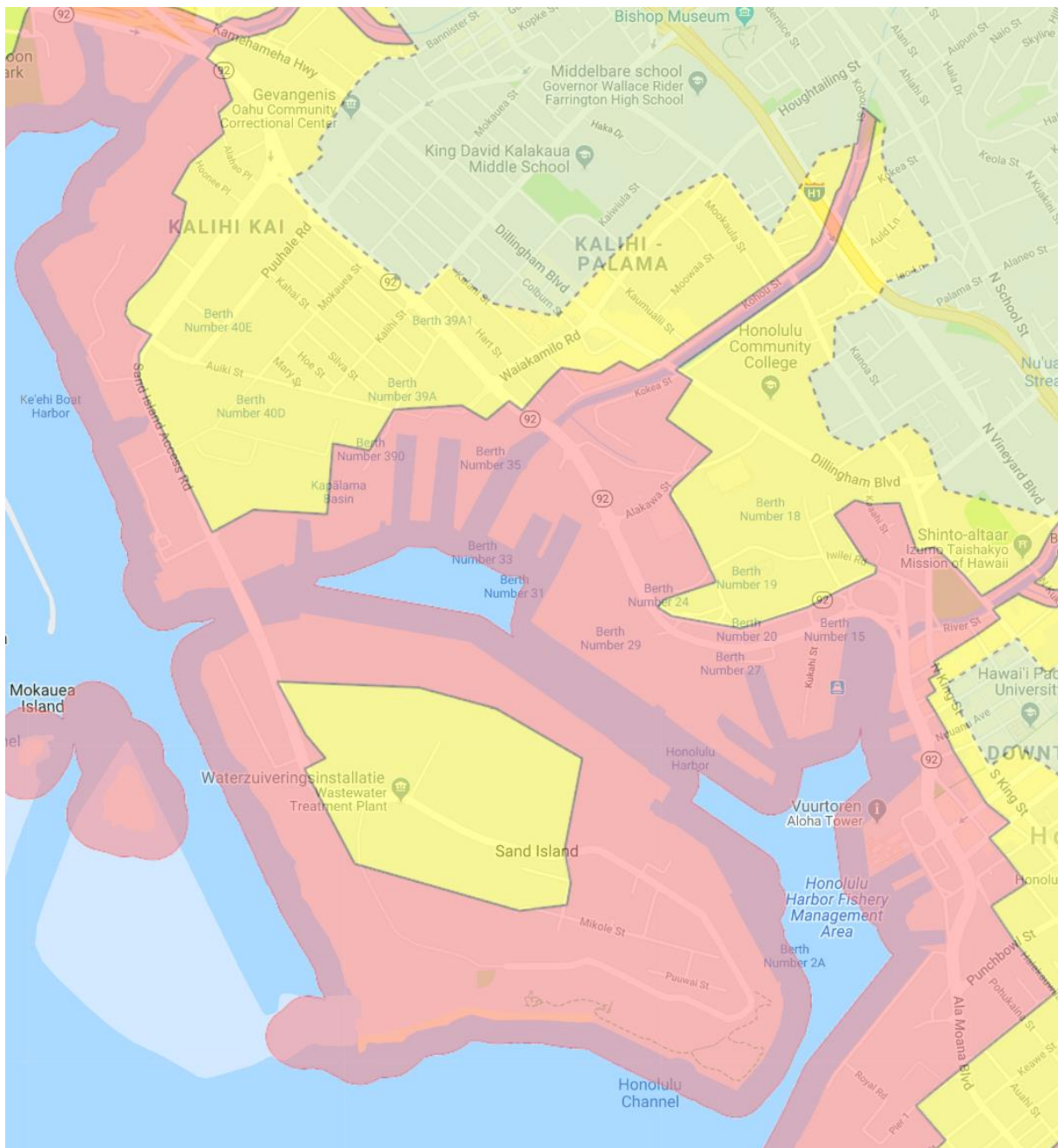


Figure 41: Capacity analysis for the evacuation of Sand Island, Oahu

Sand island is an island housing businesses. The entire area needs to be evacuated in case of a close source tsunami, meaning everyone located on the island will have to use the one bridge leading to the mainland. In case this bridge is damaged and becomes unusable, everyone on the island will be trapped. Because there is only one main road leading away from the island, congestion problems are not expected on Sand Island itself. Problems can occur when the stream of evacuees reaches the main land and has to merge with the evacuees from the mainland.



Figure 42: Capacity analysis for the evacuation of Waikiki, Oahu

Waikiki is a touristic area with many hotels, parks, beaches, shops etc. This means there will be a large amount of people in the area during the night and during the day. In case the area needs to be evacuated the options are three bridges (indicated with the red circles) on the north west side, or the south east side of the area. In case one or more of the bridges are damaged and unusable, which can be considered a likely scenario due to the many bridges of low quality on Hawaii, the evacuation routes are possibly decreased further. Evacuation on foot from the area to a safe location takes approximately 30 minutes. In case everyone evacuates by car, congestion is very likely.

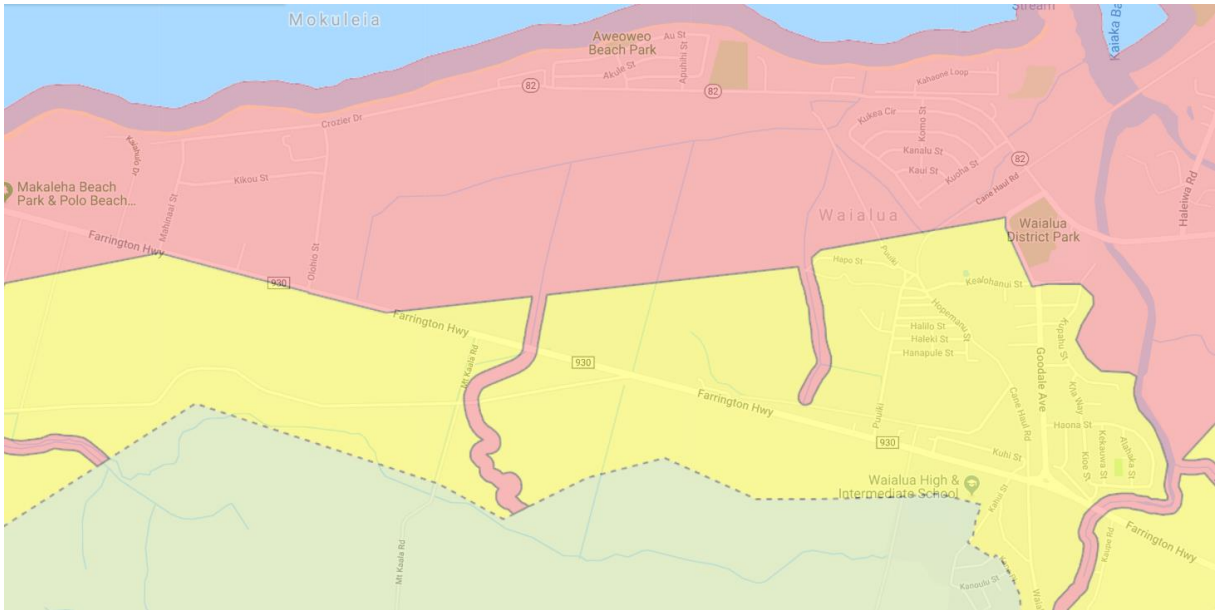


Figure 43: Capacity analysis for the evacuation of Waialua, Oahu

Waialua is a residential area with houses along the coast and along the roads on the right side of the pictures. There are no clear roads leading away from the dangerous area. The residential area above the “Waialua” text offers only two ways out, most likely causing congestion in case of a vehicle based evacuation. In case of evacuation on foot, evacuating from the same residential area to a safe area takes approximately 35 minutes.

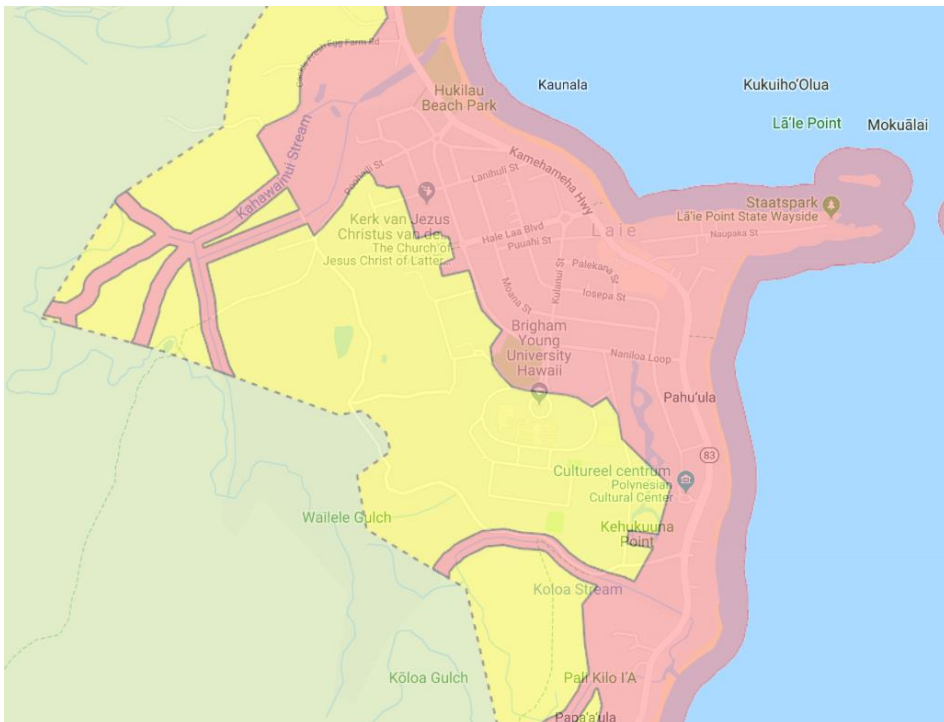


Figure 44: Capacity analysis for the evacuation of Laie, Oahu

Laie offers a mix of residential and business areas. Evacuation on foot from the east side of Laie to a safe area will take approximately 30 minutes. Car based evacuation is difficult because there are no roads leading directly to a safe area. So the last part of the evacuation will have to be done on foot in any case.



Figure 45: Capacity analysis for the evacuation of Kailua, Oahu

Kailua is a residential area surrounded by water; the ocean on one side and a canal on the other sides. In case of an evacuation, people can evacuate the area by means of the bridges. However, in case some (or all) of the bridges suffered heavy damages due to the earthquake, it is no longer possible for people to evacuate Kailua.



Figure 46: Capacity analysis for the evacuation of Iroquois point, Oahu

Iroquois point is a residential area. The parallel streets are all connected by two perpendicular roads which need to be used in order to reach Iroquois drive to evacuate the area. Problems are likely to occur at the street crossings, especially where Iroquois drive connects to Ibis Avenue and Heron Avenue.

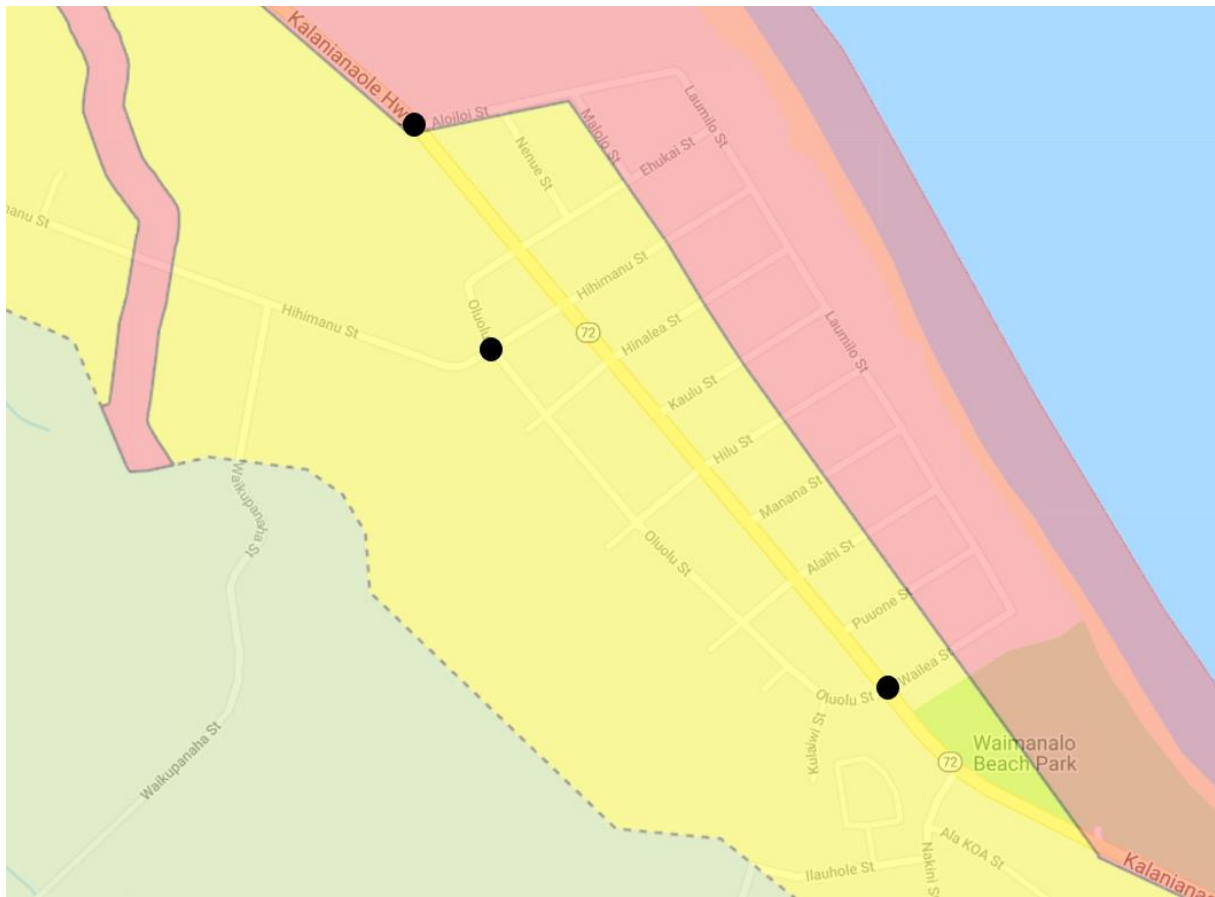


Figure 47: Capacity analysis for the evacuation of Waimanolo beach, Oahu

Waimanolo is a high density residential area. In case people decide to evacuate by car, there are only three points to leave the area, which gives no direct access to safe areas (indicated with the black circles). In case people decide to evacuate on foot, they can reach higher areas within 15 minutes. Problems are expected to arise in case people decide to use their cars.

Mapped ground motion values for Hawaii

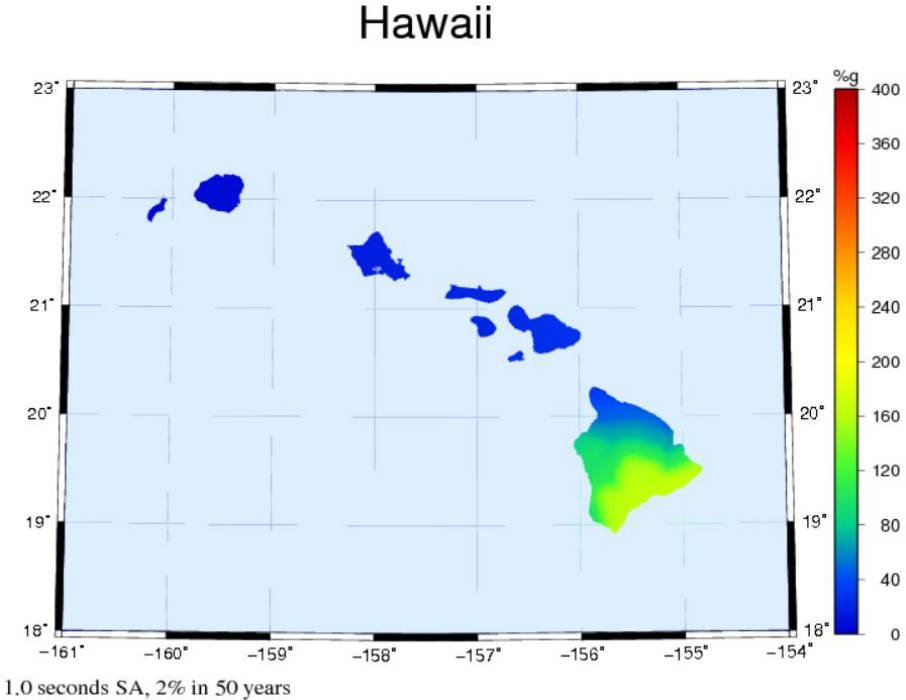


Figure 48: Mapped ground motion values (1.0 seconds SA, 2% in 50 years) for Hawaii. (USGS, n.d.-b)

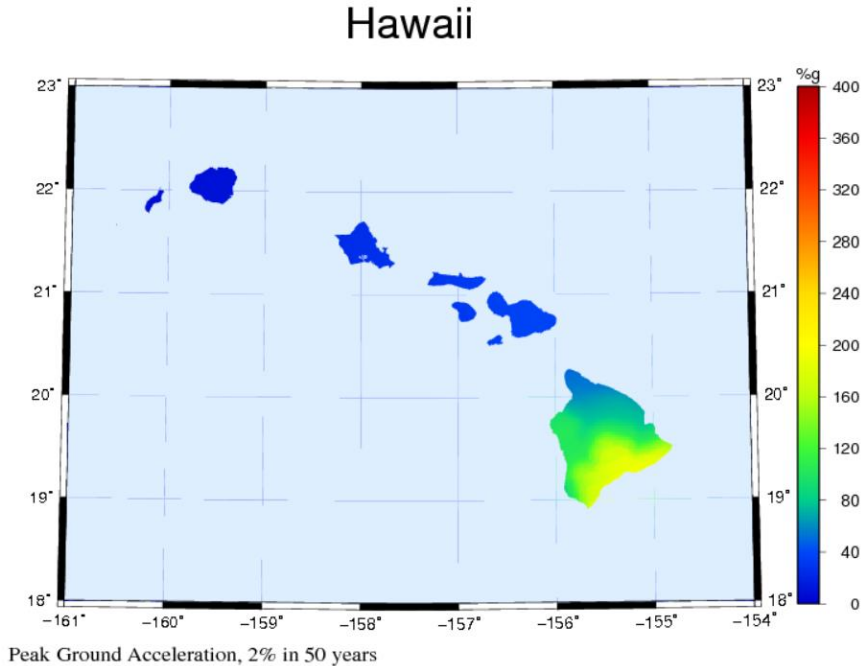


Figure 49: Mapped ground motion values PGA, 2% in 50 years) for Hawaii. (USGS, n.d.-b)

Fragility curves for infrastructural components subject to estimated SA and PGA values for Oahu

All figures in this section are retrieved from (Department of Homeland Security and the Federal Emergency Management Agency, 2017b). The red line represents the seismic forces expected for Oahu.

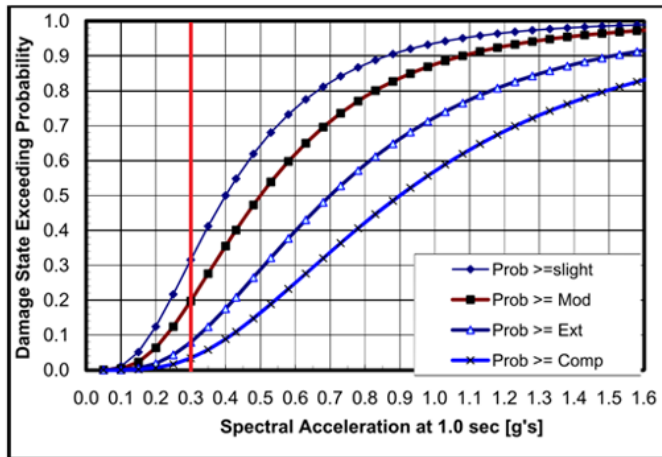


Figure 50: Fragility curves for conventionally designed major bridges.

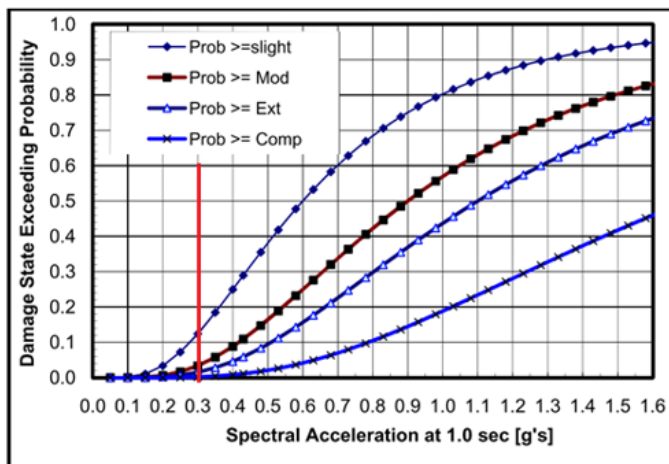


Figure 51: Fragility curves for seismically designed major bridges

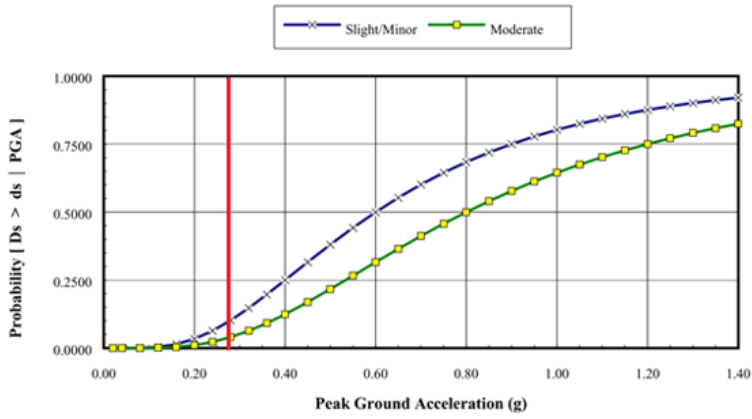


Figure 52: Fragility curves for bored/drilled tunnels

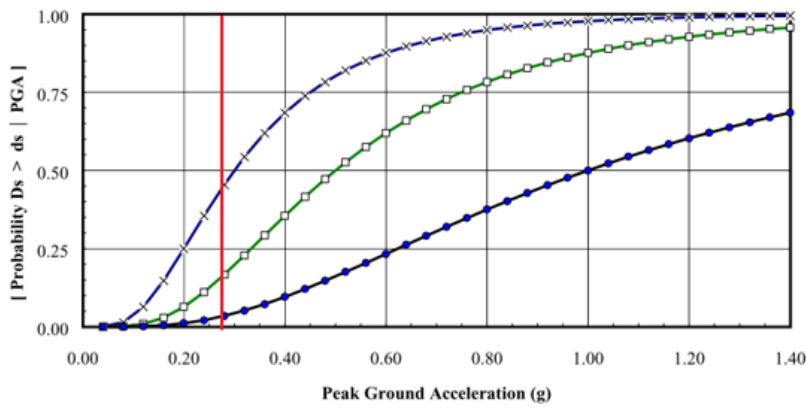


Figure 53: Fragility curves for stationary cranes/cargo handling equipment

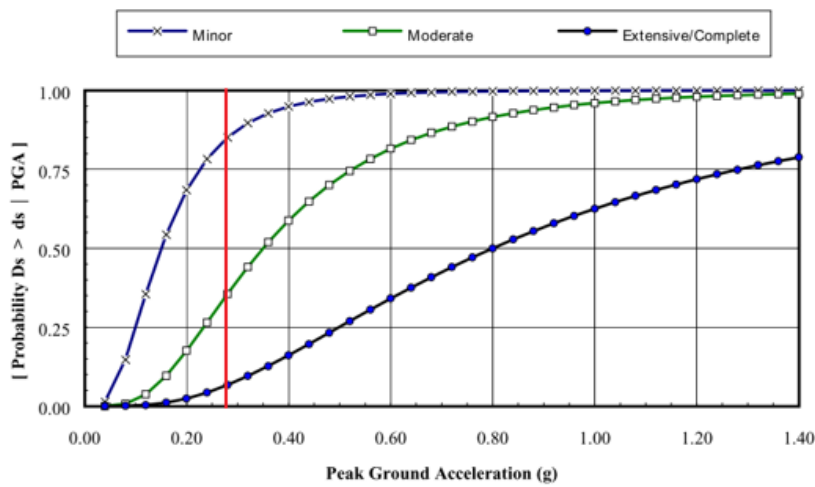


Figure 54: Fragility curves for rail mounted cranes/cargo handling equipment

Restoration curves for infrastructure components on Oahu

This section contains the predicted time necessary to restore damaged infrastructure components and are retrieved from (Department of Homeland Security and the Federal Emergency Management Agency, 2017b).

Table 22: Discretized restoration functions airport components

Classification	Damage State	1 day	3 days	7 days	30 days	90 days
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	100	100	100	100	100
	moderate	37	84	100	100	100
	extensive	16	17	20	34	79
	complete	11	11	12	16	31
Runways	slight/moderate	27	57	100	100	100
	extensive	17	18	21	44	95
	complete	10	11	12	20	53

Table 23: Discretized restoration functions port components

Classification	Damage State	1 day	3 days	7 days	30 days	90 days
Buildings, Waterfront Structures	slight/minor	96	100	100	100	100
	moderate	24	43	84	100	100
	extensive	17	19	25	63	100
	complete	12	13	14	22	53
Cranes/Cargo Handling Equipment	slight/minor	96	100	100	100	100
	moderate	20	31	57	100	100
	extensive	17	18	22	50	100
	complete	9	10	11	21	62

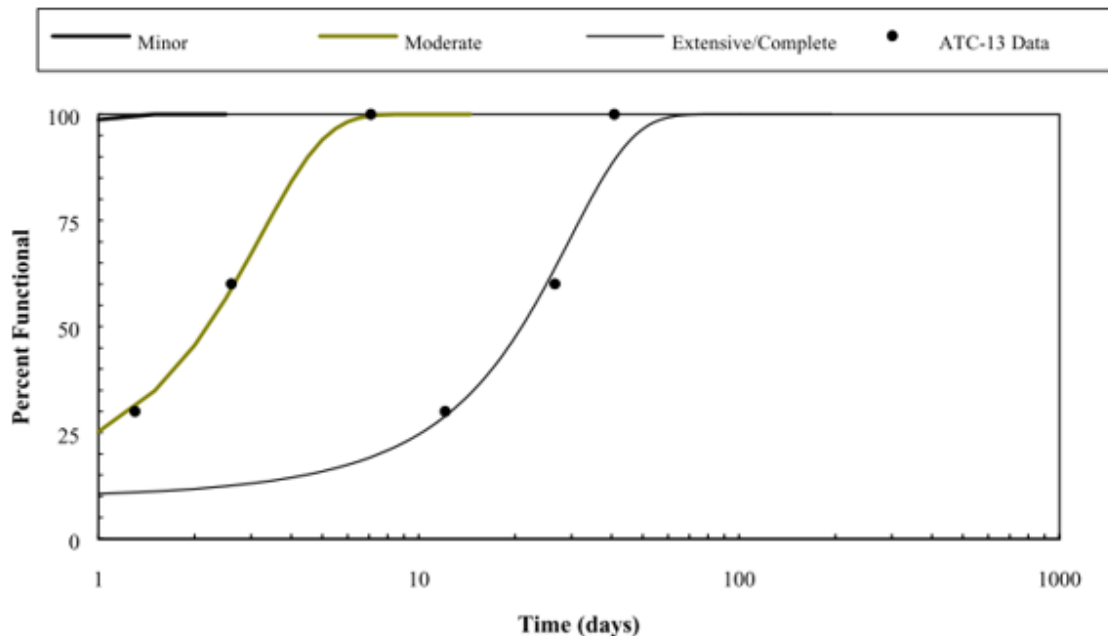


Figure 55: Restoration curve for major and urban roads

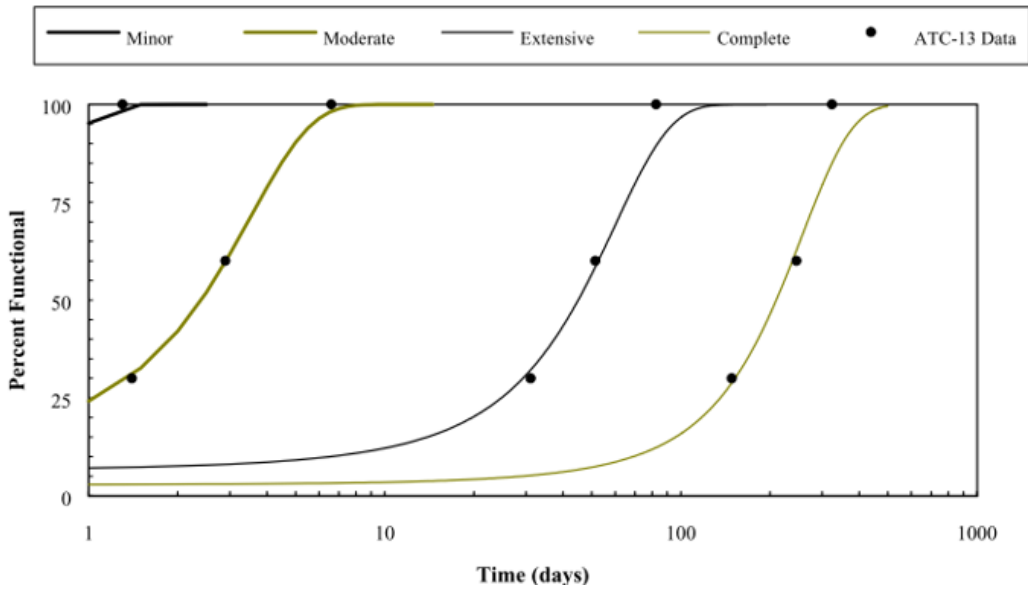


Figure 56: Restoration curves for highway tunnels

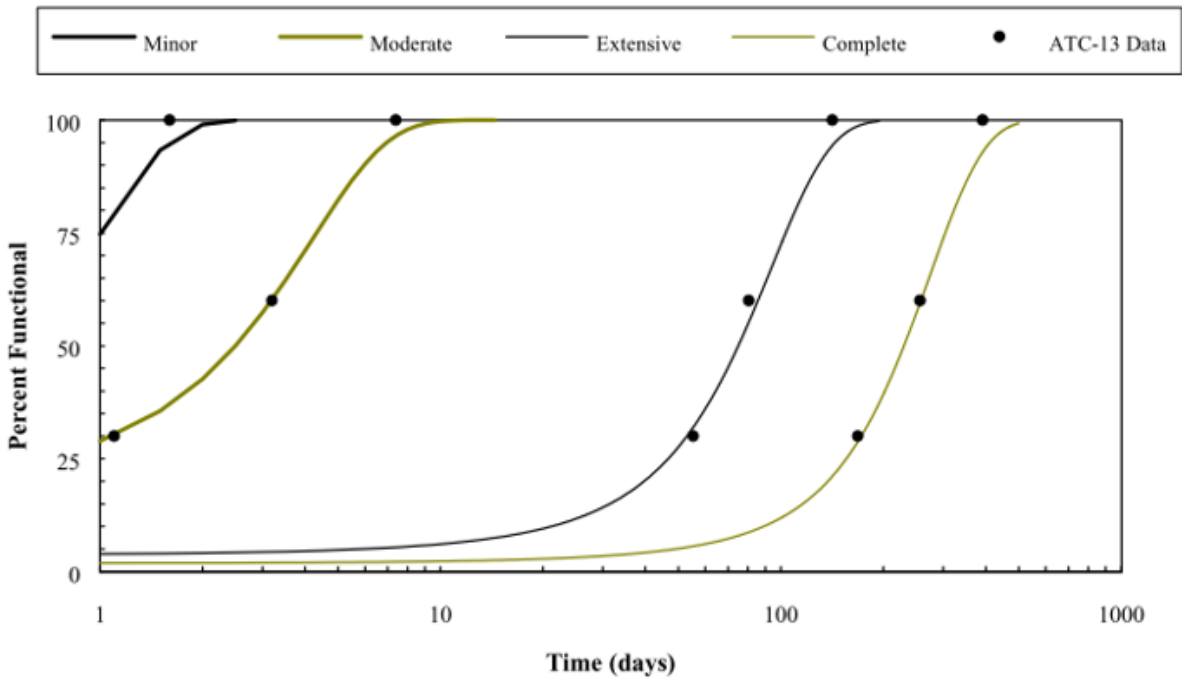


Figure 57: Restoration curves for highway bridges

Oahu transit line

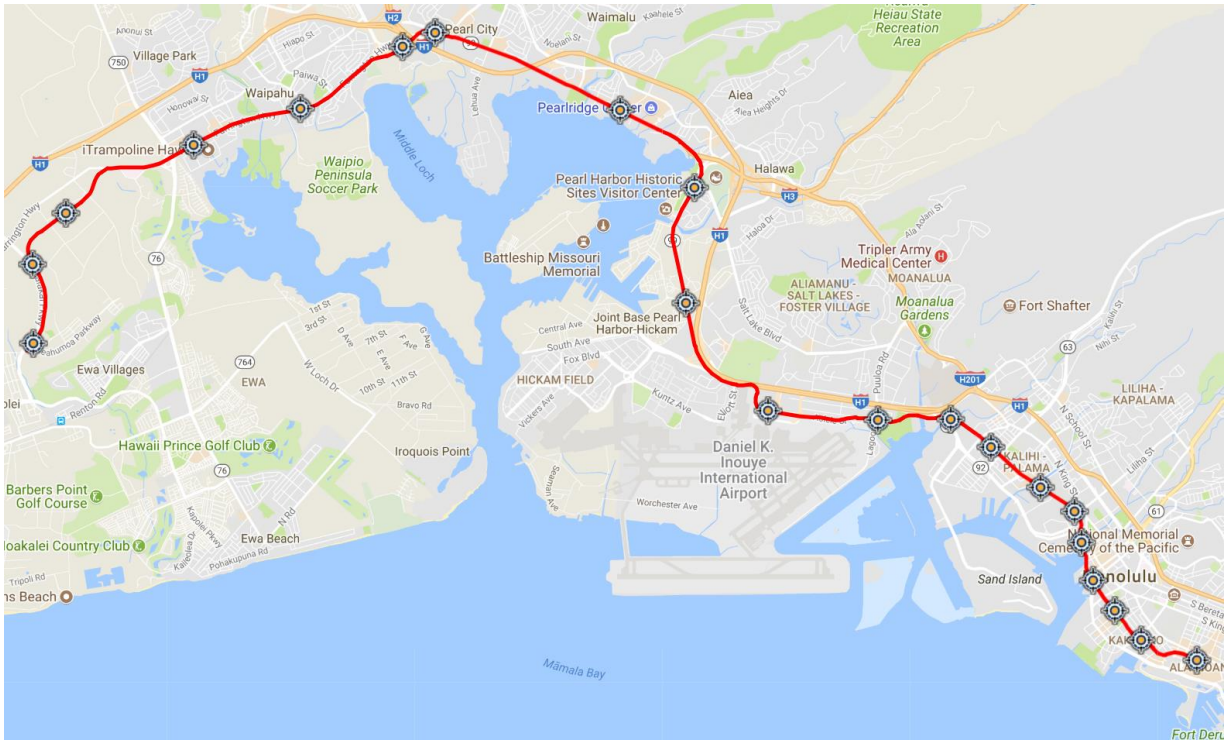


Figure 58: Planned route for the Oahu transit line (Honolulu Authority for Rapid Transportation, n.d.)



Figure 59: Evacuation map showing the area where the transit line will be built (NOAA Office for Coastal Management, 2015)

Appendix D: Assessment matrix filled in for Oahu

	1	2	3	4	5	Argumentation
Disaster						
Tsunami warning Time	No warning system in place.	Functioning sensing system in place that is capable of sensing a tsunami but is slow in the communication of the danger.	Malfunctioning warning system. System sometimes sends warnings in case there is no tsunami.	Functioning sensing system in place that does not immediately recognizes tsunami danger, but is capable of communicating the warning as soon as the danger is recognized.	Functioning sensing system in place, capable of sensing a tsunami and communicating the warning	There were false alarms due to insect nests in the warning sirens causing the tsunami alarms to sound when there was no tsunami threat(Hawaii News Now, 2013).
earthquake warning time	No warning system in place.	Warning system in place that has a low reliability of passing the warning.	Warning system in place but not connected to transport control.	Warning system in place, that can sense seismic activity but the communication to transport control takes a long time.	Well-functioning warning system in place that can sense seismic activity and communicate the warning to transport control.	No sources were found on existing seismic warning systems.

	1	2	3	4	5	Argumentation
Ability to cope with a tsunami/ earthquake						
Location	All infrastructure components will be inundated.	75% of infrastructural components are inundated	50% of infrastructural components are inundated	25% of infrastructure components are inundated	No infrastructure will be inundated in case of a tsunami.	air: more than 75% water: everything inundated road: app. 25% is inundated Chosen for 50% because road has more components than water and air.
Capacity	Capacity of the infrastructure is insufficient in normal use	Capacity of the infrastructure is mostly sufficient for normal use, there are some small exceptions	Capacity of the infrastructure is sufficient for normal use. Some bottlenecks may lead to major crowding in case of evacuation.	Capacity of the infrastructure is sufficient for normal use, but there are some bottlenecks leading to crowding in case of evacuation	Capacity of the infrastructure is sufficient in case of a disaster as well.	air: no data found water: no data was found road: already heavy congestion in day to day situations.
Fragility	Infrastructure components have a probability of major damage higher than 75%	Infrastructure components have a probability of major damage between 50 and 75%	Infrastructure components have a probability of minor damages higher than 50%	Infrastructure components have a probability of minor damages between 10 and 50%	Infrastructure components have a probability of minor damages of less than 10%	no data on roads, but bridges and tunnels are between 0.1 and 0.3, port infrastructure between 0.45 and 0.83
Network structure	less than 2 of the following: road and rail: Linear network air: only 1 airport water: only 1 port	Road and rail: linear network air: only 1 airport water: only 1 port	road and rail: linear network with some extra connections air: 1 airport water: 1 port	road and rail: medium connected network (multiple routes available between two points) air: 2 airports water: 2 ports	Road and rail: Highly connected network, high node degree. Air: 2 or more airports or helipads water: 2 or more ports	road: linear with some extra connections air: five airports water: 1 major port chosen for score between 3 and 4. The road network doesn't have a high connectivity. The water network has some redundancy by having 2 ports. The air network consists of 5 airports and is redundant.

Proximity to evacuation location	So far away that even when evacuating by car, safe location cannot be reached in time.	So far that evacuation by car is possible when there is no congestion	Allows evacuation on foot in less than 30 minutes	Close enough to allow evacuation on foot between 5 and 10 minutes.	Close enough to allow evacuation on foot in less than 5 minutes.	example: sand island. 8 minutes driving in case there is no congestion.
Location of people	Large number of people located in tsunami dangerous area at night and during the day.	Large number of people are in tsunami dangerous area during the day, small number of people located in tsunami dangerous area at night.	Large number of people are in tsunami dangerous areas (business area overlaps with tsunami dangerous area)	Small number of people are in tsunami dangerous areas during the day (for instance recreational areas, but no offices are located in tsunami dangerous areas)	No people are ever in the tsunami dangerous area.	business located at sand island, residential areas close to the coast.
Information	No means to know whether an area is safe or not. No signs. No maps. No warning.	No means to know whether an area is safe, no signs or maps, but a warning is given in case of a tsunami	People know if they are in a risk area, but not where they should go in case of a warning	Most information can be provided. There is a warning, people know if they are in a dangerous area and where to evacuate to. But they don't know how.	All information can be provided. A warning is given, people know if they have to evacuate and if so where to and how.	tsunami inundation zones, evacuation signs and warnings.
Personal context	Elderly, multiple person households, low income, ethnic minority, no experience with tsunamis				young, single person households, high income and education, experienced with tsunamis	Mix of tourists and inhabitants.

Choice options	No routes available	one route available, but no transportation means	more than one route available, only 1 mode of transportation available	more than one route available, transportation means available	multiple routes are available and multiple choices for mode	limited number of routes available. Choice between car and walking. Relatively high car ownership. (U.S. Department of Transportation, 2015)
Location of emergency services	Emergency services are all located in areas likely to inundate	Most of the emergency services are inundated	Half of the emergency services will be inundated	a small part of the emergency service locations are inundated, other locations remain usable.	Emergency services are spread over the area and will not be inundated.	fire stations, police department and hospitals located over the island, some along the coast, some further inland
Proximity to disaster area	Emergency services are not located within 10 km of the disaster area.	Emergency services are located between 1 and 10 km of the disaster area.	Emergency services are located within 1 km of the disaster area.	Most emergency services are located throughout the disaster area, one type is located further away.	Emergency services are located throughout the disaster area	on average. Some locations are close to the coast, other emergency service locations are located further inland (example west coast of Hawaii)
Accessibility of the disaster area	Earthquake and tsunami have destroyed all access to the disaster area.	Earthquake and tsunami have isolated parts of the disaster area.	Some locations are more difficult to access and they isolate large groups of people.	A few locations are more difficult to access. But the locations don't have many people.	Disaster had no impact on the accessibility between the emergency dispatch and the disaster area.	especially the towns along the west coast and the north part of the island become inaccessible after a tsunami. Within the larger cities, parts are inaccessible as well.

	1	2	3	4	5	Argumentation
Resources						
People	No people available for recovery.	People are available, but they lack the proper skills for rebuilding.	Sufficient number of people are available but a limited number of skillful people available	Insufficient number of people directly available.	Sufficient number of people directly available.	Oahu houses many military forces that could help recovering. Question is how many skillful people there are on Oahu itself, that data was not found.
Materials	No materials available with any recovering properties.	insufficient amount of materials available and of a lesser quality than ideal.	Materials are available, but of a lesser quality than ideal.	Insufficient amount of materials available with the right properties	Sufficient amount of materials available with the right properties.	Oahu is highly dependent on imported goods. There is no overview of what materials there are on Oahu, but the assumption is made that the amount of any type of material is insufficient to recover from a tsunami and earthquake.

	1	2	3	4	5	Reasoning
Ability to recover after a disaster						
Supply of relief goods	Not possible to supply the disaster area with relief goods due to damaged access points ((air)ports, roads)	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods within the disaster area is not possible or very difficult because of damaged roads.	Possible to supply the disaster area with sufficient relief goods. Access points are usable, but distributing is difficult due to damaged roads.	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods is possible because the roads are usable.	Possible to supply the disaster area with sufficient relief goods. Access points are still usable, from there relief goods can be distributed relatively easily within the disaster area.	One airport remains usable after a tsunami, the others will be inundated. That airport is located inland, meaning the roads surrounding it are not flooded. If the roads further inland are destroyed by an earthquake, it will become more difficult. Parts of Oahu will be difficult to supply because the roads leading there are inundated. Example Puerto Rico, containers full of relief goods were standing at the port for several days (NPR, 2017).
Preparedness	Tsunami or earthquake is never considered, and no disaster plans exist.				Tsunamis or earthquakes are planned for. Disaster plan is thought through, consists of multiple scenarios so in case of a disaster no time has to be wasted on who has to do what.	Inhabitants are prepared or are encouraged to be: (American RedCross, 2018) and should have supplies for 14 days. On governmental preparedness, no info was found.

Resource allocation	No planning is used at all. Resources are allocated randomly.				Based on damage overviews and resources available, recovery time is minimized.	Not possible to assess, not known how allocation will be after a disaster.
Governance	Governance prevents recovering activities. For example by having to reach consensus with everyone, or a need for permission from someone for every decision.				Governance enables recovering activities. For example by clear delegation of tasks in case of an emergency and emergency funding.	Look at Puerto Rico as sample case (Also USA island).

Appendix E: Scientific summary

The development of a tsunami resiliency assessment method for transport systems

ABSTRACT. Water related disasters with higher impacts due to climate change and the possible occurrence of higher magnitude earthquakes that are expected to hit increase the need for tsunami resilient systems. Transport systems enable evacuation, and access for emergency services and materials for rebuilding. This research aims to clarify the term tsunami resiliency for transport systems by means of decomposing the concept of ‘tsunami resiliency’ into separate factors first and then design an assessment method based on these factors. The measurements and best and worst case scenarios for the factors form the basis for a scoring range for each factor. This allows the assessing of a transport system on its tsunami resiliency.

Keywords: tsunami resiliency, transport systems , assessment method

1. Introduction

Earthquakes and follow up tsunamis damage houses, infrastructure and the land itself. This destruction makes it harder for people to evacuate from the area and for emergency traffic to reach it. It is of great importance that a resilient transport system is in place to accommodate these functions. Generally said, such a system should be able to absorb the impact of a disaster and maintain functional to facilitate outbound evacuation traffic and inbound emergency services during and directly after the disaster. On the longer term, a resilient transport network is a network that returns faster to its original functional state than a less resilient network when it is impacted by an event that disrupts their functioning. That such a system is desired is understandable. However up to this date, there is no guidebook on how to build a tsunami resilient transport system, or even what comprises a tsunami resilient transport system. If there is a desire for a tsunami resilient transport system but the knowledge on how to (re)design such a system is missing. Current resilience research is not sufficient to determine the resilience of a transport system hit by a tsunami. It is not known what the impact of such a disaster is on the performance of the transport system, or even what the right measure(s) of performance should be. If there is a way to assess tsunami resiliency, it will become possible to determine whether a transport system is tsunami resilient. It will also become possible to analyze current systems for possible future disasters in order to prepare for them in a better way. This research will therefore focus on the design of an assessment method for tsunami resiliency.

2. Methodology

The methodology of Peffers, Tuunanen, Rothenberger, & Chatterjee (2007) is used. They developed their methodology so that designers can approach a design problem in a systematic way. They have developed and applied their method on four cases with different characteristics. Their method is chosen for this research because it turned out to be effective for all four cases, one including the design of an assessment method. This method divides the design process into six steps that are comparable with methods as given by Howard, Culley, & Dekoninck (2008):

- Identify the problem
- Define the objectives and requirements of the solution
- Design and develop solution
- Demonstrate the use of the solution
- Evaluate the solution
- Communicate the solution

This paper will focus on the design and evaluation of the solution. The design and developing of the solution is the step where “the artifact is created” (Peffers et al., 2007). Such artifacts can be

constructs, models, methods, etc. For this thesis, this step is the design of the actual assessment method. This step includes determining the methods' functionality, its design and the creation. In this step the composite indicator model theory is used. An indicator model is the combining of a set of indicators that represent the dimensions of a topic that cannot be described by means of only one indicator. The model can summarize and clearly show how a system is performing with regard to the defined indicators and not lead to an absolute measure (Nardo et al., 2008). The benefits of using the composite indicator model for the topic of tsunami resiliency assessment is that it is easy to interpret and it can be used as a policy decision support tool. A point of attention is that when the indicators are poorly constructed they can lead to simplistic or wrong conclusions or even be misused to support a desired policy. However, these problems can be prevented when the indicators are derived in a transparent way and tested thoroughly. The entire method as explained by Nardo et al., (2008) consists of ten steps and took too long to perform fully during this research. The first two steps provide a theoretical framework and include data selection and can be used to make the assessment method.

3. Literature

The literature review provided an overview of the existing research on the resilience of systems. These systems are diverse; research exists on social systems as well as on telecommunication networks. Some research on transportation resilience also exists. As diverse as the research may be, there is some clear overlap. Resiliency consists of different properties, depending on the system of study. All literature on conceptual frameworks starts with properties defining the resiliency of the system. In most cases this lead to an overview of indicators, sometimes together with a range (Hosseini, Barker, & Ramirez-Marquez, 2016). Such an overview for tsunami resiliency of transport systems – which is currently lacking - is a good first step for the eventual assessment.

4. Design of the method

A tsunami resilient transport system is a difficult concept to fully grasp. Therefore a hierarchical structure with tsunami resiliency at the top is created. The further down in the decomposition, the more detailed and tangible the subjects will become. The subjects at the bottom of the hierarchy should be usable for the assessing of tsunami resiliency. This approach is similar to the first step of making a composite indicator model. The model structures characteristics or factors in a transparent way and enables a relative scoring of a system based on these factors. The factors can be qualitatively or quantitatively measured and are derived from observations of the system of interest. They should be precise, clear, interpretable and understandable (Merz et al., 2013).

The performance of a system is measured by means of one or multiple measures which depend on the system of interest. The resilience curve uses different phases; normal functioning, impact and recovery, this can be seen in Figure 1, where the impact (I) and recovery (R) are visualized. The left side of the curve is the performance level of the system under normal circumstances, then the system is impacted and the performance level decreases until further decrease stops. This is the impact phase. The impact phase is followed by the recovery phase, during which efforts are made to repair damages in order to increase the performance level of the system on the long term. Both the impact and the recovery phase are related to the decrease or increase of the performance level of the system. The 4 R's of Bruneau et al. (2003) can also be linked to these disaster phases. When a system has a high level of redundancy and robustness, the impact of a disaster is likely to be smaller. When there are plenty

of resources and the system recovers rapidly, the recovery phase will likely be shorter.

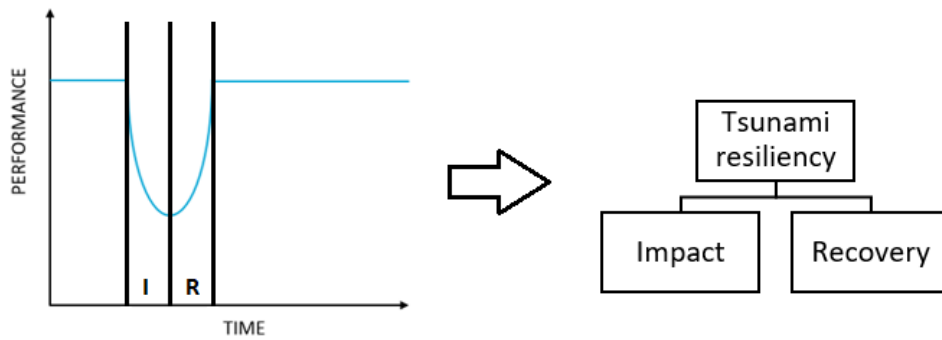


Figure 60: Decomposition of tsunami resiliency based on the disaster phases

The first step in the decomposition of tsunami resiliency for a transport system is a temporal decomposition based on the disaster phases. A transport system can be tested towards its resilience in relation to different time intervals surrounding a tsunami. The decomposition to the lower level indicates the two complementary factors that jointly determine the extent of the impact and the two factors that jointly determine the course of recovery. When the same system is impacted by a disaster, the severity of the impact depends on the severity of the disaster itself (disaster is visualized in the red block). On the other hand, if exactly the same disaster were to impact two different systems, the system that was designed for that disaster will likely suffer less damage than a system that was not designed for it; it has a higher ability to cope with that disaster (visible in the blue block). The course of recovery is also dependent on two factors. Resources and the recovering ability of the transport system. When system A and B have suffered exactly the same impact, but system A has more resources (visible in the yellow block) it is likely that system A will recover faster than system B. On the other hand, if the amount of resources is the same, but system A is designed in such a way that it enables easy repairs and system B is not designed with a possible reconstruction kept in mind, system A has a higher ability to recover (visible in the green block) and is likely to recover faster than system B.

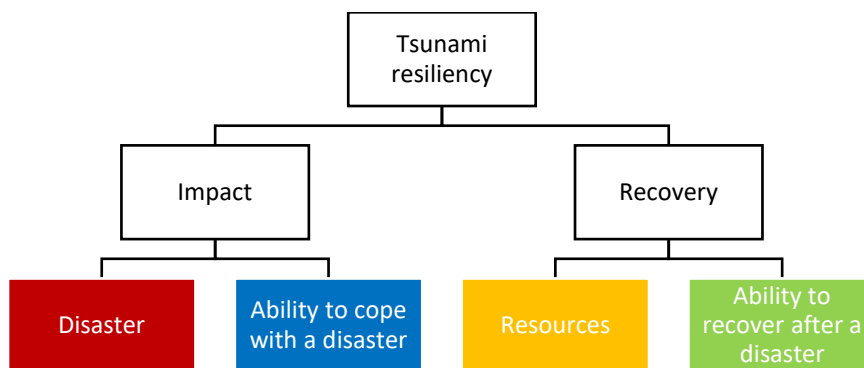


Figure 61: Second step in decomposing tsunami resiliency

The four blocks are decomposed into separate factors. By determining the form of measurement and the worst and best case for each of the factors, assessment matrices are created. These matrices are based on the four themes. The factors can be given scores between 1 and 5 where a score of 1 corresponds to the worst case and a score of 5 corresponds to the best case. This leads to the matrices visible in Table 1, 2, 3 and 4.

Table 24: Assessment matrix for disaster related factors

	1	2	3	4	5
Tsunami warning time	No warning system in place.	Malfunctioning warning system. System sometimes sends warnings in case there is no tsunami.	Functioning sensing system in place that is capable of sensing a tsunami but is slow in the communication of the danger.	Functioning sensing system in place that does not immediately recognizes tsunami danger, but is capable of communicating the warning as soon as the danger is recognized.	Functioning sensing system in place, capable of sensing a tsunami and communicating the warning
Earthquake warning time	No warning system in place.	Warning system in place that has a low reliability of passing the warning.	Warning system in place but not connected to transport control.	Warning system in place, that can sense seismic activity but the communication to transport control takes a long time.	Well-functioning warning system in place that can sense seismic activity and communicate the warning to transport control.

Table 25: Assessment matrix for 'ability to cope with a disaster' related factors

	1	2	3	4	5
Location	All infrastructure components will be inundated.	75% of infrastructural components are inundated	50% of infrastructural components are inundated	25% of infrastructure components are inundated	No infrastructure will be inundated in case of a tsunami.
Capacity	Capacity of the infrastructure is insufficient in normal use	Capacity of the infrastructure is mostly sufficient for normal use, there are some small exceptions	Capacity of the infrastructure is sufficient for normal use. Some bottlenecks may lead to major crowding in case of evacuation.	Capacity of the infrastructure is sufficient for normal use, but there are some bottlenecks leading to crowding in case of evacuation	Capacity of the infrastructure is sufficient in case of a disaster as well.
Fragility	Infrastructure components have a probability of major damage higher than 75%	Infrastructure components have a probability of major damage between 50 and 75%	Infrastructure components have a probability of minor damages higher than 50%	Infrastructure components have a probability of minor damages between 10 and 30%	Infrastructure components have a probability of minor damages of less than 10%
Network structure	less than 2 of the following: road and rail: Linear network air: only 1 airport water: only 1 port	Road and rail: linear network air: only 1 airport water: only 1 port	road and rail: linear network with some extra connections air: 1 airport water: 1 port	road and rail: medium connected network (multiple routes available between two points) air: 2 airports water: 2 ports	Road and rail: Highly connected network, high node degree. Air: 2 or more airports or helipads water: 2 or more ports
Proximity to evacuation location	So far away that even when evacuating by car, safe location cannot be reached in time.	So far that evacuation by car is possible when there is no congestion	Allows evacuation on foot in less than 30 minutes	Close enough to allow evacuation on foot between 5 and 10 minutes.	Close enough to allow evacuation on foot in less than 5 minutes.
Location of people	Large number of people located in tsunami dangerous area at night and during the day.	Large number of people are in tsunami dangerous area during the day, small number of people located in tsunami dangerous area at night.	Large number of people are in tsunami dangerous areas (business area overlaps with tsunami dangerous area)	Small number of people are in tsunami dangerous areas during the day (for instance recreational areas, but no offices are located in tsunami dangerous areas)	No people are ever in the tsunami dangerous area.

Information	No means to know whether an area is safe or not. No signs. No maps. No warning.	No means to know whether an area is safe, no signs or maps, but a warning is given in case of a tsunami.	People know if they are in a risk area, but not where they should go in case of a warning.	Most information can be provided. There is a warning, people know if they are in a dangerous area and where to evacuate to. But they don't know how.	All information can be provided. A warning is given, people know if they have to evacuate and if so where to and how.
Personal context	Elderly, multiple person households, low income, ethnic minority, no experience with tsunamis				Young, single person households, high income and education, experienced with tsunamis
Choice options	No routes available	One route available, but no transportation means	More than one route available, but no transportation means	More than one route available, transportation means available	Multiple routes are available and multiple choices for mode
Location of emergency services	Emergency services are all located in areas likely to inundate	75% of the locations will be inundated	50% of the locations will be inundated	no more than 25% of the locations will be inundated	Emergency services are spread over the area and none will be inundated.
Proximity to disaster area	Emergency services are not located within 10 km of the disaster area.	Emergency services are located between 1 and 10 km of the disaster area.	Emergency services are located within 1 km of the disaster area.	Most emergency services are located throughout the disaster area, one type is located further away.	Emergency services are located throughout the disaster area
Accessibility of the disaster area	Earthquake and tsunami have destroyed all access to the disaster area.	Only possible to access the disaster area via air.	Possible to access the disaster area via roads, but with access is very difficult due to large damages.	Possible to access the disaster area via roads, but with increased travel times due to damages and decreased capacity on the roads	Disaster had no impact on the accessibility between the emergency dispatch and the disaster area.

Table 26: Assessment matrix for resource related factors

	1	2	3	4	5
Location, amount and skills of people	No people available for recovery.	People are available, but they lack the proper skills for rebuilding.	Sufficient number of people are available but a limited number of skillful people available	Insufficient number of people directly available.	Sufficient number of people directly available.
Location, amount and properties of materials	No materials available with any recovering properties.	insufficient amount of materials available and of a lesser quality than ideal.	Materials are available, but of a lesser quality than ideal.	Insufficient amount of materials available with the right properties	Sufficient amount of materials available with the right properties.

Table 27: Assessment matrix for 'ability to recover from a disaster' related factors

	1	2	3	4	5
Supply of relief goods	Not possible to supply the disaster area with relief goods due to damaged access points ((air)ports, roads)	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods within the disaster area is not possible because of damaged roads.	Possible to supply the disaster area with sufficient relief goods. Access points are usable, but distributing is difficult due to damaged roads.	Possible to supply the disaster area with a limited amount of relief goods. Distribution of the relief goods is possible because the roads are usable.	Possible to supply the disaster area with sufficient relief goods. Access points are still usable, from there relief goods can be distributed relatively easily within the disaster area.

Preparedness	Tsunami or earthquake is never considered, and no disaster plans exist.				Tsunamis or earthquakes are planned for. Disaster plan is thought through, consists of multiple scenarios so in case of a disaster no time has to be wasted on who has to do what.
Resource allocation	No planning is used at all. Resources are allocated randomly.				Based on damage overviews and resources available, recovery time is minimized.
Governance	Governance prevents recovering activities.				Governance enables recovering activities.

The method is tested by applying it to the transport system of the Hawaiian island Oahu. Some factors proved difficult to score because they consist of more than one topic, for instance the location of infrastructure. Because there are different modalities, this factor should have been decomposed further in order to make it easier to score. The factor ‘personal context’ does not have a full scoring range. This is because the factor consist of several characteristics such as age, income and experience with tsunamis, it is not known which factor contributes most to the personal context factor as a whole. Overall, the factors related to the impact phase proved useful and lead to an overview of strengths and weaknesses of Oahu. The factors related to the recovery phase did not lead to strong conclusions. It can be seen that the factors ‘preparedness’, ‘resource allocation’ and ‘governance’ do not have a full scoring range but only have a best and worst case. Within the time frame of this research, it was not possible to develop a logical scoring range.

The assessment matrices provide an initial exploration and cannot be used as a decision making tool. It is not precise enough; only one scenario is considered and the different factors are not weighed so it cannot be said which factor contributes most to the tsunami resiliency. However it does provide an overview of factors to take into account when analyzing the transport system in relation to tsunamis and earthquakes. The developed method can be seen as a first step in the analysis of the tsunami resiliency of a transport system and could prove to be a useful decision making tool when developed further.

5. Conclusion

In order to assess the tsunami resiliency of transport systems several steps are necessary. The first step was the deriving of factors that affect the tsunami resiliency of transport systems. The desired and undesired values of these factors are determined and lead to a scoring range between 1 and 5 for most factors, some factors require further research before the 1-5 scale can be determined. The next step is to fill in the assessment matrix by giving the tsunami resiliency factors a score between 1 and 5. This results in a color coded assessment matrix which at first glance gives an average idea about the tsunami resiliency, if all factors are graded with a green cell, the transport system is tsunami resilient. When all factors are graded with a red cell, the transport system is not tsunami resilient. The assessment matrix also allows the comparing of two transport systems and can determine on which factors one system scores better than the other. However, the assessment method as designed in this research is not usable as a decision making tool. The developed method could be improved by validating the factors

and developing the scoring ranges by interviewing more experts in the transport or disaster management field. Also, the method could be developed further by following the methodology of the composite indicator model. The factors will then all be weighed and tested on interdependencies leading to a more usable method suitable for decision making.

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