How tsunami transmission is influenced by floating city design parameters

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How tsunami transmission is influenced by floating city design parameters

by

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Preface

Dear reader,

This thesis is written as part of the Master of Science in Hydraulic Engineering (Coastal Engineering) at the Technical University of Delft. In this work I present the result of modeling both a floating structure and a large wave representing a tsunami. This topic made me enthusiastic as it touches futuristic society supporting technology, but theory based and therefore understandable as based on mathematics. I would like to thank all my supervisors for guiding me trough this project. Sometimes can be rather difficult, especially in these challenging Corona times.

I could not have performed this research without my family and my friends. I would like to express my gratitude to my family, who never doubted that I could finish my study, but also help me see things from a different perspective. Next to that I would like to thank my room mates. Cooked up in our tiny house, they really feel like a second family. Of course also everyone who helped read a page or two.. Bieke, Laura, Charlotte, Lieke for being my "Leek", thank you so much! Finally I would like to thank myself, for my patience and perseverance. I learned so much from this process and I am really happy that it is now ready and finished.

Summary

For both developed and developing nations, coastal zones form an attractive location for urban settlements. With the expected increase in the earth's population, coastal areas will experience a further increase of inhabitants. Floating city development could therefore be an interesting alternative for land-based urban expansion on land [41]. Expanding an urban settlement towards the ocean however, will make it more susceptible to extreme forces such as a tsunami waves. By generating more knowledge on how a floating structure interacts with a tsunami wave, it can show the potential value that a floating city can bring. If a floating city limits the effect of (extreme) events such as tsunamis, it can protect the coastal zone which is located near a floating city. To provide an answer to this question, this research will focus on how a floating structure can reduce the transmission of a tsunami.

With the construction of an analytical model, representing the floating structure and the tsunami wave as simplistic as possible, the system can be understood more quickly. If the problem is solvable by generic programming language, this would mean that it can solve a larger range in the spectrum of the problem. The conceptual model features two options: one where the platform has no freedom of movement, the other where the platform can move vertically. They both assume that hydrostatic pressure holds during wave propagation and a linearization of the momentum equation describing the water particle interaction. For each option, the transmitted wave height is determined based on varying the floating structure dimensions. This gives an indication on which parameters are of influence in the transmission of the wave.

First, the conceptual model is analysed by changing the platform draft and the length for both the motionless and the vertically moving platform. Both options are influenced most by the length of the structure. The situation with the motionless platform shows this effect earlier, by a higher wave attenuation percentage for the same platform length. Whether the draft also has an influence is strongly dependent on the value representing the length of the platform. The difference between the two platform movement options shows that the effect of changing the allowed movement of the platform is significant. Next to the reduction in transmission, the conceptual model shows signs of resonance. The moving platform option in the model is formed by a second order differential equation. Fitting this equation, resonance is evident and therefore visible for certain combinations of the platform dimensions. In addition damping is present, ensuring that there are some parts where, despite the natural frequency pointing there, no resonance occurs. The amount of damping is strongly linked to the platform length, with a higher level of damping for a longer platform length.

Finally, the results from the conceptual model are compared to the outcome in SWASH. This numerically based model has the possibility to simulate a tsunami wave in its development towards the coast and also features a buoyancy function for structures. This comparison serves as a validation of the conceptual model. In general, the conceptual model always results in a less reduced wave attenuation percentage and can be said to be more conservative. Due to the assumptions of leaving out the non-hydrostatic pressure and a lower level of detail, a maximum of 5% deviation in both model results occured. This however, matches with the fact that it is a less detailed model and adds to the reasoning that the conceptual model provides what it is meant for.

Next to the effect of the structure itself, the positioning of the structure is also of large importance. Wave height and intensity of the wave will vary due to the surrounding local coastal features. Next to that, the local water depth is determinant in compressing the wave, therefore decreasing the wave length when the water depth decreases. The maximum wave attenuation that can be achieved according to both models is 10%, considering platform dimensions and location variations. The conceptual model appears to work for which it is intended: modelling the resulting transmission between a floating structure and a linear tsunami. It is expected that modelling programs can be expanded and/or improved, so that more realistic floating structures can be modelled. However, it will remain difficult to accurately model a tsunami as it is complex in behaviour. Yet, this research brought the field one step closer to evaluating the transmission of tsunami waves when interacting with a floating structure of certain dimensions.

Contents

1 Introduction

1.1. Context

Since 2007 more people are living in an urban environment instead of a rural community. This is expected to grow even further, so that two third of the world's population will be living in an urban area halfway through this century [8]. For both developed and developing nations, coastal zones form an attractive location for urban settlements. This results in 60% of the largest 39 cities in the world to be within 100 km of the coast [28]. With the expected increase in the earth's population, the coastal urbanization is expected to only increase. Floating urban development could therefore be an interesting alternative for land-based urban expansion and urban renewal on land [41], in particular for port cities that are more keen to have sheltered water available. Next to that they often feature broad economic activity and maritime expertise to support upcoming technologies. As population density around the coast is relatively high, alternatives of living need to be thought of. Especially as these areas are under risk of sea level rise. Depending on the severity of this rise coastal areas could benefit from urban floating development. Floating structures can adapt easier to sea level rise compared to traditional urban expansions which is a beneficial aspect for this technology. It can appear as an extension of an already existing city or form an entire new community by itself.

Traditionally, homes on water developed out of necessity connected to the type of livelihood (such as fishing) and because it was a cheap option compared to land-based urban development. The first occurrence of using floating structures as homes in the Netherlands started from the end of the 19th century [32]. To this day, floating homes are much more regulated and not necessarily a cheaper option but can still be found as a part of almost every Dutch city. A current hot topic in floating urban development is building floating communities, as those also often form a link with circular development. These projects often combine singular family homes into a community. Floating structures are also used in other ways, for example to form a bridge, serve as storage or host a power plant. Next to that, known examples are for harbours in the form of floating piers [39].

The development towards a larger community living on water is also on its way. Some floating city inspired design concepts can be seen in figure 1.1. The left image (1.1a) shows the planned development of an old harbour area in the city of Rotterdam. The development incorporates a floating park in addition to several floating community buildings [1]. The other figure (1.1b) shows a visualisation of a floating city design presented by Oceanix from 2019. This design forms a conceptual solution for coastal regions under pressure of sea level rise and a more sustainable option considering the topics of energy, water, food, and waste [29].

(a) Rotterdam Rijnhaven - harbour development including several floating structures [1]

(b) Oceanix floating city design [29]

Figure 1.1: Examples of several floating city related visualisations

Expanding an urban settlement towards the ocean will make it more susceptible to nature's forces. These forces can impact such a settlement in the form of waves, wind and currents. Next to the more regular forces that such a city might experience, extreme forces should also be considered. An example of such an extreme force is a tsunami wave. Tsunamis are well known hydraulic phenomena that once arriving to a coastal stretch are often responsible for loss of life and significant damage to an area. These waves can occur in every large water body after the occurrence of strong seaquakes or large submarine landslides. Regions that are not even in close vicinity of the origin of the tsunami may be affected due to the fact that it travels significant distances without attenuation[3]. A well known impactful event is the 2011 tsunami, flooding a large coastal region of Japan.

By generating more knowledge on how a floating structure interacts with a tsunami wave, it can show the potential value that a floating city can bring in addition to coping with sea level rise. Can a floating city limit the effect of (extreme) events such as tsunamis? This could mean that it can protect the coastal zone which is located near a floating city. This research will therefore mainly focus on how a floating structure can reduce the transmission of a tsunami.

Marine construction company, Blue21 is active in designing and producing floating structures. They aim to provide a solution to coastal cities in their problem with housing the growing world population. This research supports Blue21 by gaining more knowledge on tsunami hydrodynamics and their interaction with floating structures.

1.2. Problem statement

To be able to implement a floating city design, especially the interaction with hydrodynamic forces need to be analysed. It is important for both the safety of the structure and also the structural design of such a city that more is known about this topic. Floating cities are still in the conceptual phase, so a lot can still be changed in design parameters. For example, the dimensions of a platform or the way multiple platforms are connected. This research serves to provide insight how design parameters can influence and possibly reduce the impact of hydrodynamic forces. This research specifically focuses on the dynamics between a floating city and a tsunami wave and how this influences the wave transmission, as this still is a relatively unknown subject.

A way of analysing how a change in design might change the interaction with hydrodynamic forces, is through numerical modelling. Models are a good alternative compared to lab experiments for this problem as it deals more easily with (small) adaptations and it reduces costs of the research. However, modelling the interaction between a floating structure and a tsunami wave is not yet possible to a high level of detail. It entails combining numerous processes such as detailed tsunami propagation to the coast, correct bathymetry representation and 3D movement of a floating platform. Next to that, environmental aspects differ strongly per location which makes every location unique, making this even more complicated. This research will bring us a step closer to gain a better understanding of how a floating community can change the transmission of a tsunami wave.

1.3. Objective

This research will have the following questions as main driver:

- How do design parameters of a floating city influence tsunami propagation?
- How well can a simplified analytical model work in representing a floating structure and a tsunami?

To be able to answer these question, the following sub-questions are used to provide additional information. This will help in understanding specific aspects of the research questions and support the process of finding and formulating an answer.

I What are typical dimensions of a floating city?

II How does a tsunami behave and what are important features of such a wave?

III What influences a tsunami wave and how does it develop into a coastal hazard?

IV How can the interaction between a tsunami and a floating city be modelled?

V How does an in complexity reduced analytical model work compared to more detailed and computationally expensive models.

1.4. Approach

To find out more about the specifics of a floating city and the behaviour of tsunamis in their approach to the coast, a literature study is performed. This provides more insight in the parts of a floating city that should be represented in a model. Next to that, understanding the origin of a tsunami wave and how it develops towards the coast, helps in understanding what is important for the tsunami and structure interaction and about representing a tsunami in a model.

As accurately modelling such a situation requires a sufficient amount of detail of the situation, this creates a difficulty. Creating a model for each specific location takes a long time and is therefore not an efficient way to work. A more simplistic and general model that can give a first indication can form a good alternative. This essentially means a more general approach, which has the advantage to allow to look at the problem as broad as possible. Next to that it means that the problem is solvable by generic programming languages and results in quick answers. Which is useful in understanding a system more quickly.

This research features a simplified analytical model that was constructed. A conceptual model such that it becomes a representation of reality, first the theoretical background and basis of the model should be investigated and described. The representation of the structure and the wave are as simplistic as possible and then extended to incorporate more detail where necessary. This is done by introducing more degrees of freedom, such as vertical movement in the structure. Doing this step by step, creates the opportunity to learn how the system works. With the ultimate goal to give an indication which design parameters are of influence in the transmission of the wave due to interaction with the floating system. This model if referred to as 'conceptual model' in the remainder of this report.

Next to creating this conceptual model, a comparable situation is created in SWASH. SWASH provides can simulate different types of flow and transport phenomena in coastal waters as driven by waves, tides, buoyancy and wind forces. It therefore has the possibility to simulate a tsunami wave in its development towards the coast. Besides simulating various wave transformation options, SWASH features a buoyancy function for structures. This is useful for this specific research and provides the opportunity to compare the outcome of the different models for similar situations. By replicating this situation, it is possible to validate the conceptual model and certain assumptions that are made to build this model. The process and equations behind the modeling of SWASH are also described so that it is more clear on what aspects the two models will differ.

This report features a literature research featuring background information on both the development in the floating city concept and important structural design feature. Then a connection is formed to hydrodynamic forcing of floating structures. Additionally tsunami development towards the coast is analysed (Ch. 2). The next chapter is dealing with the model theory behind both the conceptual model and SWASH (Ch. 3). The following two chapters feature the results of both models (Ch. 4 + 5). Finally validation of the used models and remarkable features within the results are discussed, next to the concluding remarks and recommendations for future research in the field of floating structures interacting with large waves.

2
Literature research

This chapter will describe multiple theoretical aspects. First it will focus on the (recent) development in floating city design followed by the most important hydrodynamic forcing mechanisms that have an impact on a floating city. After this the theory behind the origin and development of a tsunami wave will be discussed.

2.1. Development in floating city design

The concept of a floating city in itself is a new concept which dates from the last few decades. It is still a conceptual idea and not yet implemented. However with the upcoming expected land scarcity and improvement of technology this might become reality in this century [39]. Several conceptual designs have been made so far. In general they feature large platforms that fulfill multiple functions such as industrial, food or energy related use, with the most important being housing inhabitants. The combination of multiple floating platforms can form a large community up to a city featuring forms of homes, industry or leisure.

Currently there is no example of large-scale floating development with the purpose of living available. Current knowledge that is available includes floating offshore accommodation in the offshore and shipping industry, and floating urbanisation on the calm inland and coastal areas [22]. Since the early development of floating structures, different architectural and urban planning floating applications like floating piers, hotels, fuel storage facilities, stadiums, bridges and airports have been thought of and build [12]. Especially in Asia concepts and realised projects exist for some decades. The fact that the applications of floating structures are variable helps in the development towards the existence of a floating city. The following examples show a few of these applications.

- Floating bridge
  An example of a floating structure is the following bridge (Figure 2.1). The Yumemai Bridge is a floating swing arch bridge, supported by two steel pontoons in the Port of Osaka, Japan. It has been used since 2001 and it connects two reclaimed islands to the regional road network. Larger marine vessels, that normally would not fit underneath, can pass with ease as the bridge can swing open by use of tug boats. This reduces the required structural height of the bridge. Especially for areas that are susceptible to extreme weather events this is a favourable option to withstand typhoon-level winds and waves [38].

Figure 2.1: The Yumemai floating bridge in Osaka, Japan [40]

- Floating solar farms
  For a community, a source of energy is key. Not every potential floating city location will have the possibility to connect to the main land for its power. Floating solar energy uses the technique of floating and the advantage of open water areas to generate power. Although it cannot yet support a community as a single power source, it is an interesting and useful development. Floating solar can be found in locations all over the world. Asia however has been active in the earliest developments. For example Singapore, there the installed capacity in 2020 was 350 MWp and is to increase significantly by 2030 [11]. Most of the installations today are based on relatively small and calm inland waters like industrial basins, reservoirs and other inland water surfaces. A development however is still required to be able to withstand challenging conditions on sea, and for the structure to remain durable and reliable. [11].

Figure 2.2: An example of a floating solar installation on water in Singapore [11]

- Floating Farm
  Next to infrastructure options and energy related solutions, food is also a required aspect for (remote) communities. A specific example of floating food production that is currently present is a floating farm that can be found in Rotterdam, the Netherlands. As of this moment it is located inside an old harbor area, existing next to a traditional land based city. The farm is an example of alternative use of space inside a city. It houses a number of cows and plans to also feature a vegetable farm. Providing the city with a food source within it's center. Next to that it runs on local sources for food and energy, with the goal to be as circular as possible [14]. This provides potential for floating communities as well, as it provides knowledge, which can provide its worth once larger floating communities start to emerge.

Figure 2.3: The floating farm that houses cows and a dairy production site [9]

All the examples above show that floating structures exist in all shapes and sizes and with numerous functions. Floating structures have advanced noticeably through the last decades and now the focus shifts to creating the situation where large communities on a floating base are possible. Next to land scarcity and technological development, the sustainable aspects of a floating city will speed up the development. In general several aspects of a floating city can be considered as sustainable. Where a sustainable building is a term describing environmentally conscious design techniques in the field of architecture [26]. Sustainable features for floating cities can be one of the following:

- Modularity
  The idea is that communities will consist out of multiple floating structures that are modular and that the general shape and size of the structure can therefore change. This creates an advantage in length of use towards land based communities as they are not as flexible towards change in demand of the structure.
- Increased renewable energy production
  For specific situations such as generating renewable energy, it will be easier to obtain higher production rates. This has to do with the fact that there are less obstacles present that could potentially block sun or reduce wind speeds. Easier to obtain renewable energies, as on sea you won't find obstacles [26]
- Self sufficiency
  Depending on the location of a floating community, connections to the main land can be difficult. This forms a driving a force for self-sufficiency, as obtaining energy or food from the main land may be more difficult and expensive. An example of this is a way to recycle nutrients and carbon dioxide that are produced in an environment. They can be used as input for algae cultivation. The algae production can then be used for bio-fuel and food production [41]. A different way of reaching self-sufficiency is by looking to use resources as efficient as a sustainable possibility. Structures fore example can be designed to make efficient use of daylight and the heat of the sun [7].

An example of ongoing research in the floating city concept was the Space@Sea project, which was active from 2017 - 2020. Several European institutes, such as Marin (Maritime Research Institute Netherlands), participated in researching and testing various aspects regarding this concept. To show the potential of multi-use modular floating islands the Space@Sea research covered the following aspects [36] :

- Business case of several potential use cases
- Regulations & guidelines
- Proposal for a design including building instructions and info on operation and maintenance
- Risk assessment on this specific project and it is deliverables
- Important social factors to consider
- Structure demonstration in wave tank

As part of the design proposal, hydrodynamic interaction was also featured. to a limited extent.
An example of that was the demonstration in a wave tank, where a large floating structure was tested in the Offshore Basin of the Marin (see figure 2.4). With help of this test facility, the hydrodynamic response of the island forced by waves and current loads was analysed. Focusing on the motions between and forces in the multiple interacting bodies. This test used an irregular sea state as wave input, simulating a wide variety of waves. From this the following aspect could be concluded: "The overall stability should not pose any issues due to the large scale of the floating body (island)" [22]. A useful feature for floating city design in general, this however is without considering extreme events such as storms or tsunamis into account. The tank test campaign however showed that the modular concept of the Space@Sea island is technically feasible under these specific conditions. Next to that, the hydrodynamic response of the island and its sub-components matched the expectations from pre-studies and simulations. The general recommendation that is made [30] directs towards more developing work to be done in future, to make the islands more reliable in storm conditions.

In general, the research from the Space@Sea project adds a lot to the branch of floating city research. Next to the wave-structure interaction that it covers, also many other preconditions that are important for the possible development of living at sea on floating platforms are covered.

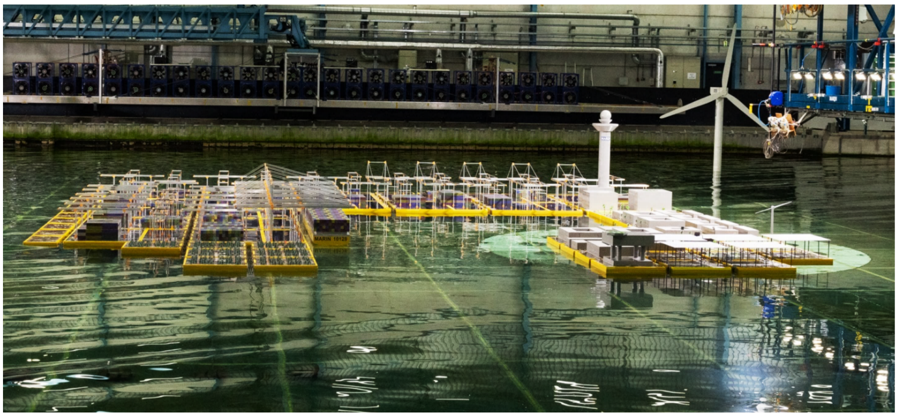

Figure 2.4: Photo of the realized integrated demonstrator model for Space@Sea program [30]

The technology and mindset of the current time we live in is ready for floating cities, The necessity however is not yet urgent enough to decide towards investing in such a large project. In addition, the extreme situation that a floating city might encounter, such as storm winds, waves and possible tsunamis, still create unknown situations. The following chapters are to contribute to those low researched areas.

2.2. Technical design aspects in floating city design

A floating city will consist out of several different floaters. Combined they can form a community. The size of the structure as a whole and that of the different platforms is important in representing a length scale. This length scale will determine to what extent a structure interacts with a wave. What the length of a structure should be is determined by several factors. First of all on the function that the platform should fulfill. The material that it is made is another as it may limit the maximum size of the platform. Thirdly, the wave climate at the location of a project can influence the desired size or structure type of a floater. As a more energetic wave climate desires more stability from the structure and the size of a structure can influence wave attenuation. Making size of the structure an interesting variable for designing a floating city.

Different float techniques can be used for a floating structure and they differ in stability towards waves. Where semi-submersibles are more suitable for open sea waves (bottom 2.5). They use stabilizing column tubes or a ballast structure to minimize the effect of waves while maintaining a constant buoyancy force. Due to the more difficult structure however they are less interesting for use in large floater constructions [39].

Pontoons (top Figure 2.5) are in itself more suitable for sheltered lagoons and low wave energy areas, as they float on the water surface. The structure of the platform is much more simplistic, which makes it easier and relatively cheaper to manufacture [39]. This is why most designs feature a pontoon type of structure for the floating platforms.

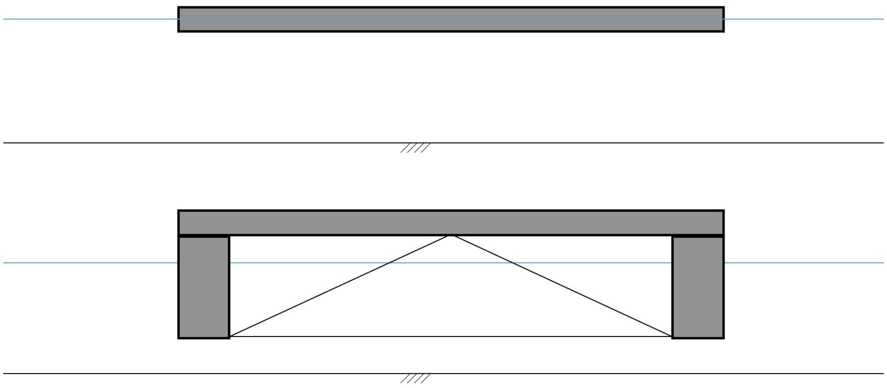

Figure 2.5: Different floating platform types

The way different floaters are oriented towards each other and shaped into a larger structure can happen in numerous ways. An example of combining this can be seen in Figure 2.6. The way individual modules are combined to form a structure can also make a difference in stability of the structure and the wave damping [6]. The necessity of combining floaters is because the structure should be able to host a (large) community. Mainly because of that, a floating city will be too big to construct out of one piece. This is why a system of connections are required. Figure 2.6 shows an example of floater components and how they could be combined to form a larger structure. The inter-connections are present to keep the combined structure together and can also function to absorb movement and stabilize the floater [39]. This is of importance when modelling a system of floaters, the type of connection determines the type of response from the floater. For example, a hinged connection allows for movement up to a certain extent. This means that the different floaters can experience different movements relative to each other. For a rigid connection however the platform combination should be considered as a more or less rigid system.

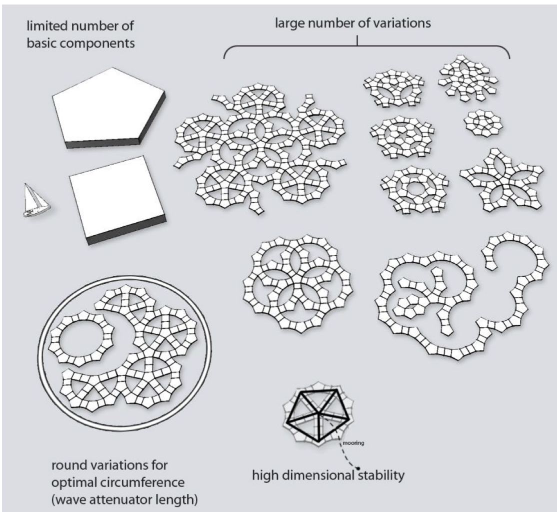

Figure 2.6: Seasteading / DeltaSync modular design shapes to form a floating city [6]

To make sure that the floating structures do not drift off, they are connected to the sea floor by a mooring system. The mooring system steadies the floating structures and must be well designed as it secures the position of the (combined) floating structure, ensuring stability and preventing the structure from drifting away under critical sea conditions and storms [39]. Mooring systems can be designed based on experience in field of offshore engineering [20].

The necessity for a mooring system limits the depth that a floating city can be placed in. This provides an opportunity towards the desired level of self-sufficiency, a floating community will always be dependent on a connection to the main land. With this reasoning it would be most logical if a floating structure is placed as close to the coast as possible. However this is also the location where a general peak in wave height and impact occurs, as will be explained in the following section. The location is therefore of importance for analysing the wave-structure interaction. For more information on the considered floating city dimensions considered for this research, see Section 3.1.

2.3. Hydrodynamic forcing mechanisms specific to floating city design

For a structure to float, there should be a balance in the vertical forces. The balance is formed by on one side, the weight of the structure and the payload. The weight of the structure will be mainly depending on the size of the structure and used materials for construction. The payload represents all the forces that result from the buildings that will be built on top of the floating structure. Next to regular houses this could include residential flat buildings or office buildings. Industry facility buildings are also of importance as floating cities bring the potential and necessity for a self sustaining environment. Combined they form a force directed downward (red part of Equation 2.1). The upward force is the resulting buoyancy , due to the displaced fluid and the density difference (blue part of Equation 2.1) [25]. Also known as the *Archimedes principle*, balancing these two forces, makes it possible for the structure to float.

$$F = mg - D_f g V \tag{2.1}$$

Where:

- m - equals the object mass
- g - equals the gravitational constant
- D_f - equals the fluid density
- V - equals the volume of the part of the object that is submerged

Once floating, the structure is under influence of several external forces. Wind can cause the structure to move in a lateral direction and depending on the type of buildings placed on the structure it can create a disbalance in the floater. The amount of force that wind can exert on a structure is dependent on wind velocity, duration and the size the structure on a floater (surface of the structure perpendicular to the wind direction). The wind velocity is then dependent on the general location of the floating city and the height of the structures featured on the floaters. For a known location, it is possible to determine what the maximum wind speed will be that occurs once every T years [31]. The intensity of the wind force is highly specific for a location and therefore important to consider. For a floating city wind will be of influence especially if it features high rise buildings. As the horizontal wind force becomes larger in higher altitudes, it can create rotational movement in the floating platform. Once a location is known and the design of the floating city is more detailed it is possible to analyse the present wind force and determine to what extend mitigation measures are required. Next to that, horizontal movement of the floating structure might occur if the wind force is from a single direction with sufficient strength for a long period of time. To make sure the structure does not drift off, it can be moored.

Ocean currents are mainly formed by the rotation of the earth/wind, tide and waves. The currents caused by these phenomena are of a more constant nature, amplification can occur in more extreme weather situations. As the origin of currents can be so different, the scale on which they work are also quite different[16]. Depending on the location of floating city, the main contributor to a possible current should be identified. As the location will most probably be relatively close to the coast, the most important currents to consider are those caused by tide, waves an possible extreme weather events.

Currents will cause a pressure on the hull of the structure, depending on both the intensity of the current and that portion of the hull that is located beneath the surface. If this is the case, the hull of the structure should be strong enough to withstand this pressure. Additionally, a flow under the structure will occur which will cause drag. This forces create a horizontal force acting on the structure. Mooring of the structure will prevent drifting of the structures resulting from this horizontal force. Finally currents can be connected to erosion of soil, which is especially important for the mooring system. Erosion of the soil surrounding an anchor for this system can reduce it's stability. This again is a location dependent feature and should be analysed once a location is known.

It is important to recognize these forces as they will be important in designing certain aspects of a floating city. The focus of this research however lies with the interaction between waves and a floating structure.
The largest impact on a coastal system in general is formed by wind-generated waves. These waves are formed by wind and occur in multiple forms, strongly varying due to environmental differences [5]. Depending on wave height, period and length they can have serious impact on a floating structure. The length scale connected to wind-generated waves in the order of tens of meters. As a floating city can be expected to have significant size, the response movement of the structure can be limited [20]. If the structure is much larger compared to wave length, platform motion due to the interaction is expected to be limited. Although the impact of wind-generated waves in exciting a large structure are expected to be minimal, these waves however still can locally impact the structure.

For more extreme forces, such as tsunamis, the response of a floating city design may be different. A tsunami event is caused by a displacement or shock in the ocean bed. Followed by multiple waves travelling from the place of origin, which are hardly visible in the open oceans. Where water depth is significant, combined with the large wave length and low wave height, a tsunami wave can be considered a shallow-water wave. Which allows them to travel great distances in a short amount of time. Once approaching the coast, the decrease in water depth compresses the wave and it becomes significant in height. The length scale for a tsunami is much larger compared to wind waves, and therefore the interaction with a floating structure can be present. The impact on a floating city is next to that highly dependent on the location of the city, as the wave height of a tsunami is strongly depth and site specific.

2.4. Tsunami - a generation mechanism

Tsunamis originate due to subsea earthquakes, volcanic eruptions or landslides. For an earthquake to be able to cause such a tsunami wave, it must be sufficient in strength and move a significant volume of water during its occurrence. This happens in locations where plates of the earth's crust coinside and move towards each other. Earthquakes that happen due to this movement of the earth's crust experience a form of tension release as the upper plate suddenly moves towards the lower plate. The physical displacement of the plates can be significant, so that it also creates a movement of water. This volume of water radiates away from this source and with that a tsunami wave can originate [10].

The fact that tectonic activity is not spread evenly throughout the earth causes for some areas to be more prone to experience tsunamis compared to other locations. An example of this is the so called 'ring of fire'; the tectonic ridges that enclose the Pacific Ocean. Along a large part of the ring of fire, plates overlap and subduction zones are present. It therefore represents the majority of earth's (active) volcanoes and experiences frequent earthquakes [13]. To make this more illustrative, take a look at the data shown in figure 2.7. These dots represent known historic origin locations of earthquakes and landslides, leading to tsunamis causing damage or casualties. Not surprisingly, coinciding with known locations of the edge of the earth's crust plates and in specific subduction zones. Indicating that Asia and the east coast of the Americas experience these situations more often, but also Europe and countries surrounding the Indian ocean have had historic occurrences of tsunami events with impact.

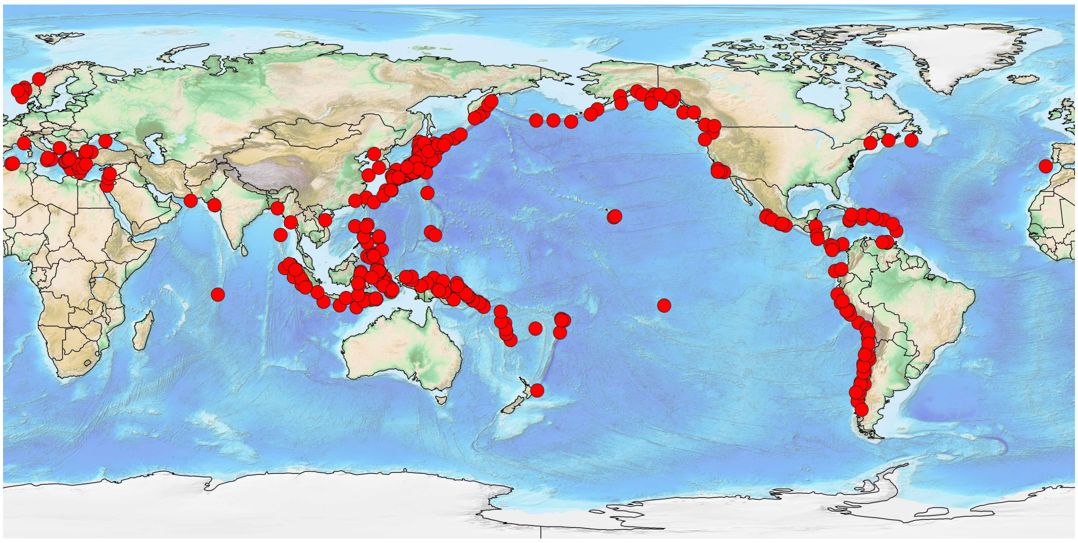

Figure 2.7: Locations of earthquakes, volcanic eruptions and landslides generating tsunamis that caused damage or casualties locally [18]

Depending on the location of origin of the wave, tsunami waves radiate away from their source in almost every direction. [19]. This is why large regions can be impacted by a single tsunami wave event. Travelling across ocean basins with little loss of energy, they proceed as ordinary gravity waves with a typical period between 10 and 60 minutes [18].

2.5. Tsunami wave propagation

For reference, it is also important to look into how a tsunami wave varies compared to regular sea waves. As this gives perspective and makes it easier to understand due to the comparison possibility. The main difference lies with a tsunami's origin. Regular sea waves are formed by storm fronts above large water bodies and tidal waves by the interaction between the sun and the moon. For a tsunami wave as explained earlier, the origin lies with tectonic activity. Figure 2.8 indicates this difference in origin combined with the resulting difference in wave period.

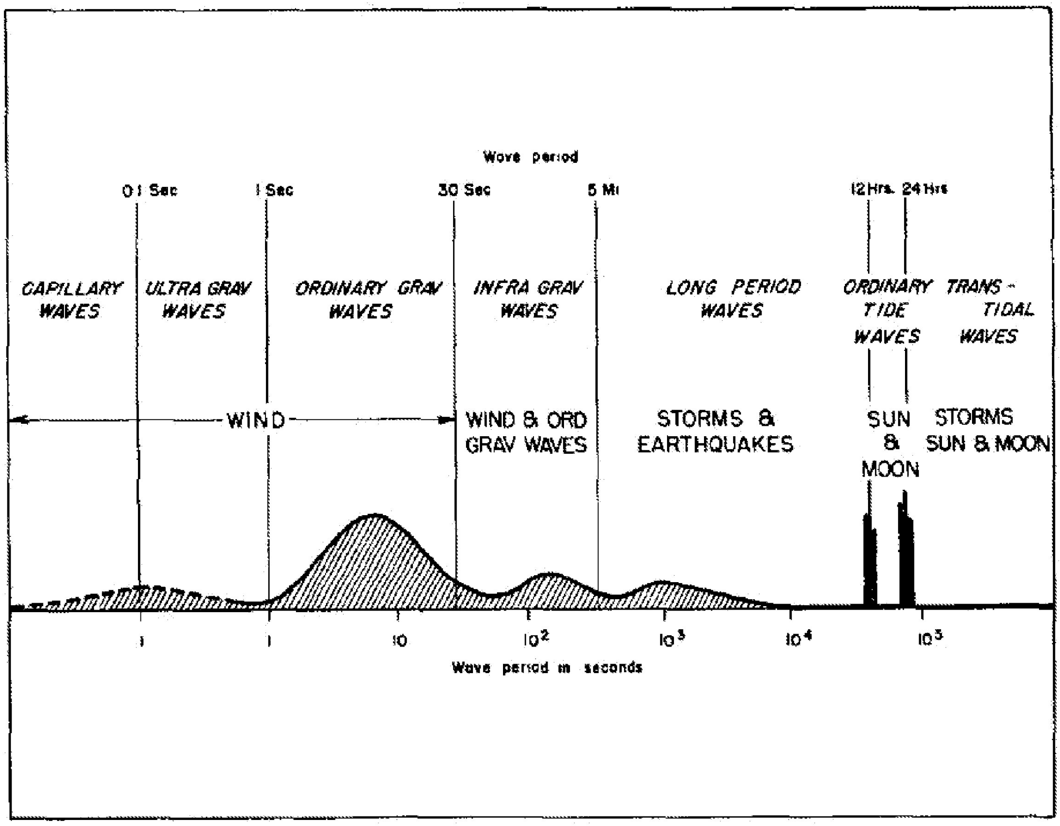

Figure 2.8: Classification of waves based on wave period [27]

As the wave period is linearly related to the wave length, tsunami waves are smaller than tidal waves and much longer compared to wind-waves. This impacts the observation opportunity and level of potential impact of a tsunami. A typical wavelength of a 15 minute period tsunami is in the order of 180 km in a deep water situation. The wave height compared to its length is so small that it is therefore very difficult to detect when travelling through deep water. Combined with the effect that in the nearshore/run-up domain a tsunami experience regions of major amplification of the sea level and intense local currents [21]. Similar to a tidal wave, a tsunami due to its long wave length can be considered a shallow-water wave. This holds when meeting the following condition [2]:

$$\frac{\omega^2 d}{g} \ll 1 \tag{2.2}$$

For the situation mentioned earlier, for a water depth of d = 4 kilometer and the wave period equals 15 minutes, Equation 2.2 results into a value of 0.02 and therefore meets the condition.

There are two important aspects that can be considered valid for the situation where a tsunami can be considered a "long-wave". On the one hand it provides the situation where the pressure distribution of the water can be considered hydrostatic. This simplifies the equations describing the water movement.

On the other hand, wave speed can be determined by water depth and gravity only and is therefore non-dispersive. Supported by the dispersion relation, indicating a relation between the angular wave frequency and the wave number and other variables, this can be shown also based on the long wave approximation.

$$\omega = \sqrt{gk \tanh kh} \tag{2.3}$$

$$c = \omega / k \tag{2.4}$$

$$k = \frac{2\pi}{L} \tag{2.5}$$

Since $tanh(kh)$ equals kh for $kh \rightarrow 0$, the dispersion relation reduces to Equation 2.6. For a tsunami the offshore wave length is easily 100 km, much larger than the average ocean water depth, making this a valid assumption for a tsunami.

$$c = \sqrt{gh} \tag{2.6}$$

As the wave celerity can be called non-dispersive, tsunamis do not dissipate energy through friction by the seabed. Therefore tsunamis can travel at these high speeds for along period of time and lose very little energy in the process [5]. An example in the Pacific Ocean, where a tsunami can experience a wave speed in the order of 700 km/h. Say a tsunami originates somewhere around the middle of the Pacific Ocean. It would only less than 5.5 hours to reach the coastline of California. At the same time, multiple tsunami waves can travel to the coast of eastern Asia in a similar time frame. Combined with the difficulty of detecting these waves while in open ocean, they form a huge threat for coastal communities.

Several other important (local) processes are *shoaling*, *reflection* and *refraction*. All processes depend on local bathymetry and are explained in more detail below.

2.6. Wave shoaling

Combined with their high speed through deep water, tsunamis are unique in that the energy extends through the entire water column from sea surface to the ocean bottom. It is this characteristic that accounts for the great amount of energy propagated by a tsunami [18]. As it preserves its energy rather well during travelling over vast distances, tsunamis can have large impact on coastal areas. Which has mainly to do with the process of shoaling.

When a wave reaches the shallow-water areas near the coast, the wave slows down and compresses due to reducing water depth that is typical of coastal zones. The reduction of water depth along the wave length causes the front of the wave to slow down. As the back of the wave travels faster, the wave is compressed. Reducing the wave length, concentrating the wave energy into a shorter distance, results in a corresponding increase in wave height, otherwise called shoaling [19].

The reason that tsunami waves has such significant impact is partly because of its wave height and the fact that it inundates the hinterland of a coastal area. Both these aspects can be causally linked to the large wave length and the corresponding amount of energy. A way to approximate the development of the wave amplitude and determine the maximum wave height is through Green's law [19] to:

$$H_{max} = H_{offshore} \cdot \left(\frac{d_{offshore}}{d_{onshore}} \right)^{-\frac{1}{4}} \tag{2.7}$$

However this equation only gives a first approximation. It does not account for various local aspects that can also influence a tsunami wave. When a tsunami enters confined water bodies such as bays, inlets, harbors, estuaries, the observed tsunami amplification can be considerably larger than that estimated in Equation 2.7 [19].

Next to the influence of the decrease in water depth, tides can interact with tsunamis. Depending on the situation, low- or high-tide, the interaction of a tsunami with the shallow water approaching a coastline will be different. High-tide for example, amplifies a tsunami as the mean water level is higher to begin with, causing for a combined higher maximum wave height. Next to that it delays possible wave breaking processes. The opposite happens for a low-tide situation.

2.6.1. Reflection

Wave reflection can be observed from small to larger scales. Wave reflection for a tsunami wave occurs mainly on a larger scale due its length and the wave therefore reflects from land masses and ocean ridges. Continental land masses of the earth enclose an ocean. Which, in case of a tsunami generated in that ocean, present oceans as semi-enclosed bodies of water. This causes for tsunamis to appear at places far from the origin and to evolve from a single wave into a set of waves due to multiple reflections.

Next to the continental boundaries, smaller scales such as bays, estuaries, or backwaters can influence the reflection of a tsunami. Due to the combination of different wave oscillations that are formed by an enclosed system, a standing wave or Seiche can be created. These standing wave reflections can be present days after the tsunami has first impacted a coastline [19]. Especially for harbours, possible development of a standing wave is of importance. Due to the specific geometry of a harbour it can experience resonance. The natural frequency of amplified waves entering estuaries or smaller semi-enclosed systems can be determined with [19]:

$$w_n \equiv c\sqrt{\frac{A}{lV}} \tag{2.8}$$

Where, c is the wave velocity, A is the cross-sectional area, l is the length of the channel entering the estuary and V is the volume of the water body. This frequency can be compared to the natural frequency of the bay and the magnitude of the amplification can be determined.

2.6.2. Refraction

Similar to reflection, refraction has an impact on the wave height. Refraction is a depth dependent feature, so it is observed near the coast where the water depth is shallower. Tsunami waves are subject to refraction, when they are approaching a coastline under an angle. As wave speed is higher in a larger water depth, a variation in wave speed along the wave crest will be present. This difference in speed, causes waves to curve more perpendicular towards the shoreline [19]. As the coastline is often shaped in forms of bays or headlands, the wave height that is experienced locally will differ. Headlands that stick out of the coastline will experience a more intense wave heights as the wave focuses towards the headland. As can be seen in figure 2.9. More energy will be directed to this point onshore and the waves will amplify the wave height. Oppositely in bays, the wave height reduces as the wave to spreads out more. Creating situations where in some areas a tsunami wave is experienced more intensely compared to other locations. The process is highly variable on the location, as the bathymetry along the coast can be very different for different locations.

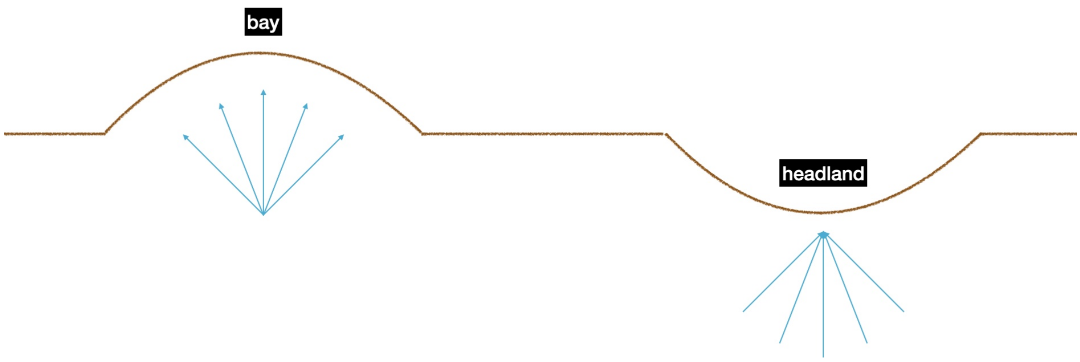

Figure 2.9: Wave refraction patterns based on coastline orientation

2.7. Currents

High flow velocities or currents can create hazardous situations for every object that is in proximity of the coastline, sometimes even if sufficiently anchored. For a tsunami high flow velocities are a known risk. Similar to the situation where far offshore, a tsunami wave height is hardly noticeable, the current velocities are also rather low. This changes however changes when entering the coastal zone. Narrow channels or confined water body's such as bays, harbours or offshore breakwaters can cause to form spiral flow patterns. Mainly due to the fact that coastal areas, both natural and man-made, often have specific shapes that may enhance tsunami phenomena [4].

Both the features of inundation and draw back of the water level are connected to high (local) flow velocities. With a receding (ocean) waterline, sometimes by a kilometre or more, strong and unusual ocean currents may also accompany even small tsunamis [18]. Next to the inundation related currents, the potential for damage at remote (with respect to the maximum impact area) maritime facilities due to currents induced by tsunamis is also something to consider. Especially of more recent tsunami occurrences such as the Tohoku tsunami in 2011 more data is available. There it was observed that even far from the source local high flow velocities were experienced. Without the clear inundation feature, but with negative effects on local marine structures. [4]. Both aspects, based on historic occurrence, cause that a lot of problems for maritime infrastructure.

2.8. Interaction with a floating structure

The type of damage that a tsunami can create depends and varies in severity. Damage is caused by inundation, wave impact on structures and/or coastal erosion [18]. Due to its relatively long wave length and the potential to impact a coastal area, the way that a tsunami interacts with a floating structure is different compared to 'wind-waves'. The following paragraph describes several aspects of a tsunami wave in larger detail so that this interaction can be understood better and choices and assumptions in modelling the interaction can be explained.

- Wave length
  The interaction between waves and floating structures leads to movement of floating structure. Waves of specific length similar to the structure length might resonate the movement of the platform. Depending on how similar the excitement frequencies are. Wind-waves for example have a much smaller wave length and therefore also excite a floating structure differently.

  As the size of the floating structures will be expected to be significant, the length scale of the structure will be much larger compared to for example that of regular wind-generated waves. Combined with breakwater structures, impact of wind-generated waves is expected to be relatively low. For more extreme forces, such as tsunamis, the response may be different.

  A tsunami increases in wave height and shortens in length when approaching the coast, while the period of the wave remains constant. During this research the wave length however is determined based on this wave period. As a floating city will be located in the coastal area compared to far offshore, a reduction in wave length is taken into account. This is why the largest considered wave period is shorter than the maximum mentioned in Section 2.4.

- Wave height
  The impact of a wave directly on the floating platform is highly dependent on the location of the platform. In case it is located further offshore, the tsunami does not yet has a steep wave front at the location of the island, and no significant wave impact will occur at the barrier of the platform [23].

  Next to that the situation exist that the floating structure will be in a location where a maximum wave height occurs. This should be avoided, if possible, as this could lead to large amounts of water on top of the structure. This could create risks for the buoyancy balance and damage to buildings/structures and human life.

- Currents
  As explained earlier, even anchored structures can be severely impacted by tsunami induced currents. If separated from the mooring system, drifting for such a large structure can be hazardous for numerous other marine infrastructure/activities. Next to that, being disconnect from the mooring system can induce degrees of freedom to the structure that are unwanted. If currents will be a problem is highly dependent on the site location as more offshore the currents are also less noticeable.

  With regard to currents, it is important to distinguish between the 'orbital velocity' of the wave and more complex wave-induced currents. This research only includes the 'orbital velocity' of the tsunami. The more complex wave-induced currents due to varying bottom positions (such as around breakwaters in harbours) are not included in the simulations.

3
Model theory

3.1. Floating city model representation

One of the important research projects that has been performed in the floating city domain is by Space@Sea research group. There are some important aspects of that research which are useful for modelling a floating platform combined with a tsunami. The most conclusions can be drawn from the outcome of the laboratory tests that were performed. During these tests, varying environmental conditions were applied, to multiple connected floating structures (see Figure 2.4). These conditions included up to a 100-years sea state and a current reaching 1 m/s as a maximum. This 100-year sea state consisted of waves with a height of approximately 5.5 meters and a peak period equalling 10.5 seconds. Although this is far off from the wave characteristics of a tsunami, the aspects that are of importance and interesting to make a comparison with for this research are listed below.

- In currents, the island was stable [30]
  Especially when considering a more offshore placement of a floating city, this can be also useful considering a tsunami. In closer proximity to the coast, variations in bathymetry may cause for high currents and certain current patterns such as eddies. Especially for these locations more research should be done once a location is known. However when further placed offshore, tsunami currents will be in the same order of magnitude as considered in the Space@Sea research. Next to that this research does not take a detailed bathymetry into account which makes it not possible to study these specific current situations.

- In storm sea states, a significant amount of green water on deck of the platforms has been observed [30]
  This is something that is important to consider when designing a wave barrier and the lay-out of the platform. Especially when considering the fact that tsunami waves can reach significant extreme heights. For now this has no implication for the modelling of the situation in this research.

- A harbor basin with the entry facing away from the waves provides a shelter for vessels due to the reduced wave intensity [30]
  The fact that the structure reduces the waves is significantly is of interest to this research. As from this one can conclude that in case the structure is larger than the incoming waves (in length) a reduction of the wave height will take place. But in case of a tsunami, this might not be true due to it's significant length for instance. That is why this research is a useful addition in the field of floating city design.

The research of Space@Sea [36] features a more complete concept of a floating city, so that the combined structure is more realistic. The scope of this research however did not include extreme situations such as a tsunami. The above mentioned aspects however are still interesting aspects that are useful in future research in this subject and importance of laboratory work.

Because it is rather difficult to set up a laboratory test situation with tsunami and large floating structures, using a (conceptual) numerical model to estimate a first reaction is, time efficient, financially favorable and therefore very useful. To still however consider realistic design values, maximum design parameter values can be used. This is possible with the help of design company Blue21 (R Gomes 2021, personal communication, 17 September).

The design criteria mainly consist of four aspects:

(a) Minimum draft/depth ratio
This is determined by the smallest possible draft of the structure and the largest possible depth. The draft of the platform will depend on the mass of the buildings that are build on top of the floating structure combined with the mass of the floating platform itself. As a reference a minimum 3 meter draft for a typical floating structure is considered. Regarding the maximum water depth, this mainly depends on the type of structure and possibilities for mooring. Large water depths require mooring lines (e.g. chains), however in that case the platform moves horizontally and the connection to land is more complex. Therefore a maximum water depth of 30 m is considered.

(b) Maximum draft/depth ratio
This is determined by the largest possible structural draft and the smallest considerable water depth. However, low water depth is convenient for pile mooring systems (then the platform only moves in heave). Very low water depths should be avoided so that the platform does not hit the floor during the low tide. Therefore a minimum water depth of 10 m is considered.

(c) Minimum structure length / wave length
This is determined by the smallest considered structural length and the longest wave possible. This longest wave is found through the previously mentioned largest water depth combined with the largest considered wave period (Section 2.8). The structural length is determined by two factors, the single platform structure and the combined floating city length. The maximum single platform length can be referenced from other large platforms. The Megafloat (Japan) [15] is an example of such a platform. For a floating city however, modular platform with connections will have significant structural benefits and have the potential to form a larger community. Therefore it makes sense to simulate both larger and smaller lengths as well to see their effect on wave reduction.

(d) Maximum structure length / wave length
This is determined by the shortest possible wave length combined with the largest possible structure length. Again the wave length is determined by the (smallest) wave period and water depth. It is difficult to make a precise estimate for the platform length value. The maximum is determined on the one hand by the limit on what is structurally possible with infinite rigidity for the construction. In addition, the fact that the combined length of several platforms can be much greater. By opting for a maximum structural length of 1500 m, both aspects are taken into account. All considered values for the design parameters can be observed in Table 3.1.

Parameter	**minimum**	**maximum**	**[unit]**
Water depth	10	30	[m]
Wave period	300 (5)	1200 (20)	[s] (min)
Wave length	3000	20000	[m]
Single Platform length	50	1500	[m]
Platform draft	3	6	[m]
Length-ratio L/L_{wave}	**0.0025**	**0.5**	**-**
Draft-ratio a/d	**0.1**	**0.6**	**-**

Table 3.1: Maximum design parameters of a floating structure to consider based on discussions with Blue21 design company

3.2. Conceptual model

This section holds the theory behind the two options of the conceptual model. Each option features a difference in allowed platform movement. The first option is the one where the platform has no freedom of movement. The other option within the conceptual model is the one where the platform can move vertically. The theory behind this is an extension of the (non-moving platform) option. Each subsection will indicate the outlook of the model and its most important parameters and assumptions.

3.2.1. Motionless platform - theory background

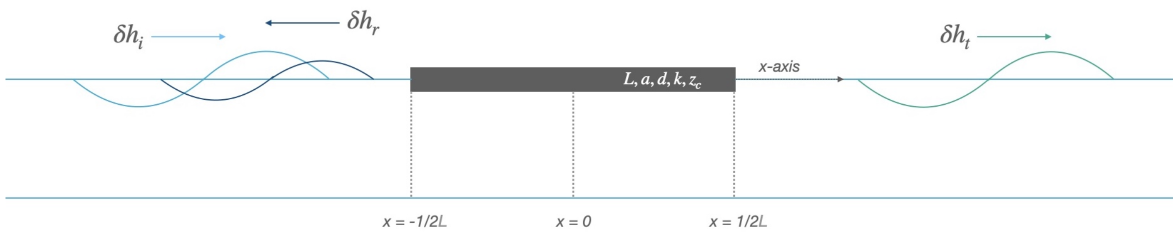

Figure 3.1: Graphic model overview - indicating important parameters

Parameter	Description	Unit []
L	Platform length	$[m]$
a	Draft of the platform	$[m]$
d	Undisturbed water depth	$[m]$
k	Clearance below the platform at rest	$[m]$
z_c	Location of platform center with relative to the x-axis	$[m]$
c	Wave speed	$[m/s]$
g	Gravitational constant	$[m^2/s]$
q	specific discharge below the platform	$[m^2/s]$
h	piezometric level relative to the rest state	$[kg^2/m/s^2]$
δh_i	incoming wave height	$[m]$
δh_r	reflected wave height	$[m]$
δh_t	transmitted wave height	$[m]$
τ	(damping) time-scale	$[s]$

Table 3.2: System parameters of structure in conceptual model

Important assumptions that are made for this model are listed below:

- The vertical pressure distribution is assumed to be hydrostatic which is allowed if the ratios of water depth to wave length and water depth to platform length are small ($< 1/20$). For this research the considered water depth is small enough compared to the presumed length of the tsunami for this assumption to hold.
- The momentum equation describes the force leading to movement interaction in the water column. The conceptual model is linearized when looking to this equation (Equation 3.3). The equation does not account for non-linear effects such as advection. This makes it so that the model only can use shallow-water waves, which in the case of a tsunami is a mostly valid assumption.
- The bed level is kept horizontal. In general, considering the location of such a floating structure, for coastal zones this is not considered as realistic. Especially when considering the construction length

is of significance and it is possible that the bed level varies over the length of the construction. As the draft of the platform relative to the water depth is considered in this research as a design variable, a conclusion can be made on how much this will have an effect.

- The model only looks at the cross-sectional direction, with that the assumption that the incoming wave alongshore uniform. In general this is not true as it is strongly depending on the topography surrounding such a structure. If one were to include this, the movement would become more complex and the response of such a platform could deviate. For this situation, this does not matter as much as this initial calculation are mostly used to generate ideas of the most interesting area within this subject and not the most accurate representation of reality. Next to that, this simplification reduces the problem's required calculation power.

To be able to find a solution, a relation between the incoming wave height and the transmitted wave height should be found. As the specific discharge at each edge of the platform is directly determined by the wave height, this is useful first relation to further expand towards finding a solution.

$$q\left(-\frac{1}{2}l\right) = c\left(\delta h_i - \delta h_r\right),\ q\left(\frac{1}{2}l\right) = c\delta h_t \tag{3.1}$$

The platform location is rigid for this situation, therefore it can be assumed that the specific discharge below the platform is constant with respect to the x-axis. Due to continuity, the discharge at the different locations (Equation 3.1) should therefore equal each other. Resulting in the Equation 3.2, indicating a rearranged balance between the different wave heights.

$$\delta h_r + \delta h_t = \delta h_i \tag{3.2}$$

In addition to the continuity equation, the momentum equation is of importance as it represents movement in the fluid column due to pressure differences below the platform,

$$\frac{\partial q}{\partial t} + gk\frac{\partial h}{\partial x} = 0 \tag{3.3}$$

Next to that, as the platform not able to move, the piezometric level is linearly varying in space and defined in the following equation, (for $-\frac{1}{2}l \leq x \leq \frac{1}{2}l$).

$$h(x,t) = p_0(t) + p_1(t)x \tag{3.4}$$

Observing the momentum equation at the middle of the platform (x = 0), it can be rewritten resulting in Equation 3.6. Using that q_0 is the average of the discharges at the platform ends.

$$\left.\frac{\partial q}{\partial t}\right|_{x=0} = -gk\left.\frac{\partial h}{\partial x}\right|_{x=0} \tag{3.5}$$

$$\frac{1}{2}c\frac{\partial}{\partial t}(\delta h_i - \delta h_r + \delta h_t) = -gkp_1 \tag{3.6}$$

To find the value for p_1, the following is substituted in Equation 3.4,

$$h\left(\frac{1}{2}l\right) - h\left(-\frac{1}{2}l\right) = \delta h_t - \delta h_i - \delta h_r = lp_1 \tag{3.7}$$

With knowing the value for p_1, it can be eliminated from Equation 3.6 and rearranged it forms:

$$\left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)(\delta h_r - \delta h_t) = \left(\frac{\partial}{\partial t} - \frac{2gk}{lc}\right)\delta h_i \tag{3.8}$$

Rewriting using Equation 3.2 provides the following equation:

$$\left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)(\delta h_t + \delta h_r) = \left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)\delta h_i \tag{3.9}$$

Subtracting these two equations (3.8 & 3.9) and re-writing the result with τ results in Equation 3.11.

$$\tau = \frac{l}{2c} \tag{3.10}$$

This equation forms a relation between the incoming wave height and the transmitted wave height. It is most interesting to indicate the interaction between the tsunami and the platform, based on the difference between the incoming and transmitted wave height. As this will give the best impression on how the structure interacts and impacts the wave propagation.

$$\tau\frac{\delta h_t}{\delta t} + \frac{k}{d}\delta h_t = \frac{k}{d}\delta h_i \tag{3.11}$$

The incoming wave is relatively easy to obtain as this is the incoming wave signal that is determined as a boundary condition. The conceptual model however also features a reflected wave, as presented in Figure 3.1. As can be seen, the reflected wave is required to solve for the transmitted wave height but is an initial unknown and therefore written out of the solution. The value for the reflected wave height is of less interest in this research and therefore not considered in further steps of analysis. Once all parameters are determined, it is however possible to find a value for this parameter.

To solve this relation between the incoming and transmitted wave height and form an analysis of the interaction of several design parameters of the system, both a periodic solution and a numerical solution are featured in this research and explained below.

3.2.2. Motionless platform - model solution methods

Two options of solution methods are used to find a way of visualising and understanding the interaction between waves and a floating platform. A difference between these two ways of solving considered for this research lies with the way of interpreting the incoming wave signal. The periodic solution uses a complex surface level amplitude and with that mainly considers the maximum wave height. Whereas with the numerical solution the wave input requires a time dependent wave amplitude. This provides the opportunity to analyse different wave shapes and other details. The different solution methods are useful alternatives as they present the option to investigate a quick result with less parameters compared to more a more detailed one.

- ☐ **Periodic solution**
  The periodic solution is based on using complex values for the incoming and transmitted wave. Using complex representation for these parameters provides the opportunity for the time derivatives of the parameters to form simpler mathematical replacements. As can be seen in Equation 3.11 time derivatives are present for the transmitted wave height. This means that the time derivative can be replaced by by the complex surface level amplitude $\left(\delta\tilde{h}_t\right)$ and a multitude of the wave frequency (ω).

  This results in the following relation that makes it able to solve for the transmitted wave height.

$$\delta\tilde{h}_t = \frac{\frac{k}{d}\delta\tilde{h}_i}{i\omega\tau + \frac{k}{d}} \tag{3.12}$$

- ☐ **Numerical solution**
  The numerical solution is somewhat more extensive compared to the periodic solution. This has to do with the fact that time is an important factor that is incorporated in this solution type. Introducing, Δt, θ and n. Where, Δt is the time step, identifying the time that passes between each solution that is calculated. n represents the total amount of steps until a final answer is determined. θ is the numerical parameter belonging to an implicit numerical scheme. For this research, θ will have a value of 0.5. All wave parameters present in Equation 3.11 are now replaced by a time dependent solution step.

$$\tau\frac{\delta h_t^{n+1} - \delta h_t^n}{\Delta t} + \frac{k}{d}\delta h_t^{n+1} = \frac{k}{d}\delta h_i^{n+1} \tag{3.13}$$

Rearranged and combined with an additional update step for the transmitted wave, Equation 3.13 becomes the numerical solution based way to determine the transmitted wave height for the conceptual model featuring a non-moving floating platform.

$$\delta h_t^{n+1} = \frac{\frac{k}{d} H_i + \frac{\tau}{\Delta t}\delta h_t^n}{\frac{\tau}{\Delta t} + \frac{k}{d}} \tag{3.14}$$

$$H_i = (1-\theta)\cdot h_i^n + \theta \cdot \left(h_i^{n+1}\right) \tag{3.15}$$

$$\delta h_t^{n+1} = \delta h_t^n + \frac{\delta h_t^{n+1} - \delta h_t^n}{\theta} \tag{3.16}$$

3.2.3. Moving platform - theory background

To be able to analyse how the movement of the floating structure influences the transmission of a tsunami along this structure, this model where the platform can move in a vertical direction is used. It will provide a first indication of what the most interesting parameter ranges are that have to be researched. For example, what length of the structure (in cross-shore direction) results in the highest transmitted wave.

A visual overview of the model is presented in Figure 3.2. The additional system parameters, next to those presented in Table 3.2 and used for the motionless platform model, that are important in representing the moving platform in the conceptual model are indicated in Table 3.3

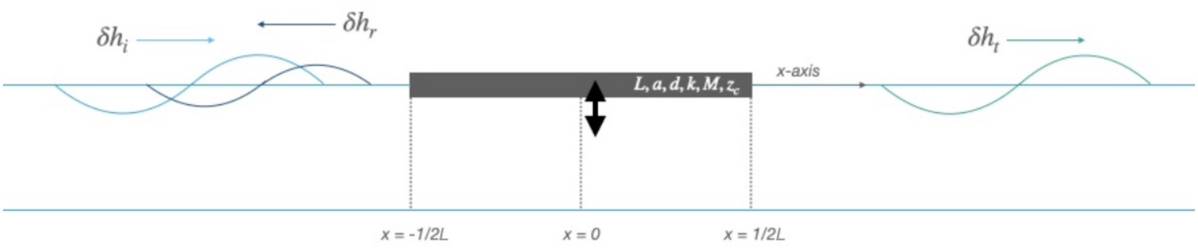

Figure 3.2: Graphic model overview - indicating important parameters

Parameter	Description	Unit []
M	Mass of the platform	$[kg]$
w	Velocity of the platform center with respect to the x-axis	$[kg]$
ω_0	Natural frequency of the floating system	$[1/s]$

Table 3.3: Addition system parameters for moving platform in conceptual model

As in this model vertical movement of the platform is allowed, the equations used in the previous option within the conceptual model are extended. The platform is allowed to move freely, as it will not be connected to the sea bed within this model. The several other possibilities of movement are ignored. The movement of the platform is described the increase or decrease of z_c, the location of the center of the platform platform, starting at x = 0 equal to the mean of the water level at rest.

The model is also based on a balance through the momentum and continuity equation. The continuity equation represents the water mass below the platform, ensuring a relation between the movement of the platform and additional resulting discharge variation in the x-direction.

$$\frac{\partial z_c}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{3.17}$$

Next to this variation of discharge in x-direction, the discharge variation can also be related to the waves travelling to and from the platform. The equation describing that link between the discharge and the different wave heights, is also used in the previous model option, and equal to Equation 3.1.

The momentum equation uses a combination of neglecting the effects of resistance and momentum advection to linearize the previously set-up momentum equation (3.3) and Equation 3.17. Forming a balance between the movement of the platform and the piezometric level.

$$\frac{\partial^2 z_c}{\partial t^2} + gk\frac{\partial^2 h}{\partial x^2} = 0 \tag{3.18}$$

The piezometric level, due to the ability of the platform to (only) move vertically, is a quadratic relation with respect to the cross-sectional flow direction, as z_c does not vary in this direction.

$$h(x,t) = p_0(t) + p_1(t)x + p_2(t)x^2 \tag{3.19}$$

Combining the equations mentioned above, a relation that solves for the movement of the platform based on the incoming wave can be formed. The same holds for the transmitted wave height which is dependent on both the incoming wave height and the platform surface level variation. All steps required to form these relations can be found below, for each of the two reaction indicators mentioned separately.

- ☐ **Platform movement -** z_c

  To start this of, the equation of motion is decribed below.

$$M\frac{\partial^2 z_c}{\partial t^2} = \rho g \int_{-l/2}^{l/2} (h - z_c)\, dx \tag{3.20}$$

The mass of the platform, as this system considers a floating platform, equals the initial water displacement by the platform $M = \rho l a$. Using the relation for the piezometric level and writing out the integral of the mentioned equation of motion, it can be rewritten.

$$\frac{\partial^2 z_c}{\partial t^2} = \frac{g}{a}\left(p_0 + \frac{1}{12}l^2 p_2 - z_c\right) \tag{3.21}$$

To reduce the number of unknowns in this equation, first the values for the piezometric level at the edges of the platform are substituted in the equation for the piezometric level.

$$p_0 = \frac{1}{2}(\delta h_i + \delta h_r + \delta h_t) - \frac{1}{4}l^2 p_2 \tag{3.22}$$

Combining the result of this equation with the equation of motion, results in the equation described below. To be able to use this solution however, the value for p_2 should be known.

$$\frac{\partial^2 z_c}{\partial t^2} = \frac{g}{a}\left(\frac{1}{2}(\delta h_i + \delta h_r + \delta h_t) - \frac{1}{6}l^2 p_2 - z_c\right) \tag{3.23}$$

The value for p_2 can be found through combining the momentum equation, where the second derivative of the piezometric equals a form of the second derivation of the platform location (see also Equation 3.18).

$$p_2 = \frac{1}{2}\frac{\partial^2 h}{\partial x^2} = \frac{1}{2}\frac{1}{gk}\frac{\partial^2 z_c}{\partial t^2} \tag{3.24}$$

This value is then used in Equation 3.21 and rearranged this gives the following evolved version of the equation of motion,

$$\left(1 + \frac{1}{12}\frac{l^2}{ka}\right)\frac{\partial^2 z_c}{\partial t^2} + \frac{g}{a}z_c = \frac{1}{2}\frac{g}{a}(\delta h_i + \delta h_r + \delta h_t) \tag{3.25}$$

To now further reduce the amount different of parameters in the equation of motion, a rearranged form of the continuity equation is used.

$$\delta h_r + \delta h_t = \delta h_i - \frac{l}{c}\frac{\partial z_c}{\partial t} \tag{3.26}$$

Resulting in,

$$\frac{a}{g}\left(1+\frac{1}{12}\frac{l^2}{ka}\right)\frac{\partial^2 z_c}{\partial t^2} + \frac{l}{2c}\frac{\partial z_c}{\partial t} + z_c = \delta h_i \tag{3.27}$$

Using the following system parameters, the final equation to determine the reaction of the platform is found. First, the natural frequency of the system, ω_0 is presented. This and the (damping time-scale), τ can be obtained as the equation of motion represents a 2nd order differential equation. More about this and potential resonance due to similarities between the system frequency and that of the wave can be found in Section 4.2. Equation 3.10 are used to re-write Equation 3.27 to determine a simpler form of the reaction of the platform based on the incoming wave height.

$$\omega_0 = 1/\sqrt{\frac{a}{g}\left(1+\frac{1}{12}\frac{l^2}{ka}\right)} \tag{3.28}$$

$$\frac{1}{\omega_0^2}\frac{\partial^2 z_c}{\partial t^2} + \tau\frac{\partial z_c}{\partial t} + z_c = h_i \tag{3.29}$$

□ **Transmitted wave height -** h_t

To find a relation between the platform movement, z_c, the incoming wave and the resulting transmitted wave height, the continuity equation is used as a starting point.

$$\delta h_r + \delta h_t = \delta h_i - \frac{l}{c}\frac{\partial z_c}{\partial t} \tag{3.30}$$

Combined with another equation that can be obtained by the observation of the momentum equation at the middle of the platform, similar to the situation in Subsection 3.2.1.

$$\left.\frac{\partial q}{\partial t}\right|_{x=0} = -gk\left.\frac{\partial h}{\partial x}\right|_{x=0} \tag{3.31}$$

Combined with using the fact that the discharge equals half the discharge at the platform ends, this results into the follwoing equation.

$$\frac{1}{2}c\frac{\partial}{\partial t}(\delta h_i - \delta h_r + \delta h_t) = gkp_1 \tag{3.32}$$

To then find a value for p_1, the values for the piezometric level at the edge of the platform are used.

$$h\left(\frac{1}{2}l\right) - h\left(-\frac{1}{2}l\right) = \delta h_t - \delta h_i - \delta h_r = lp_1 \tag{3.33}$$

Finally resulting in the following two equations,

$$\left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)(\delta h_t - \delta h_r) = \left(\frac{\partial}{\partial t} - \frac{2gk}{lc}\right)\delta h_i \tag{3.34}$$

$$\left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)(\delta h_t + \delta h_r) = \left(\frac{\partial}{\partial t} + \frac{2gk}{lc}\right)\left(\delta h_i - \frac{l}{c}\frac{\partial z_c}{\partial t}\right) \tag{3.35}$$

Subtracting the above two equations, results into,

$$\frac{\partial \delta h_t}{\partial t} + \frac{2gk}{lc}\delta h_t = \frac{2gk}{lc}\delta h_i - \frac{l}{2c}\frac{\partial^2 z_c}{\partial t^2} - \frac{k}{d}\frac{\partial z_c}{\partial t} \tag{3.36}$$

The final version of the equation to determine the transmitted wave height, is presented below. Which is found by multiplying Equation 3.36 with the time scale, τ.

$$\tau\frac{\partial\delta h_t}{\partial t}+\frac{k}{d}\delta h_t=\frac{k}{d}h_i-\tau^2\frac{\partial^2 z_c}{\partial t^2}-\frac{k}{d}\tau\frac{\partial z_c}{\partial t} \tag{3.37}$$

Similar to the situation with the motionless platform, both a periodic solution and a numerical solution are used to find a solution.

3.2.4. Moving platform - model solution methods

For the moving platform, the same type of solution methods are used and explained below in more detail. As the platform excitation is also part of this system, the equations describing the solution for the wave structure interaction are extended to include the movement. The system as explained in Section 3.2.3, is therefore more complicated compared to the system with the motionless platform.

- **Periodic solution**
  The periodic solution again uses the complex values for the incoming wave and for the moving platform also the surface level amplitude. With a similar procedure as discussed in Section 3.2.2 the derivatives presented in the solutions for the moving platform and the transmitted wave are rearranged and the full complex representatives are shown below.

$$h_i=\delta\tilde{h}_i e^{i\omega t} \tag{3.38}$$

$$z_c=\delta\tilde{z}_c e^{i\omega t} \tag{3.39}$$

$$h_t=\delta\tilde{h}_t e^{i\omega t} \tag{3.40}$$

  Using the derivatives of these equations, combined with equations 3.29 & 3.37, the following solutions are formed:

$$\tilde{z}_c=\frac{\delta\tilde{h}_i}{1-\omega^2/\omega_0^2+i\omega\tau} \tag{3.41}$$

$$\delta\tilde{h}_t=\frac{\frac{k}{d}\delta\tilde{h}_i+\left((\omega\tau)^2-i\omega\tau\frac{k}{d}\right)\tilde{z}_c}{\left(i\omega\tau+\frac{k}{d}\right)} \tag{3.42}$$

  The platform response then follows from calculating all parameters and filling out equation 3.41. The resulting value of the platform response is a complex number. To be able to compare this to other results, the absolute value of this complex number is determined and used. This absolute value then resembles the maximum value for the elevation of the platform. The same procedure follows for calculating the transmitted wave height from equation 3.42.

  As this solution uses the amplitude of the incoming wave as input through the complex derivatives, the resulting values for both z_c and h_t are also amplitude values. This periodic solutions therefore provides only a single value as a reaction to each subsequent wave. This limits the solution to incorporate shape or time dependency of the system.

- **Numerical solution**
  The basic numerical solution is somewhat more extensive compared to the periodic solution for the moving platform situation. To find a value for z_c and h_t several additional steps are required. These steps are required to find updated values of a parameter due to the time dependency and therefore changing wave input. Next to the previously discussed system parameters (ω_0 and τ), several additional system parameters are required to solve the numerical system.

  The numerical solution provides the option to look into the shape of the input wave signal. To be able to do this, first Equation 3.37 and 3.29 should be rewritten to solve it numerically. An additional relation is presented, namely the vertical velocity of the platform, w. As this is the derivative from the surface level amplitude, the second-order derivative presented in equation 3.37 of the surface level amplitude, is rewritten using equation 3.43. This way a system of first-order equations is created.

$$w = \frac{\partial z_c}{\partial t} \tag{3.43}$$

Equation 3.29 is now reduced to:

$$z_c = \delta h_i - \frac{1}{\omega_0^2}\frac{\partial w}{\partial t} - \tau w \tag{3.44}$$

To now form a numerical solution, the time domain is discretized using a sequence of time levels $[t_n]_{n=0}^{N}$, with uniform step sizes Δt_n. The solution then proceeds from one time level, say t_n, to the next, t_{n+1}. The factor Δt represents the time development and will be present in several of the following equations. It is based on a manually selected time period. As this numerical model is based on an implicit scheme, the time step has a limitation.

$$\Delta t = \theta \cdot \left(t^{n+1} - t^n\right) \tag{3.45}$$

To come to a solution, first a new platform position is computed through the following equation.

$$z_c^{n+1} = z_c^n + \frac{\Delta t}{\theta} w^n \tag{3.46}$$

The vertical platform velocity (w) is then updated through a rewritten version of Equation 3.44, presented below (Equation 3.48).

$$\frac{1}{\omega_0^2}\frac{w^{n+1} - w^n}{\Delta t} + \tau w^{n+1} = \delta h_i^{n+1} - z_c^{n+1} \tag{3.47}$$

$$w^{n+1} = \frac{\omega_0^2\left(\delta h_i^{n+1} - z_c^{n+1}\right) + \frac{w^n}{\Delta t}}{\left(\frac{1}{\Delta t} + \omega_0^2 \tau\right)} \tag{3.48}$$

The transmitted wave height can then be computed through the updated version of equation 3.37. This is done with help of the new found values for w^{n+1} and z_c^{n+1}.

$$\tau\frac{\delta h_t^{n+1} - \delta h_t^n}{\Delta t} + \frac{k}{d}\delta h_t^{n+1} = \frac{k}{d}\delta h_i^{n+1} - \tau^2\frac{w^{n+1} - w^n}{\Delta t} - \frac{k}{d}\tau w^{n+1} \tag{3.49}$$

Equation 3.49 is rewritten and reduced in length (by use of Equation 3.15 representing the numerical representation of the incoming wave height). The updated version is shown in Equation 3.50, indicating the dependency of the 'new' time step of the transmitted wave height.

$$\delta h_t^{n+1} = \frac{\frac{k}{d}H_i + \frac{\tau^2}{\Delta t}w^n - \left(\frac{k}{d}\tau + \frac{\tau^2}{\Delta t}\right)w^{n+1} + \frac{\tau}{\Delta t}\delta h_t^n}{\left(\frac{\tau}{\Delta t} + \frac{k}{d}\right)} \tag{3.50}$$

The following equations represent additional update equations that the numerical solution requires to calculating a value for z_c and h_t.

$$z_c^{n+1} = z_c^n + \frac{\Delta t \cdot w_c^{n+1}}{\theta} \tag{3.51}$$

$$w^{n+1} = w_c^n + \frac{w_c^{n+1} - w_c^n}{\theta} \tag{3.52}$$

$$h_t^{n+1} = h_t^n + \frac{h_t^{n+1} - h_t^n}{\theta} \tag{3.53}$$

The result of this basic numerical model is a time dependent reaction of both the platform and the transmitted wave based on the varying wave input. This way it is possible to see how the system will react differently to time dependent variables. An example of this is the wave input, as it is possible to represent waves in different ways in respect to time.

3.2.5. Grid sizing

In general the grid sizing is determined by the variation of the parameters of the platform design. As specified earlier (Section 3.1), both the length and the draft of the platform will be varied. The amount of points that represent the total variation in the parameters, determines de grid size for the conceptual model.

For the numerical solution method discussed in this chapter, an additional level of grid definition is present through chosen and variation of the time step in the numerical solution. This method therefore both has a spacial and time dependent grid size. They can be independently varied to for example include more complex wave signals. But for this situation, they are chosen to be of a similar magnitudes. This appeared to be sufficient. Decreasing the grid size in both time and space does not alter the solutions but does increase the calculation time. Increasing the grid size can lead to loss of details and therefore wrongful conclusions.

3.3. SWASH

This section explains the use of the tool SWASH. The numerical experiments in SWASH for this research feature both a motionless and (vertically) moving platform, similar to the situation for the conceptual model. Important aspects that are discussed are the general lay-out of the model and important settings required as input for SWASH.

SWASH can simulate non-hydrostatic, free-surface flow in multiple dimensions. The features of SWASH that are specifically useful for this research are [37]:

- ☐ Wave transformation in the coastal zone
- ☐ Interaction between waves and structures within the coastal zone
- ☐ Large-scale ocean circulation, tides and storm surges

Because of these features it is possible to model the interaction between tsunamis (large-scale) and floating cities (structures in coastal zones). SWASH models wave development using the numerical implementation of the Reynolds-averaged Navier-Stokes equations. These equations consider an incompressible fluid with a constant density and a free surface. The important variables for the co-ordinate system are, t describing time and x and z are Cartesian co-ordinates. x describing the cross-shore direction and z the vertical scale. The still water level is located at z = 0. Similar to Rijnsdorp et al. [34], a two-dimensional framework bounded by the free surface $z = \zeta$(x,t) and the bottom $z = -d$(x) is used. The governing equations describing the water motion through the domain, are described below:

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial wu}{\partial z} = -\frac{1}{\rho}\frac{\partial (p_h + p_{nh})}{\partial x} \tag{3.54}$$

$$\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial ww}{\partial z} = -\frac{1}{\rho}\frac{\partial (p_h + p_{nh})}{\partial z} \tag{3.55}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{3.56}$$

Where $u(x, z, t)$ is the horizontal water velocity, $w(x, z, t)$ is the vertical velocity, g represents the gravitation acceleration, ρ the water density and p_h describes the resulting hydrostatic and p_{nh} the non-hydrostatic pressure in the water column. The balance for the water movement in SWASH is formed by the time derivative, advection terms, hydrostatic and non-hydrostatic pressure.

In addition to the wave developing however, also a floating platform is present interacting with the water particles. The interaction is one the one hand formed by the water particles that move due to the wave forcing and with that exert a force on the platform (in the form of pressure). On the other hand, the resulting movement of the platform then again also causes for a movement of the water particles. This relation of acceleration and resulting force is described by the following relation.

$$m\frac{\partial^2 \mathbf{Z}}{\partial t^2} = \mathbf{F} \tag{3.57}$$

The description of the motion of the platform is based on Newton's second law. Where **Z** describes the translations and of the floating body with respect to its centre of gravity. m is the mass of the body [33]. The forcing term **F** represents the water pressure formed by the incoming wave. The process is illustrated in Figure 3.3.

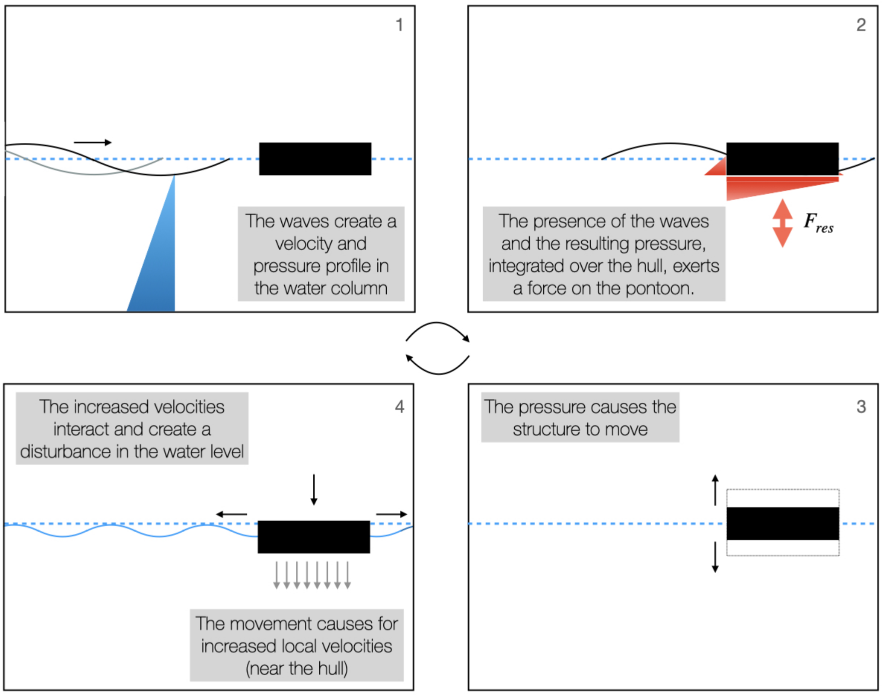

Figure 3.3: Overview of process within SWASH representing the iterative process towards a solution

The figure shows a four step process, that is iteratively solved in SWASH. The process describes the situation where the platform has a potential to move (vertically). In the case where the platform can not move, Equations 3.54, 3.55 and 3.56 still hold. The forcing connection with the platform however is now not possible as the potential translation **X** of the platform is set to zero. This reduces the complexity of the model and the transmitted wave is then only dependent on the relation between the incoming and reflected wave.

In comparison to the conceptual model, the following aspects can be noted:

- ☐ SWASH can include non-hydrostatic pressure
- ☐ SWASH describes the water movement in more detail due to the non-linear terms

The SWASH runs however are still a simplified version of what the model has the capability to. SWASH can feature a platform of a specific size in a 3D-simulation with a varying topography and and multi-direction wave transmission. However, it takes a long time to create such a simulation, thus a simplified approach is also used for SWASH. As this reduces implementation time, it also ensures a shorter run time as the model is less complex. Next to that a simplified version was required to make comparison to the conceptual model possible.

Although simplified, convergence still has to be met to produce a solution. Numerous previous studies have shown that in this case a large number of iterations are required to reach convergence when solving the fluid-structure interactions (e.g., Borazjani et al., 2008; Yu et al., 2015) [33]. To overcome this, an under relaxation scheme can be used when computing the wave interaction and movement response of the floating structure.

The method of under-relaxation reduces the amount by which a variable changes for each following iteration. Due to the non-linearity in the equations, it is important to control the rate of change of the variable. This can be done by altering the value for α, the under-relaxation parameter. Generally between $(0 \leq \alpha \leq 1)$, as when $\alpha \leq 1$, the convergence rate of the solution is slowed down but the stability is increased [35]. When α equals 1, no relaxation is present. For this research the initially used value is set to 0.15. Later this changed, due to increased instabilities and converging issues to 0.001.

3.3.1. Model lay-out

Figure 3.4 shows the input of the domain that is considered for the run in SWASH for the motionless platform. It features the floating platform and shows the specific dimensions that are used. For example the platform location is determined by the length of the general domain. It is located in the middle of this domain.

The length of the horizontal axis is defined by on one hand the general domain length combined with the sponge layer. This sponge layer is present to make sure that the wave is dampened at the end of the run so that the wave will not reflect back into the area of interest and interfere with the wave signal. Its influence starts at the red dot seen in Figure 3.4 and ends at the left boundary. The length of the sponge layer is determined as it should fit at least two times the wave length. The general domain length is determined based on that this domain fits both the platform and a multitude of incoming waves.

The vertical axis indicates values for parameters such the water depth and the draft of the platform. The height of the platform is not considered for both movement situations. The model inherently assumes that the wave will never over-top the platform. Although the height is specified in the model, this is not used in any calculations in the model.

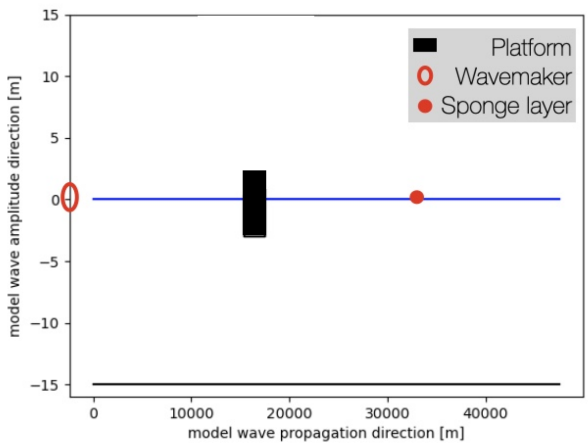

Figure 3.4: Domain lay-out in SWASH featuring a floating platform

The situation in SWASH where the platform can move vertically has the same lay-out as presented in Figure 3.4. The difference within the system lies with the allowed vertical movement of the platform. This creates the system as explained in Figure 3.3.

3.3.2. Wave generation and absorption

The wave generation and absorption occurs at $x = 0$ and around $x = 35000$m in Figure 3.4. The left boundary indicates the location where the incoming wave is generated as input. This boundary has the feature to be weakly reflective. This weakly reflective boundary however, works well for shallow water waves (kd«, wave number multiplied with the water depth is small) that propagate perpendicular to the wave maker. For the conditions of tsunami waves (long wave, k«, so kd«) this assumption holds well and there will be no significant reflections at the wave maker. The type of wave used as incoming wave will be further discussed in a later stage in this research. In front of the right boundary, the sponge layer is present, which is responsible of dampening the transmitted wave. It is not possible to place this solely at the edge of the boundary, but requires to extend further inward from that boundary. This is because the sponge layer needs space/time to dampen the wave.

3.3.3. Grid sizing

The grid size in SWASH is determined by the number of points per wave length. This is a set number, specified as input before running the model. This specific grid size is used for determining the level of detail that can be found in the transfer of information in propagation of the wave but also the interaction and transmission through the platform. The grid size can be optimised so that it is large enough to successfully show the development of the wave but also not too large so that it increases calculation time.

To obtain similar results compared to the conceptual model, the grid size for both models should be similar. This is obtained by choosing the grid size for SWASH, or the number of points per wave length similar to the data points in the variation in platform structural parameters and the wave generation data points for the conceptual model.

4
Conceptual model results

This chapter features the analysis of the conceptual model. For the model to arrive to a solution input and boundary conditions are required, these are described first. Afterwards, the equations mentioned in the previous chapter results in the figures presented in this chapter. Followed by the results that belong to these solutions.

4.1. Conceptual model input

This section shows what the effect of changing different design parameters has on the conceptual model. As explained earlier, the conceptual model features both a situation where the floating platform has no ability to move and one where the freedom of movement is allowed in the vertical direction.

Both movement options feature two solutions with a periodic input wave signal or a numerical wave signal. With the numerical signal more freedom is provided in the type of wave used, compared to the periodic signal. Using this continuous wave signal however is not the most logical option to use as tsunamis simply are not continuous waves, making this way of representation not the most realistic. To find a type of wave representation however, is difficult as other options also do not prove to be perfect. The difficult thing about a tsunami is the different stages it undergoes when travelling to the coast (see Section 2.5). Deciding what wave shape is best to represent it in a model is therefore rather challenging. A solitary wave for example, might also be of interest. As a single wave, representation for a tsunami might be quite correct. Important to consider in that aspect is that due to its large scale, it occurs that reflection off (large) land masses creates a row of waves. The numerical solution however, as it features a time dependent wave signal, provides the opportunity to compare different input wave signals.

To be able to compare the periodic solution and the numerical solution, the following steps are required. The outcome of the numerical solution is a time dependent wave signal. As the input is a periodic wave signal the outcome is of that same shape. Numerical procedures are well known for the transient effect of initial conditions. Some time is required to establish a steady signal, the time required for this system to become a steady signal can be obtained from Figure 4.1.

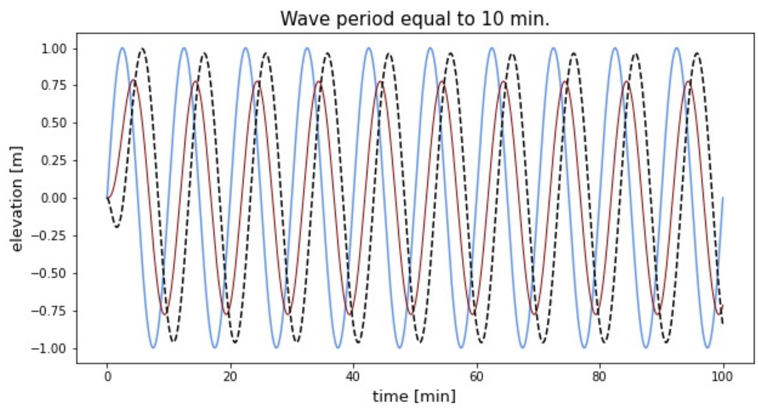

Figure 4.1: Time dependent numerical response to an incoming periodic wave

The figure shows that only one to two waves are required to obtain a steady signal. As the periodic signal results in a single maximum value for the transmitted wave height, this is also required for the numerical solution. To obtain that, in addition to a well developed signal, a resulting maximum value is taken from the numerical solution at the end of the time signal. Therefore for both the numerical and the periodic solution, the outcome is the resulting transmitted wave height.

The results featured in this chapter, show the calculated transmitted wave relative to the incoming wave height. This makes it easier to interpret the outcome and consider different values for the incoming wave height, if desired. The same is done for the resulting platform movement, this is scaled to the incoming wave height. A similar step is performed for the input design parameters, such as platform length and draft. Each is scaled to a system parameter making the presentation unitless. The platform length is scaled to the wave length and the platform draft is scaled to the water depth. This provides the opportunity to analyse the reaction of the system with a reduced number of single value parameters and gives a much broader design spectrum analysis. For an overview of all the results that are shown in this section, also see Table 4.1.

Figure reference	**platform movement**	**Solution method**	**x-axis**	**y-axis**
Figure 4.3	None	N + P	length - ratio	amplitude - ratio
Figure 4.4	None	N	draft - ratio	amplitude - ratio
Figure 4.5	Vertical	N + P	length - ratio	amplitude - ratio
Figure 4.6	Vertical	N	draft - ratio	amplitude - ratio
Figure 4.7	Vertical	N	length - ratio	draft - ratio
Figure 4.8	Vertical	N	length - ratio	draft - ratio
Figure 4.9	Vertical and None	N	length - ratio	amplitude - ratio
Figure 4.10	Vertical and None	N	draft - ratio	amplitude - ratio

Table 4.1: Overview of all figures representing the outcome of the conceptual model

4.2. Resonance

Resonance can be found in every mass/spring system that is imposed by a periodic form of forcing. It is an issue that should be considered, as whenever that system is capable of oscillation and the frequency of the imposed force is equal or nearly equal, the system is set into oscillation with a relatively large amplitude [17].

With the periodic wave signal representing a tsunami, or the energy input in the system. Whereas the interaction between the platform and the water represents the spring part of the system. It is interesting to see if they overlap in frequency domain. This would mean that resonance is part of solutions considered in this research. Whether this is the case depends on the considered range of the parameters on which the (natural) frequencies of both the platform and the wave are determined. The natural frequency of the moving platform is determined by Equation 4.1.

$$\omega_0 = \frac{1}{\sqrt{\frac{a}{g} \cdot \left(1 + \frac{l^2}{12 \cdot k \cdot a}\right)}} \tag{4.1}$$

This equation is derived from the equation of motion presented in Section 3.2.3. The equation is repeated here for convenience, but without applied forcing.

$$\frac{a}{g}\left(1 + \frac{1}{12}\frac{l^2}{ka}\right)\frac{\partial^2 z_c}{\partial t^2} + \frac{l}{2c}\frac{\partial z_c}{\partial t} + z_c = 0 \tag{4.2}$$

This equation represents a damped mass-spring system. The undamped angular frequency or natural frequency of the system can be found through the following steps:

- ☐ Replace coefficient of the second order derivative by F_1

$$F_1 = \frac{a}{g}\left(1 + \frac{1}{12}\frac{l^2}{ka}\right) \tag{4.3}$$

$$F_1 \cdot \frac{\partial^2 z_c}{\partial t^2} + \frac{l}{2c}\frac{\partial z_c}{\partial t} + z_c = 0 \tag{4.4}$$

- ☐ Divide by F_1

$$\frac{\partial^2 z_c}{\partial t^2} + \frac{1}{F_1}\frac{l}{2c}\frac{\partial z_c}{\partial t} + \frac{1}{F_1} z_c = 0 \tag{4.5}$$

- ☐ Natural frequency
  The natural frequency can now be obtained, as the equation now represents a standard 2nd order ordinary differential equation [24], by rewriting the coefficient of z_c.

$$\omega_0^2 = \frac{1}{F_1} = \frac{1}{\frac{a}{g}\left(1 + \frac{1}{12}\frac{l^2}{ka}\right)} \tag{4.6}$$

Finally obtaining the form represented in Equation 4.1. The main parameters that are also determining for all other aspects in this research, the platform length (l), platform draft (a) and water depth (d) (through parameter k), are featured in determining the platform frequency.

The figure below, Figure 4.2, shows the natural frequency for a range of those parameters. The horizontal axis features the variation in the platform length, l, with respect to the wave length. The vertical axis shows the variation in platform draft, a, with respect to the water depth. The colors in the plot indicate the value of the natural frequency relative to the wave frequency. Whenever these equal each other or the divided value equals 1.0, a form of resonance can be expected. Which platform dimensions combinations are responsible for potential resonance are indicated by the black line.

Earlier in this research (Section 3.1), a maximum was set for the range of the platform dimension parameters, caused by technical/physical limitations. These boundaries are also featured in Figure 4.2, indicated by the thin dotted lines. This to see if resonance can be expected in the more realistic platform dimension combinations.

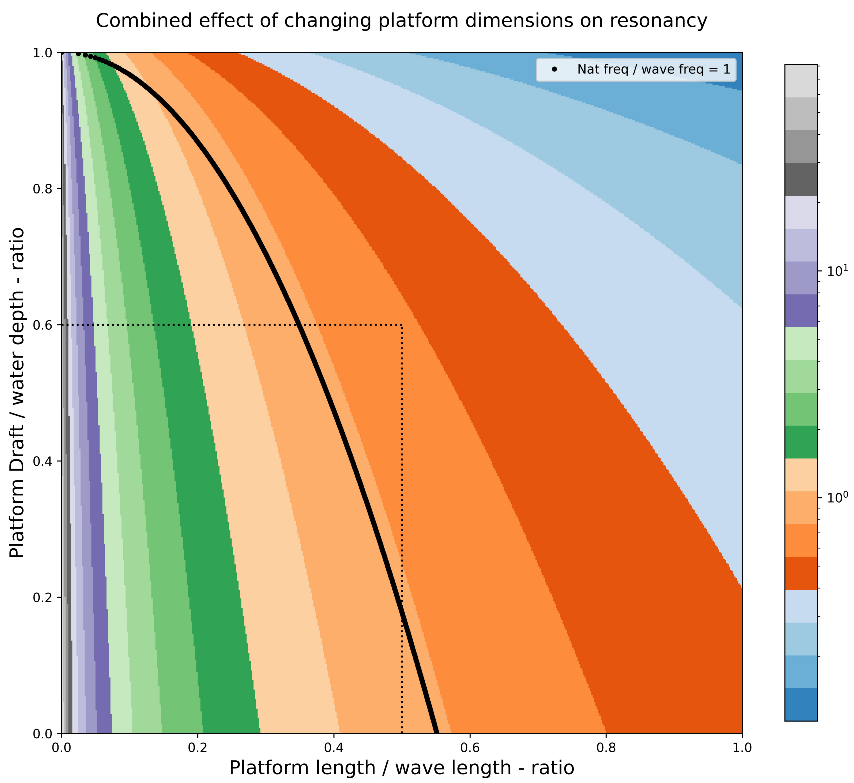

Figure 4.2: Figure indicating the effect of changing the platform length and draft on the structure's natural frequency relative to the wave frequency

Next to the natural frequency, a damping factor is present in this system. This factor is found through the general form of a second order differential equation. Where the coefficient of the first derivative of a typical second order equation (see Equation 4.7) holds the damping ratio, ξ [24]. Combining this with the system differential Equation 4.5:

$$\frac{\partial^2 z_c}{\partial t^2} + 2\xi\omega_0 \frac{\partial z_c}{\partial t} + \omega_0^2 z_c = 0 \tag{4.7}$$

$$2 \cdot \xi \cdot \omega_0 = \frac{l}{2c}\omega_0^2 \tag{4.8}$$

Rewriting this equation, ξ can be found:

$$\xi = \frac{l}{4c}\omega_0 \tag{4.9}$$

The damping factor is positive and therefore this system experiences a form of damping. This means that the line depicted in Figure 4.2 will not hold for every situation. As the damping factor features the length of the platform, l, prominently, it can be expected that the reaction of the system will decrease for the situation where the length is significant.

Each result presented in the upcoming sections in this chapter, featuring the moving platform, is accompanied by an indication of the specific structural natural frequency that belongs to the input parameters. This range indicates whether resonance can be expected. It however should be kept in mind that depicting this range does not account for the amount of damping present. Whether resonance is present also depends on the length of the platform.

4.3. Motionless platform results

This subsection shows the outcome of the conceptual model featuring a platform that has no potential to move. Indicating how the platform transmits, based on both a numerical and a complex periodical solution, an incoming tsunami.

As the platform will experience no variance from its initial location, indicating the change of movement is not interesting to show. The fact that a large structure is present with a specific draft and specific length however, will cause for a part of the incoming wave to reflect. Therefore reducing the transmitted wave height. To what amount this reduction will take place depending on the platform length, is shown in Figure 4.3. The plot below indicates the reaction of the transmitted wave in comparison to the incoming wave height, when varying the platform length compared to the wave length (further referenced to as the "*length-ratio*"). Other important model parameters use the following input values (Table 4.2):

Parameter	**parameters**	**value**	**unit [-]**
Draft-ratio	a/d	0.15	[−]
Wave Period	T	600	s
Water Depth	d	20	m

Table 4.2: Model input parameter overview

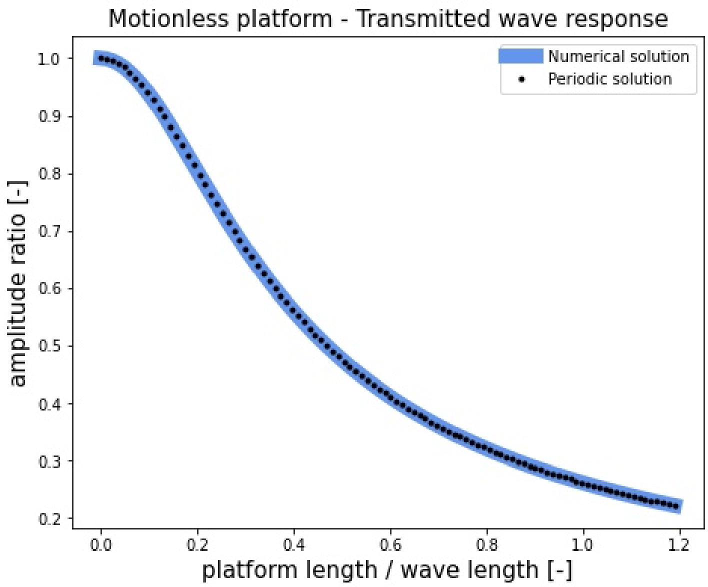

Figure 4.3: Model results based on numerical and periodic solution indicating the effect of a variable platform length compared to the wave length by showing the reaction of the transmitted wave after encountering a floating platform

From a point where the wave length is significant compared to the platform length (*length-ratio* ≤ 0.1) the transmitted wave follows the incoming wave without a reduction. The decay due to changing the platform length however is quite significant. A concave upward shape is observed, with the reacting transmitted wave converting towards zero when the *length - ratio* reaches values larger then 1.0. This is a typical shape for this specific situation as the variable parameter is length (through τ, see Equation 3.12). This is the variable parameter for this situation and can be found in the denominator of the periodic solution for the transmitted wave height.

The fact that the decay starts quicker at the beginning of the graph is a useful feature. It indicates that a small change in platform length, in the lower *length-ratio* values, has the highest resulting change in transmitted wave height. When considering that a tsunami wave length is in the order of kilometers even when approaching a coastal zone. Reaching such a structural length (1:1) is quite difficult, if not impossible, but this graph indicates that that might not be even necessary.

Next to that it is observed that the numerical and periodic solution are positioned on the same line. Given that periodic and numerical approach solve the same set of equations, it shows that both solution methods lead to consistent results. This is important, as it is expected for them would expect them to be consistent. It shows that both solution methods are implemented correctly.

Figure 4.4, shows the effect of a changing of the draft of the structure. This plot will therefore indicate to what amount a reduction of the transmitted wave height will take place dependent on the platform draft compared to the water depth, to make the outcome unit less and scale-able (In further reference called the "*draft-ratio*". Important other parameter values are indicated in Table 4.3 below.

Parameter	Abbreviation	value 0.15	value 0.50	unit [-]
Structural length / wave length	L/L_{wave}	0.15	0.50	[−]
Wave Period	T	600	600	s
Water depth	d	20	20	m

Table 4.3: Model input parameter overview

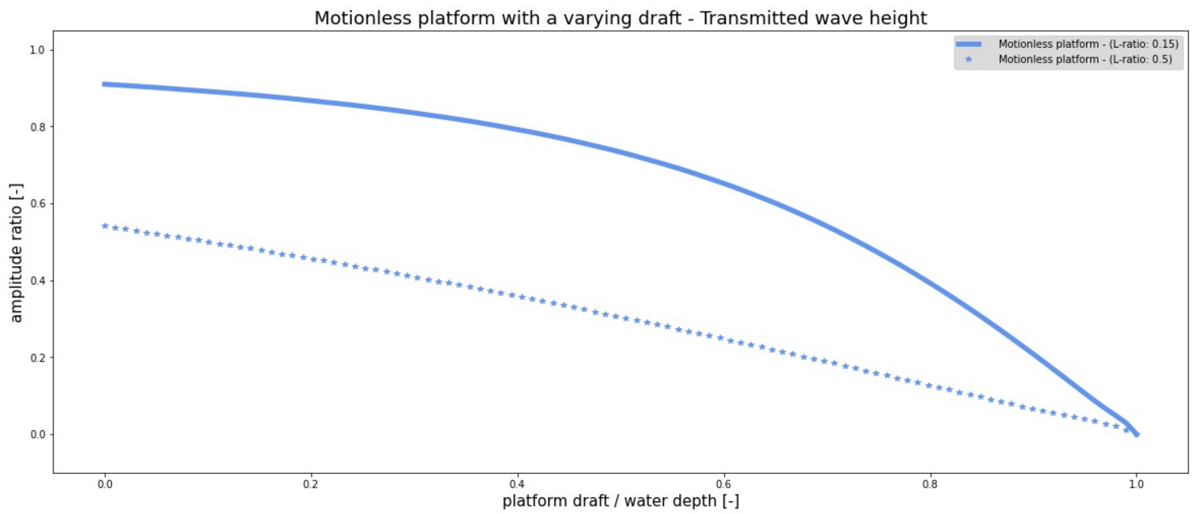

Figure 4.4: Model results based on numerical and periodic solution indicating the effect of a variable platform draft compared to the water depth by showing the reaction of the transmitted wave after encountering a floating platform

The starting point of both lines is dependent on the *length - ratio*. For the upper line (4.4) that starting point is based on this ratio being equal to 0.1. For the lower line this ratio equals 0.5. This causes for a significant difference in starting point and also general shape of the graphs. As for a smaller platform length relative to the wave length, it takes longer to see an effect of increasing the draft. Once this effect is present however, a decrease in the transmitted wave height can be observed. That the model reaches the point where the draft equals the water depth, is not realistic of course. Not only is this an undesired situation as this requires a lot of material for the construction to reach this point. Next to that it can lead to undesired local flow velocities for the situation that still a small gap is present beneath the platform. That the model still shows a result for this situation has to do with the fact that Equation 3.12, that is the basis for this plot, features the parameter combination $\frac{k}{d}$. This is where the draft is represented in determining the transmitted wave height and equals $\frac{d-a}{d} = 1 - \frac{a}{d}$, so that when the draft equals the water depth, this $\frac{k}{d}$ value equals 1.

The upper line in Figure 4.4 shows a concave downward reaction. The speed of decrease of the transmitted wave height, increases for the highest values of the *draft - ratio*. The fact that the lower line shows a more linear downward slope has to do with the value for the *length-ratio*. Not only makes it so that the graph starts at a lower amplitude ratio, but it also changes the shape of the graph. Due to the fact that there is already an effect in place reducing the transmitted wave height, because of the higher platform length, additionally increasing the draft has an immediate effect. The fact that the draft has a relatively smaller effect has to do with the fact that it is scaled down by dividing it by the water depth (see Equation 3.12). The impact of the draft therefore ranges between one and zero. Whereas the length of the platform is fully represented through τ in Equation 3.12.

The effect of changing the draft is different depending on the value of the platform length. Therefore it is important to consider what the most realistic combination of both ratio's is to really quantify this effect. That realistic combination is mainly dependent on the water depth which then determines the wave length. With these known, a platform length can be chosen and the most efficient draft value will be known.

4.4. Moving platform results

In this section the results of the model featuring a vertically moving platform interacting with a tsunami type wave are presented. The plots feature, similar to the previous section, the transmitted wave height and in addition also the platform movement. Here the platform movement can move freely in the vertical direction and will therefore also be measured against the incoming wave height. The structural design parameters, length and draft, are again are used as variable to obtain their influence on the system.

This first figure (4.5) shows the reaction of the platform and the transmitted wave based on a ranging *length-ratio* between zero and one. Important other parameter values are indicated in Table 4.4.

Parameter	parameters	value	unit [-]
Draft-ratio	a/d	0.15	[−]
Wave Period	T	600	s
Wave Frequency	ω_w	0.010	rad/s
Water Depth	d	20	m
Platform frequency	ω_0	0.51 - 0.005	rad/s

Table 4.4: Model input parameter overview

As can be seen in Table 4.4, the platform frequency changes for the smallest possible platform (*length-ratio* = 0.01), equalling 0.51, to a value of 0.005 for the largest platform (*length-ratio* = 1.00). As the wave frequency (also mentioned in Table 4.4) falls in this ratio, purely based on this comparison, resonance should be expected. However as the platform is already relatively large when the equalling platform frequency is reached. The point where this happens is indicated by the dotted line in Figure 4.5. Damping can therefore be expected to be present and reducing this expected resonance reaction. This also appears in Figure 4.5 as no reaction from the system is observed when the system frequency equals the incoming wave frequency.

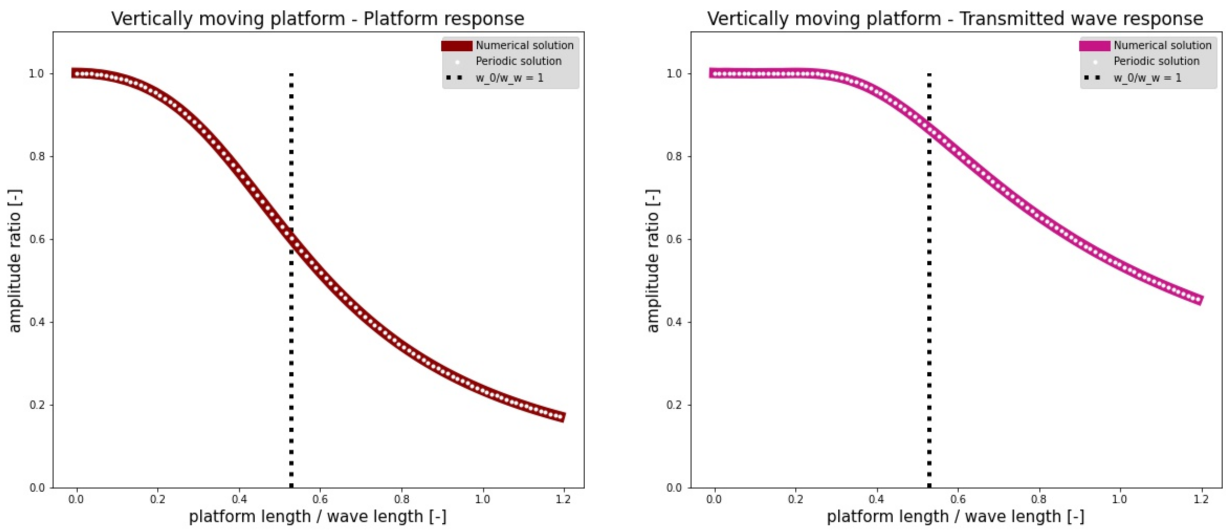

Figure 4.5: Model results based on numerical and periodic solution indicating the effect of a variable platform length with different wave period showing on both the platform response and that of the transmitted wave

Both figures show both the periodic and the numerical solution to this model with a vertically moving platform. The fact that the dotted (periodic) line shows the same outcome again indicates the validity of using both models separately ensuring similar outcomes.

The most striking difference between the two graphs is the difference in decay speed. This decay, for both graphs, is caused by the changing platform length relative to the wave length at the same rate of change.The transmitted wave height is less quick influenced by the increase in length of the platform compared to the reaction of the platform itself. In other words, for a similar platform length, the reduction in response for the transmitted wave height is smaller in comparison.

This results in a lower end value for the platform excitation, where about 20 % of the incoming wave amplitude is still present, compared to 55 %. By extending this platform length even further, finally the point will be reached where both the platform reaction and the transmitted wave height have converged to zero. For this to happen, the platform length should have to reach infinity. This is not a realistic value and so the platform will never fully reduce transmission of the tsunami.

The upcoming figure, featured in this section (Figure 4.6), shows the effect of a changing of the draft of the structure compared to the water depth, similar to the situation with the motionless platform. Section 3.1 indicates the mentioned range of the draft for a realistic range for the platform design. The situation presented in Figure 4.6 also shows more extreme *draft-ratio's* to show the full range of the model. This however is not a range in the *draft - ratio* to be considered realistic for construction. Important other parameter values indicated in Table 4.5.

Parameter	**Abbreviation**	**value**	**value**	**unit** [-]
length-ratio	L/L_{wave}	0.15	0.50	$[-]$
draft-ratio	a/d	0 - 1.0	0 - 1.0	$[-]$
Wave Period	T	600	600	s
Water depth	d	20	20	m
Natural frequency	ω_0	0.038 - 0.004	0.011 - 0.001	rad/s

Table 4.5: Model input parameter overview

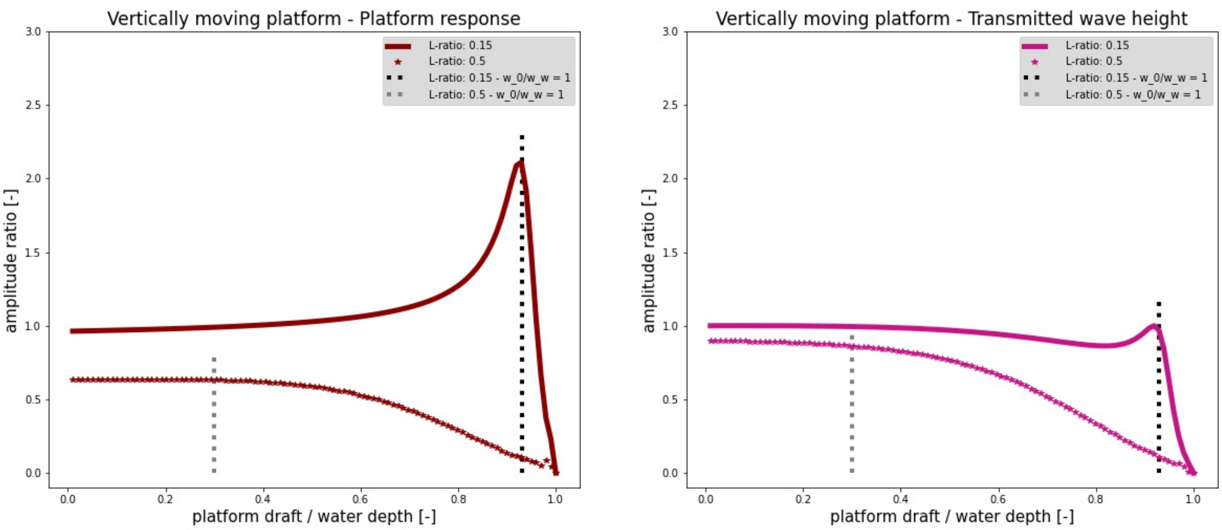

Figure 4.6: Model results based on numerical and periodic solution indicating the effect of a variable platform draft with a constant water depth showing on both the platform response and that of the transmitted wave (for a L/L_{wave} = 0.15 and = 0.5)

In both graphs in Figure 4.6 the *length-ratio* parameter equals L/L_{wave} = 0.15 or 0.5. Both examples of realistic values for the platform length, as explained earlier, in a situation where the wave length still is large (order of multiple kilometers). The value of this ratio mainly determines the starting point of the graphs in Figure 4.6, which was also the case for the motionless platform situation.

The extreme point in the upper line, where the *draft - ratio* gets closes to one, is important to observe and can be explained through the frequency of the wave and the natural platform frequency. As showed in Table 4.5, the natural frequency of the shorter platform varies between 0.038 and 0.004 rad/s. In case of the longer platform, the frequency decreases varies between 0.011 and 0.001. Compared to the wave frequency being equal to 0.010, both frequency ranges appear to equal this frequency at some point. For the smaller platform, an actual the peak in amplitude ratio can be observed. For the larger platform, where the two frequencies equal each other in a lower *draft - ratio*, no peak in amplitude ratio is present. As mentioned for the previous graph (Figure 4.5, in case of the variation in *length - ratio* for a certain length, the damping has increased so much so that the actual platform frequency is lower and therefore no resonance occurs. The extreme reaction in the case of the smaller platform, can also be seen for the transmitted wave height, but to a lesser degree. Most of the movement is taken up by the platform, but this movement also creates a reaction, which can be seen in the transmitted wave height.

There is a clear decay visible at the end of both lines. This however has more to do with the reducing space between the platform and the sea floor, so that it reaches a point where no water will flow under the platform anymore. When looking at the most interesting (smaller) draft-ratio's, no decay can be observed in both graphs in Figure 4.6. It is important however to keep in mind that this graphs is made based on a single value for the *length-ratio*. For the motionless platform for example it was already observed that the *length-* and *draft-ratio* have a certain interaction and therefore a point can be observed where both start to have an effect. For areas closer to shore, where the water depth reduces, the wave length also reduces as the wave is compressed. This causes for the *length - ratio* to be higher. Therefore it the effect of the draft can also be more substantial.

To be able to identify this point where both the length and draft of the platform will have an influence, Figure 4.7 shows the combined influence for changing both the platform draft and the length for the vertically moving platform. In addition, the same parameters are combined to show the effect on the transmitted wave, in Figure 4.8. The input for both graphs is presented in Table 4.6.

Parameter	**parameters**	**value**	**unit** [-]
Draft-ratio	a/d	0 - 1.0	$[-]$
Length-ratio	L/L_{wave}	0 - 1.2	$[-]$
Wave Period	T	600	s
Water Depth	d	20	m
Frequency-ratio	ω_0/ω_{wave}	= 1 (black dots Figure 4.7 & 4.8)	[-]

Table 4.6: Model input parameter overview

The mentioned maximum range of the platform dimension parameters (Section 3.1) is featured in Figure 4.7, indicated by the thin dotted lines.

This upcoming figure is the best indicator in showing what the effect is of damping on the natural frequency of the platform. The dotted line in Figure 4.7 indicates, the combination of the platform length and draft where the natural frequency equals the incoming wave frequency. Combined with the colors, indicating the response of the platform, areas that do show resonant like amplification can be observed as non-damped. Whereas combinations of platform and draft, that do not show this amplification are clearly damped.

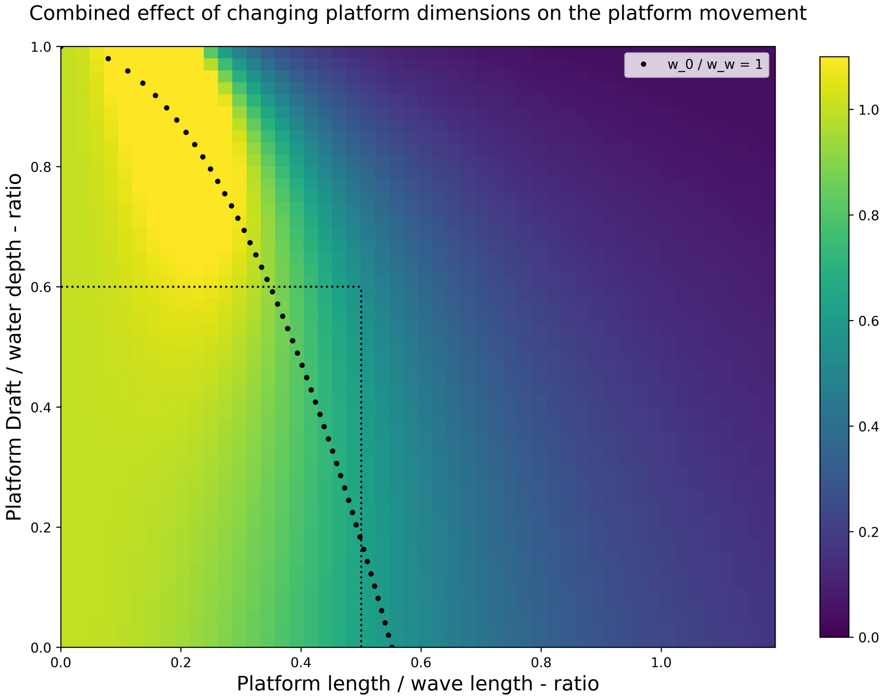

Figure 4.7: Result of combining both a varying platform draft and length and the resulting platform movement due to an incoming wave

Figure 4.7 shows a peak in platform movement, only for specific smaller platform length and a combined large platform draft. This is as explained earlier due to the combination of frequencies of the wave and of the platform are close to equalling each other and no damping is present yet. Further away from this combination, of the *length-ratio* and the *draft-ratio*, the frequencies divert due to the presence of damping and therefore no option for resonance is present. At around half of the *length-ratio*. From where this ratio equals 0.4, the wave therefore seems to have a reduced effect on the platform movement. From there it develops towards almost no interaction where the platform equals the wave length.

With help of the dimension boundaries (dotted square Figure 4.7) this figure can be analysed with regard to design aspects and wave attenuation. It appears that for most of the considered dimension combinations, little effect can be generated on the transmission of the tsunami. For a larger platform length, starting at a *length-ratio* of 0.3, up to 30% of attenuation can be achieved. The considered platform length, for a tsunami of 10 minutes, already should be 2500 - 4000 m. For a floating city community this is a considerable maximum, for a single platform however this is technically not realistic. With considering the most optimal location, a smaller water depth and a shorter wave wave attenuation can occur.

The next figure (Figure 4.8) indicates the resulting transmitted wave height based on changing the combined design parameters of draft and length. (The input parameter for this graph is presented in Table 4.6).

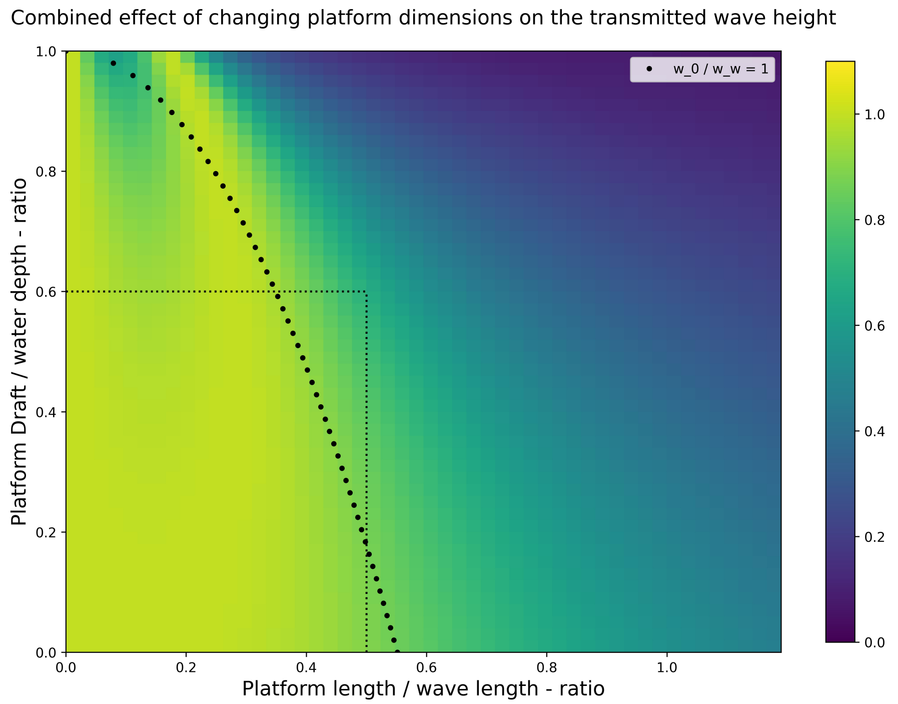

Figure 4.8: Result of combining both a varying platform draft and length and the resulting transmitted wave height due to an incoming wave

There is a sub-optimum in reducing platform movement and transmitted wave height. When looking to the figure representing the transmitted wave height there is a sort of linear relation between increasing the draft and the platform length. For higher values of the draft, an increase in platform length reduces the transmitted wave further. Based on the input of design company Blue21, the limiting black lines in Figure 4.8 are drawn. These lines represent the maximum design areas based on the data presented in Table 3.1. With help of these design criteria, the area is indicated in which design seems feasible. It however shows that it is rather difficult to influence a tsunami within this considered range. The main area within the dotted lines has a value of one or close to one. Around the edges of the design limitations, the reduction in the reaction of the transmitted wave starts to occur.

4.5. Comparison results platform movement

Next to the combined effect of the design parameters, the difference between the motionless and the moving platform is discussed. The figure shown below (Figure 4.9) features the reaction of the transmitted wave height to a combination of the two different degrees of freedom for the floating platform in the conceptual model. Where the motionless platform is indicated by the blue colour and the platform that can move in the vertical direction is indicated by the pink colour. The outcome of the two previous sections is combined into this single plot to indicate the difference between the two. The change in reaction is based on a varying platform length compared to the wave length. Not surprisingly, as this was the case in the previous sections, the periodic solution matches the numerical solution and therefore only the last is presented. The *draft-ratio* still has the value of 0.15,for all parameters see Table 4.7.

Parameter	**parameters**	**value**	**unit** [-]
Draft-ratio	a/d	0.15	$[-]$
Wave Period	T	600	s
Water Depth	d	20	m
Platform frequency[1]	ω_0	0.51 - 0.005	rad/s

Table 4.7: Model input parameter overview

As shown in Table 4.7, the platform frequency is presented as a range, dependent on the varying value for the platform length. Although there is a point where the platform frequency equals the wave frequency, indicated by the dotted line in Figure 4.9, no resonance is observed. This is due to presence of damping.

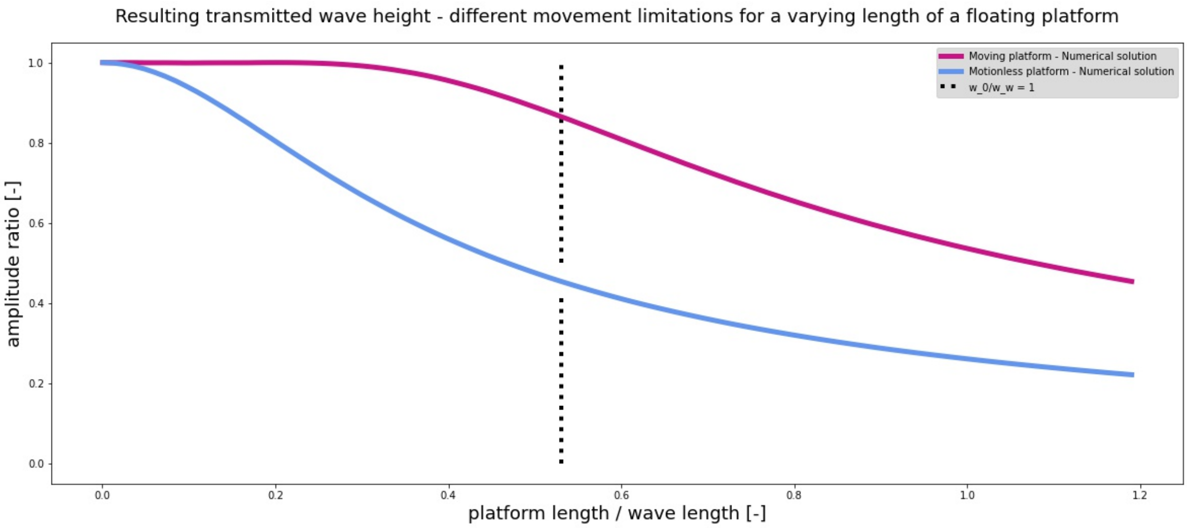

Figure 4.9: Plot indicating the difference in the resulting transmitted wave reaction, between a moving and motionless platform, due to a variation in platform length, also indicating the type of solution method

Clearly visible in Figure 4.9 is that there is a difference between the reaction time of the transmitted wave for both situations. The situation where the platform can not move responds with a larger difference in amplitude to the same change in platform length. In comparison for the situation where the platform can move (vertically), the length of the platform does have an effect in decreasing the reaction of the transmitted wave but for a much larger length. This difference must lie with the fact that the movement of the platform has an effect in keeping the wave height at the same value of the incoming wave height. A vertically moving platform generates waves by itself, which supplements the initial reaction of the transmitted wave.

[1] Only valid for the vertically moving platform

The difference between the two situations is largest for where the $L = 0.5 * L_{wave}$. The point where the platform has the highest contribution in generating additional waves. After this point the length begins to decrease the transmitted wave in both situations so that they converge to the same point. Ending at a point where no wave is transmitted anymore, this however is for an unrealistic large length of the platform.

Next to changing the platform length, the platform draft has been varied to learn how this influences the situation of a tsunami interacting with a floating platform. The comparison between the platform freedom situations, where this draft variation is featured, is presented in Figure 4.10. The input parameters to create this figure are presented in Table 4.8.

Parameter	**Abbreviation**	**value**	**unit [-]**
length-ratio	L/L_{wave}	0.15	[−]
draft-ratio	a/d	0 - 1.0	[−]
Wave Period	T	600	s
Water depth	d	20	m
Natural frequency[2]	ω_0	0.038 - 0.004	rad/s

Table 4.8: Model input parameter overview

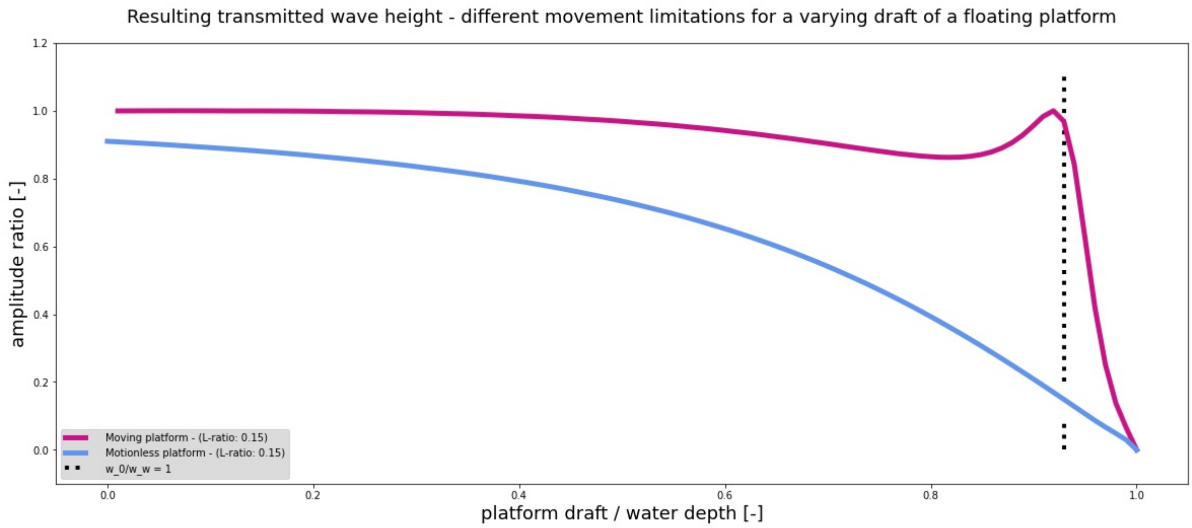

Figure 4.10: Plot indicating the difference in the resulting transmitted wave reaction, between a moving and motionless platform for a specific platform size (L/L_{wave} = 0.5), due to a variation in platform draft, also indicating the type of solution method

Firstly, addressing the initial difference of the starting points of both lines in Figure 4.10), which has to do with the difference due to the *length-ratio* already shown in Figure 4.9. The initial difference for the draft variation is maximum for L/L_{wave} = 0.5. The initial difference shown in Figure 4.10), as L/L_{wave} = 0.15, is still rather small. After the start, the difference grows between the two lines, due to the effect of resonance that is visible for the moving platform situation, (this is a physically not a possibility for the motionless platform). The peak of in the moving platform line, is mainly due to this resonant reaction of the platform (see Figure 4.6), therefore also shown in the reaction of the transmitted wave height.

Although Figure 4.10 show that in the case of the moving platform, it is rather difficult to influence the transmission of the transmitted wave. Figure 4.8 shows, that not all variations of the *length-ratio* show this peak of the moving platform for the larger draft values. Therefore when the platform length is long enough and damping is present, changing the draft has more effect. Still the maximum attenuation that changing the draft can bring, within the set design boundaries (Section 3.1), is equal to 10% (combination of a *draft-ratio* = 0.5 and a *length-ratio* = 0.45).

[2]Only valid for the vertically moving platform

4.6. Important takeaways from the conceptual model

- ☐ The length parameter is the most important design parameter
  Both models with the different freedom of movement for the platform, are influenced by the length of the structure. The situation with the motionless platform shows this effect earlier. Whether the draft also has an influence is strongly dependent on the value representing the length of the platform. Therefore the length of the structure is more important in determining the effect on the reduction on the transmitted wave.

- ☐ Strong interaction between design parameters
  For a larger length, the influence of increasing the draft reduces the transmitted wave faster or the effect of changing the draft is more efficient. This can seen at both platform movement situations and therefore a useful aspect to consider in design of the structure. An increase in draft may reduce a transmitted wave further.

- ☐ Difference between two systems of platform movement
  Next to changing the dimensions, the difference between the two platform movement options shows that the effect of the amount of movement of the platform is significant. It is interesting to see if this is also the case in the SWASH model.

- ☐ Resonance
  Resonance is evident and visible for certain combinations of the platform dimensions. This can be linked to the formula representing a second order differential equation featuring a natural frequency. In addition, there is also an important role for damping. This ensures that there are some parts where, despite the natural frequency pointing there, no resonance occurs. The amount of damping is strongly linked to the platform length, the longer the length, the higher the damping. Most importantly, the regions where resonance would occur are outside the realistic design region.

5
SWASH model results

Similar to the previous one, this chapter simulates both the results of a motionless platform and a moving platform. The results however are obtained with help of SWASH.

5.1. SWASH model input

This chapter features the results that are generated in SWASH. Due to the increased level of detail, combined with the large length wave length that is simulated, it is only possible to program the situation with a specific value for all the parameters compared to ranging some of these in the conceptual model. The input parameters to obtain a result from SWASH are the platform draft, platform width, water depth, length of general domain and sponge layer, the wave amplitude, the wave period and the number of waves generated. Finally it is important to define the grid definition for the model, indicated by the number of vertical layers and grid size in numbers of points per wave length. The higher value these both are, the finer the grid is that is applied and a more detailed the solution can be obtained.

The required input for SWASH is presented below in Table 5.1. The value d is chosen arbitrarily, but within the range described in the design requirements presented by Blue21 (Section 3.1). T is chosen to be 600 seconds or 10 minutes, based on the typical range that is known for tsunamis approaching a coastline (See Section 2.5). The value for L_{wave} is based on the wave period, through the relation of $L_{wave} = T * c$ and $c = \sqrt{gd}$. The value for the incoming wave height is small due to the non-linearity demand. Finally, the platform dimensions, draft and length, are discussed separately for each presented result.

Parameter	**Abbreviation**	**value**	**unit [-]**
Length of domain	[-]	based on wave length and platform length	m
Length sponge layer	[-]	multitude of wave length	m
Number of waves	[-]	20	[-]
Grid size	[-]	100 points per wave	[-]
Gravitational constant	g	9.81	m/s^2
Water depth	d	20	$[m]$
Wave period	T	600	$[s]$
Wave length	L_{wave}	$T * \sqrt{gd}$	$[m]$
Wave height	h_{in}	0.05	$[m]$
Platform draft	a	variable	$[m]$
Platform length	L	variable	$[m]$

Table 5.1: SWASH model input parameter overview - variable platform length

The incoming wave is a periodic wave signal which is generated for a certain time span and sent into the domain from the wave maker boundary. In SWASH it is however not possible to use the input wave height that is realistic for a tsunami wave. As a wave height in the order of meters is highly non-linear with a periodic signal in SWASH. The way to make sure that the wave stays linear, is to reduce the wave height significantly (by a factor 20).

The outcome of the SWASH model is be chosen based on the desired outcome. For this research the interesting outcome parameters is a time signal representing both the resulting wave amplitude ratio (between the incoming and transmitted wave height and a varying platform design parameter) and the location of that specific wave signal compared to the platform location. To be able to compare this to the conceptual model, a specific point is chosen where the 'maximum' value of the transmitted wave can be obtained, directly after the platform. In this chapter the resulting outcome of SWASH is therefore not presented as a time signal, but as a data point containing the maximum value for the transmitted wave height and specific information on the platform dimensions.

5.2. SWASH moving and motionless platform results

This first figure (Figure 5.1) represents the situation where the platform length is a variable compared to the incoming wave length. It features both the results of the conceptual model in addition to several specific configurations representing a value for a run in SWASH with both the moving and the motionless platform. Indicated by data points, as explained earlier in Section 5.1.

The moving platform in SWASH is more difficult to run and not as stable and therefore initially only produced five data points for the moving platform. As the runs of the non-moving platform are for comparison reasons only, the amount of created data points was also limited to five in total. Both sets of data points is presented in Figure 5.1 as star shaped points.

Due to the increase in complexity of the moving platform, the program has a difficulty in solving all the equations and form a solution. The model stability is somewhat unpredictable which made the process of finding out what helped to reduce instabilities rather difficult. It appeared that drastically decreasing the so called relaxation parameter provided an opportunity. As mentioned in Section 3.3, the value was changed from 0.15 to 0.001. This made it possible to create additional points for the moving platform situation, presented as diamond shapes in Figure 5.1.

The used general input parameters for both SWASH and the conceptual model are indicated earlier in Table 5.1. Additional information on what configurations are used for creating the SWASH data points is presented in Table 5.2. The name S_{l-1} refers to the first data point in SWASH that was created for the non-moving platform subjected to a variable platform length. The value for the platform length is based on as a factor of the wave length (determined based on the wave period). To form the draft-ratio and make it equal to 0.30, the platform draft has a value of 5 m. Both are according to the design input provided by Blue21 (Section 3.1). $S_{l-m-\Delta r-1}$ indicates an additional data point from SWASH representing the moving platform (m), with a different relaxation factor (Δr) for the reaction to a changing platform length. The resulting amplitude ratio can be either obtained from Figure 5.1 or from Table 5.1.

SWASH point	Draft - ratio	Length - ratio	Resulting amplitude ratio
S_{l-1}	0.25	0.10	0.92
S_{l-2}	0.25	0.20	0.76
S_{l-3}	0.25	0.20	0.62
S_{l-4}	0.25	0.40	0.51
S_{l-5}	0.25	0.50	0.43
S_{l-m-1}	0.25	0.10	1.01
S_{l-m-2}	0.25	0.20	1.00
S_{l-m-3}	0.25	0.30	0.97
S_{l-m-4}	0.25	0.40	0.92
S_{l-m-5}	0.25	0.50	0.82
$S_{l-m-\Delta r-1}$	0.25	0.05	0.96
$S_{l-m-\Delta r-2}$	0.25	0.24	0.97
$S_{l-m-\Delta r-3}$	0.25	0.48	0.84
$S_{l-m-\Delta r-4}$	0.25	0.71	0.71
$S_{l-m-\Delta r-5}$	0.25	0.95	0.52

Table 5.2: SWASH length-ratio results combined with (numerically solved) conceptual model results

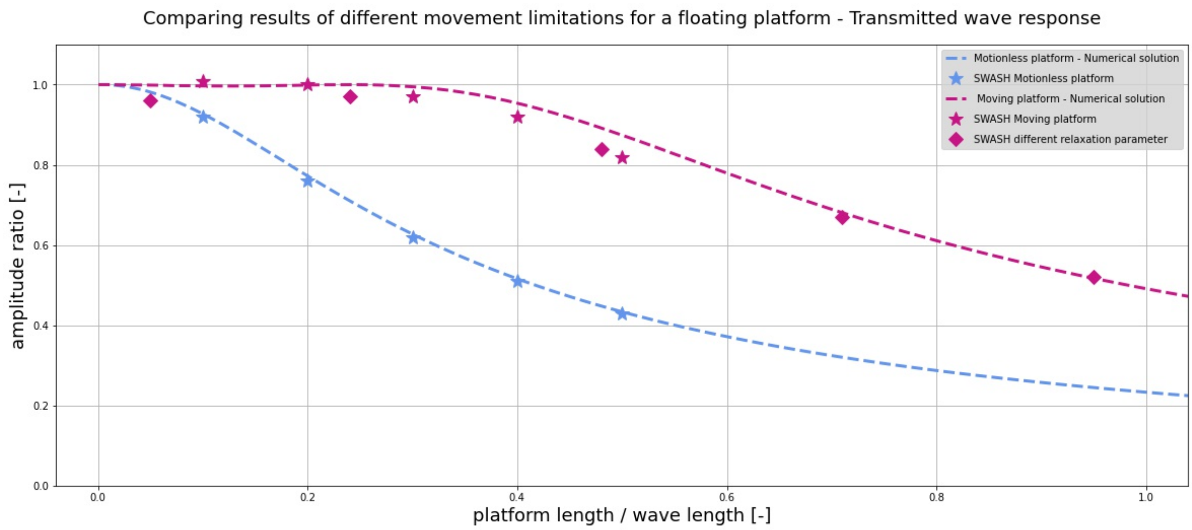

Figure 5.1: Combined results showing both the result of SWASH and the conceptual model for different movement limitations and a varying length-ratio

In shows that changing relaxation parameter made it possible to generate more model variety results and the variable itself has limited impact on the outcome. This is concluded from the fact that the diamond shaped points follow a similar path as the ones with a higher relaxation parameter.

The difference between the motionless platform and the moving platform for the conceptual model was seen earlier in Chapter 4. The data points of SWASH for both platform situations are now also introduced. Something that strikes rather immediately is that the points (and therefore SWASH) seems to agree to the outcome of the conceptual model. Especially for the motionless platform the points are almost exactly fitting the line for the conceptual model. For the moving platform the points diverge a few percent. This can be due to the following reasons:

- For the moving platform model in SWASH the interaction between the platform and the water column is described in more detail which is why more reasons exist for a difference.

☐ The grid resolution differed between the two models. Especially in the process of identifying whether this was something that had to be altered to get a stable signal. In general for SWASH however the goal was to obtain at least x grid points per wave so that no details would be missed. It is of course possible that a difference in grid resolution is responsible for a slight differentiation between the outcome of the two models.

To also compare the draft variation for the moving and motionless platform in SWASH, the input ratio's scenarios for a varying draft of the platform are similar to those presented in Table 5.2 . These input values, combined with the mentioned *draft-ratio* in Table 5.3, result into the data presented in Figure 5.2.

SWASH point	**Draft - ratio**	**Length - ratio**	**Resulting amplitude ratio**
S_{d-1}	0.2	0.30	0.64
S_{d-2}	0.3	0.30	0.60
S_{d-3}	0.4	0.30	0.54
S_{d-4}	0.5	0.30	0.47
S_{d-m-1}	0.2	0.30	0.97
S_{d-m-2}	0.25	0.30	0.97
S_{d-m-3}	0.4	0.30	0.98
S_{d-m-4}	0.5	0.30	0.95

Table 5.3: SWASH draft-ratio results combined with (numerically solved) conceptual model results

The amount of shown data points of SWASH are limited, mainly because the model experienced difficulties in creating a stable signal and outcome for larger and smaller moving platform drafts. Next to that it is probably not that realistic to have a structural draft of over half the water depth, so larger data points are not required.

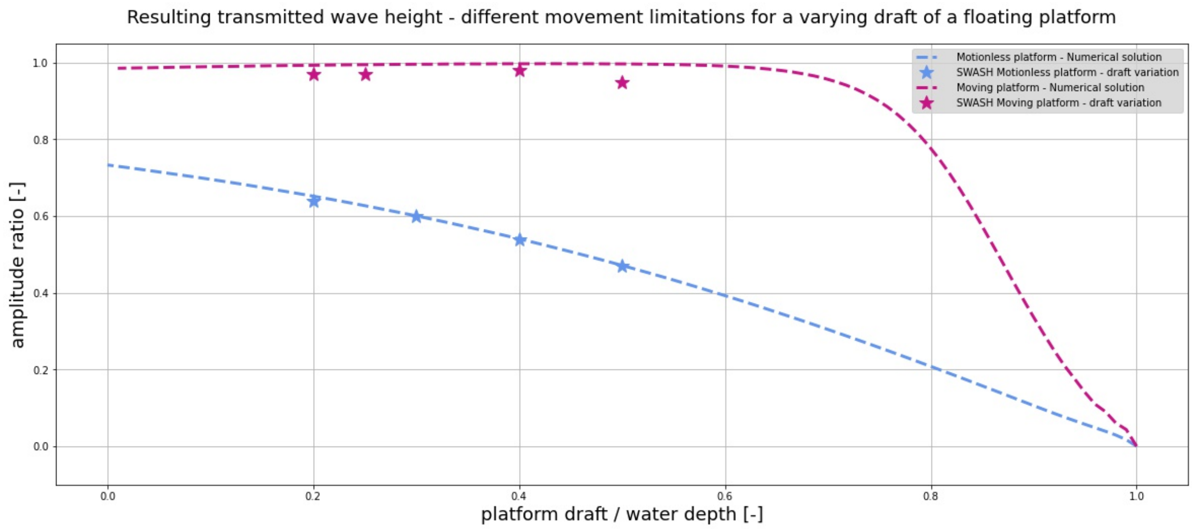

Figure 5.2: Combined results showing both the result of SWASH and the conceptual model for different movement limitations and a varying draft-ratio

Something than can immediately observed is that the points that are generated from SWASH are again really close to the conceptual model. Similarly as shown in Figure 5.1, the points generated for the motionless platform fit better compared to those for the moving platform. The moving platform results from SWASH however, are still very much alike the outcome of the conceptual model. Reasons for the observed slight deviations are similar to that described for the previous situation in Figure 5.1.

5.3. SWASH transmitted wave and platform movement results

In this section the comparison is made between the reaction of the platform and the transmitted wave for both the conceptual model and in SWASH. Figure 5.3 shows a graph indicating the effect of changing the platform length compared to the length of an incoming tsunami type signal for only the moving platform. The same assumptions for the general parameters as identified in Table 5.1 still hold.

A more detailed overview of the SWASH generated data points can be seen in Table 5.4. Each point is indicated by a name that shows the type of parameter it belongs to. S_{l-tw-1} for example is the first datapoint for the transmitted wave (tw) for the length variation run. $S_{l-pm-\Delta k-1}$ is a data point representing the platform movement (pm) but then the additional data points that were generated with a different relaxation parameter Δk, also for the length variation run.

SWASH point	Draft - ratio	Length - ratio	Resulting amplitude ratio	Icon
S_{l-tw-1}	0.25	0.1	1.01	pink star
S_{l-tw-2}	0.25	0.2	1.00	pink star
S_{l-tw-3}	0.25	0.3	0.97	pink star
S_{l-tw-4}	0.25	0.4	0.92	pink star
S_{l-tw-5}	0.25	0.5	0.82	pink star
$S_{l-tw-\Delta r-1}$	0.25	0.05	0.96	pink diamond
$S_{l-tw-\Delta r-2}$	0.25	0.24	0.97	pink diamond
$S_{l-tw-\Delta r-3}$	0.25	0.48	0.84	pink diamond
$S_{l-tw-\Delta r-4}$	0.25	0.71	0.71	pink diamond
$S_{l-tw-\Delta r-5}$	0.25	0.95	0.52	pink diamond
S_{l-pm-1}	0.25	0.1	0.99	red star
S_{l-pm-2}	0.25	0.2	0.96	red star
S_{l-pm-3}	0.25	0.3	0.89	red star
S_{l-pm-4}	0.25	0.4	0.76	red star
S_{l-pm-5}	0.25	0.5	0.63	red star
$S_{l-pm-\Delta r-1}$	0.25	0.05	1.00	red diamond
$S_{l-pm-\Delta r-2}$	0.25	0.24	0.92	red diamond
$S_{l-pm-\Delta r-3}$	0.25	0.48	0.65	red diamond
$S_{l-pm-\Delta r-4}$	0.25	0.71	0.39	red diamond
$S_{l-pm-\Delta r-5}$	0.25	0.95	0.24	red diamond

Table 5.4: SWASH length-ratio results combined with (numerically solved) conceptual model results

The diamond shaped data points again represent the values of SWASH created with a lower value for the relaxation parameter. This ensured that a larger diversity of results result from SWASH, making comparison between SWASH and the conceptual model easier. Although the more extreme points are not interesting for this research, as such a large *length-ratio* is not realistic, for sake of comparison both models it is useful to see that the points still match for these larger length values. The dots belonging to the transmitted wave are repeated from the previous graph based on the length variation (Figure 5.3), but now also showing the difference between both models with regards to the platform movement.

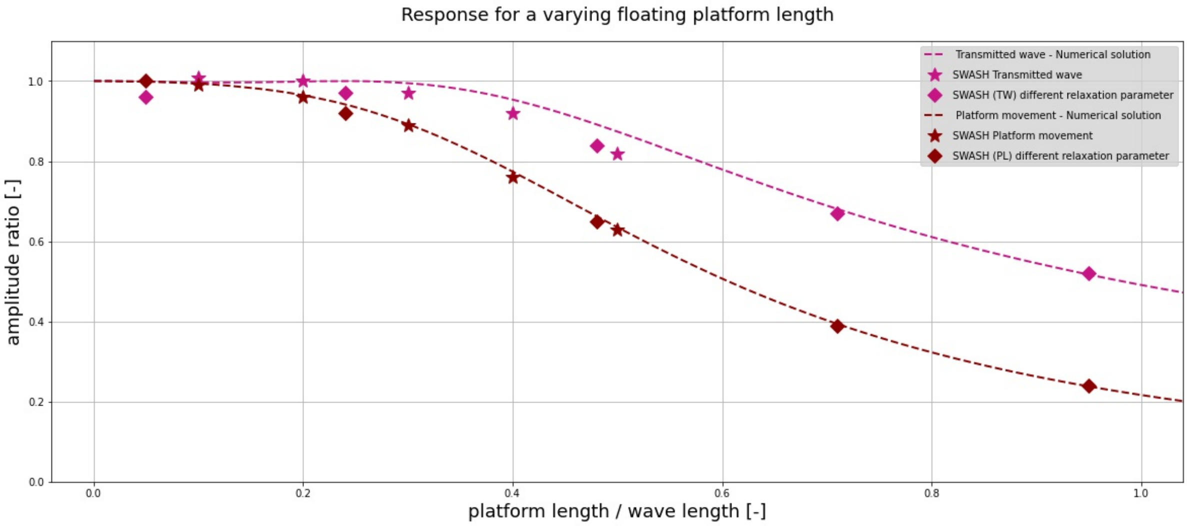

Figure 5.3: Combined results showing results of SWASH and the conceptual model for different parameters and a varying length-ratio

It seems that for both the platform movement the SWASH data points in Figure 5.3 give similar results. The comparison of the outcome of the transmitted wave was discussed earlier in Section 5.2. In case of the platform movement there appears to be a smaller difference between both models. This indicates that the difference between the reaction of the transmitted wave in both models is caused by a difference in connecting the movement of the platform to the transmitted wave. This can be further supported by the fact that in case of the motionless platform hardly any difference between SWASH and the conceptual model was shown. The only location where a difference is located, although this still limited with a maximum of ≤ 10%, is for the reaction of the transmitted wave.

This difference in decay speed between platform and transmitted wave that is observed, was explained earlier in Chapter 4. Although a difference from the conceptual outcome exists, this same phenomena is also observed by SWASH. The idea that the platform creates waves and with that increases the value of the transmitted wave is shown in both models.

Finally it is also important to note that neither of the solutions show a sign of resonance. Although especially the *draft-ratio* being equal to 0.25 shows a potential for resonance, with a combined *length-ratio* of 0.45, the natural frequency equals the wave frequency (see Section 4.2 for more information). Next to the earlier discussed effect of damping for the conceptual model, SWASH also seems to feature this same effect of damping.

The following figure, (Figure 5.4) shows the same variables, so both the outcome of the conceptual model and SWASH for a moving platform, indicating the difference in reaction between the transmitted wave height and the platform movement. The difference is changing the platform draft instead of the platform length. The main aspects for the model input in SWASH are still similar to those presented in Table 5.1. Additional data for the SWASH points belonging to Figure 5.4 is presented in Table 5.5.

SWASH point	Draft - ratio	Length - ratio	Resulting amplitude ratio	Icon
S_{d-tw-1}	0.2	0.30	0.97	pink star
S_{d-tw-2}	0.3	0.30	0.97	pink star
S_{d-tw-3}	0.4	0.30	0.98	pink star
S_{d-tw-4}	0.5	0.30	0.95	pink star
S_{d-pm-1}	0.2	0.30	0.88	red star
S_{d-pm-2}	0.25	0.30	0.89	red star
S_{d-pm-3}	0.4	0.30	0.93	red star
S_{d-pm-4}	0.5	0.30	0.96	red star

Table 5.5: SWASH draft-ratio results combined with (numerically solved) conceptual model results

Similar to comparing the motionless platform with the moving platform, the amount of shown data points of SWASH shown in Figure 5.4 are limited. Mainly because the model experienced difficulties in creating a stable signal and outcome for larger and smaller moving platform drafts. Next to that, larger data points are not required. The dots that are present fit within the Blue21 advised design range.

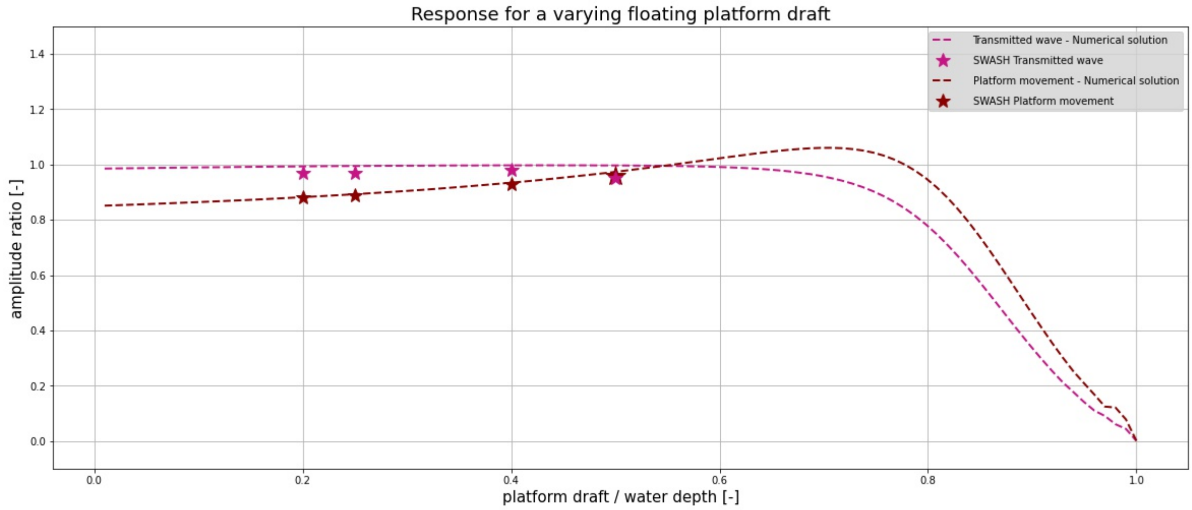

Figure 5.4: Combined results showing results of SWASH and the conceptual model for different parameters and a varying draft-ratio

For both lines, the SWASH data points seem to match up with the conceptual model. The line representing the platform movement starts lower due to the *length-ratio*, set at 0.3, already having an effect. The fact that this is not the case yet for the transmitted wave height has to do with the increased wave height due to the platform movement, which was further explained earlier this Section. This is also followed by SWASH as the points for the platform amplitude start lower too.

For the platform movement at first an increasing trend is present in both the results of SWASH and the conceptual model. It even crosses the value of 1.00, indicating that the natural frequency of the platform is close to that of the generated tsunami and that resonance is appearing. This is possible and can be explained when looking to the natural frequency. The frequency can only be determined for the conceptual model and equals the incoming wave frequency for a *length-ratio* = 0.30 and the *draft-ratio* = 0.75. This is also supported by the peak of the line in Figure 5.4. It is expected that SWASH follows this same response for resonance, as it shows the same increase trend.

5.4. Comparison SWASH and conceptual model

5.4.1. Varying the platform length

All SWASH points representing the situation for the motionless platform are situated on or in close proximity to the line representing the motionless platform reaction in the conceptual model. A similar trend can be observed for the points generated for the model in SWASH with the platform being able to move vertically. Changing the length of the platform has an effect on the wave attenuation. The difference between the two models is largest for the transmitted wave height transmission. The difference between the conceptual model and SWASH has a maximum of about 5% when looking at the transmitted wave height amplitude. As the conceptual model always shows a higher outcome, it can be said that the model is more conservative. This also matches with the fact that it is a less detailed model and adds to the reasoning that the conceptual model provides what it is meant for.

Within the considered design range mentioned in Section 3.1, the maximum obtained wave attenuation in SWASH is a maximum of 15%, with the conceptual model presenting a more conservative value.

5.4.2. Varying the platform draft

Similar to the variation in length of the platform, for the variation of the draft of the platform SWASH shows the same reaction. Each point for the transmitted wave in case of the motionless platform and the movement of platform is near the line of the conceptual model and therefore both models seem to represent these situation well.

Comparing the reaction of the transmitted wave for the moving platform in SWASH and the conceptual model, again the points do not match as well. This difference is in the order of a few percent, less than the variation observed in changing the length of the platform. In general however both models appear show to be less influenced when changing the draft of the platform, especially in the considered design range (Section 3.1). In other words it is rather difficult to change the transmission of a tsunami by only changing the draft of the platform.

5.4.3. Resonance

Both models seem to follow the same response to resonance. Strongly resonant situations in SWASH are not checked, but the most extreme point in Figure 5.2 shows that resonance can be expected as a similar upward slope can be detected in the resulting data points. Next to that, SWASH also shows that no resonance is occurring when applying the length variation. Both models have a similar relation to damping and resonance.

In general the points produced with SWASH show the same trend in reducing the transmitted wave. Next to that, platform resonance is expected to work similarly. The work of the conceptual model can be therefore be used as a quicker and easier step to determine the interaction between a large (single) floating platform and a long linear incoming wave.

6
Discussion

This chapter includes various aspects that are useful for understanding this research and puts it in context of other work in this field. This is done by providing validation of the used models, analysing the results presented and discussing the most important limits to this research. Finally a general overview of what this research means for floating city design is provided.

The conceptual model presented in this research solves the interaction with a structure and a wave, with means of a reduction in detail and simplification in the equations. Although this representation finds itself far from reality, this was done with intention. The goal was to create a general model that, although simplified, can produce a first guess of the interaction with a tsunami and a floating platform. The main aim is finding out if the wave transmission can be influenced by the design parameters.

For comparison reasons, the numerical modelling program Swash is chosen. Swash has been used in research for numerous tsunami related topics, mainly with respect to the 2011 Tohoku tsunami. When modeling with respect to data, it is known what the outcome of a model should represent. The fact that Swash has been successfully used in representing a tsunami wave, means that it is possible to use the outcome of this program as reference. This however is tricky, as comparing two models based on a difference in assumptions and background modelling does not guarantee a resemblance to reality. With this indirect validation however, a good first step is made in discovering this area of research.

When analysing the results, it is useful to notice the visible effect on attenuating the wave when changing the length of the platform. This means that changing the design can play a role in coastal defence. This attenuation already happens for a situation where the platform is small compared to the wave length. However, some remarks need to made about this result.

First of all, the way the results are presented introduces the risk to be observed as too optimistic outcome for the design process. Most graphs indicate a variation of the design parameters relative to either the water depth or wave length, up to a value of 1.0. Although in most graphs it is indicated that especially the higher regions can not be considered realistic, showing them does indicate that they matter. As these regions show the highest percentage of attenuation, caution is required when looking at the model outcomes. The higher regions for these parameter ranges do matter, but mostly for showing how the model works and for example indicating model specifics such as the effect of resonance more clearly.

Secondly, it is important that the distinction is made in considering the length of the structure as a single structure or as the combination of multiple structures forming a floating city. The highest obtained wave attenuation, within the boundaries set in this research, is in the order of 10% This level of attenuation is obtained with the indicated boundaries by Blue 21, that actually consider the structure as a whole. For a single platform, as represented in this research, a different outcome can be expected. As the boundary for the maximum size of a platform should be lower.

To get to a wave attenuation of 10%, the wave period equals of 5 minutes and with a water depth of 20 meters, the structure can equal a length of 2 kilometer. Reaching a length of 2 kilometers for a single structure is not possible. This comparison is therefore not completely accurate. In reality however the city will be able to reach this size but it will consist out of a connected system of platforms. The outcome for the connected system can therefore be different but this is not considered in this research.

Changing the draft of the platform shows little effect in the area of a realistic draft value compared to the water depth. In contrast to changing the platform length, changing the draft of the structure is also less desirable as it does not add any function or additional space to the project. However, when comparing this to changing the length, the changed length can also mean added project potential for the economic or utilitarian aspects.

Interestingly enough, resonance only takes place when varying the draft of the platform. Especially in the higher ranges of the draft compared to water depth. This is explained through the fact that the system is actually a damped second order differential system, with a specific amount of damping present. This amount of damping is mostly regulated by the length of the platform. With the length of the platform increasing, the amount of damping also increases. The situations where both models (conceptual and Swash) experienced a form of resonance, only occurred for large (unrealistic) values for platform design combinations. However because of additional steps that are required to make the conceptual model more realistic, it is expected that the regions in the natural frequency where resonance will occur will be altered. This is therefore an important aspect that needs to be checked when designing a floating city.

The following aspects can be improved making future versions of for example the conceptual model even more valuable. The first aspect that is important to mention is the limited movement freedom of the platform. For both models the maximum tested degree of freedom is the singular vertical movement freedom. Although a platform will be moored and this system will provide some type of resistance, full motionless or a single direction in freedom of movement are both not the most realistic when trying to mimic reality.

The second aspect is the representation of the floating city by a single platform. This was already briefly mentioned in this chapter. The representation of a single platform for a floating city is not realistic, additionally the platform can not deform. The structural system will change in stiffness both due to including connections and by including a more realistic single platform structural stiffness.

Finally the problems that occurred while running Swash are also worth mentioning. During the extension of the model within Swash, where the platform movement vertically was added, several running errors occurred. Specific regions of the runs could be identified where this happened. Mainly the situation where the platform was really small and oppositely where the platform had a significant size so that the platform measured multiple kilometers in length, caused problems. Due to the complexity and lack of transparency of the program, this presents a problem for potential further expansion of such a model within Swash.

For the future of floating cities the fact that some form of attenuation of a tsunami wave can be obtained, indicates that these structures can play a role as in coastal defence. This research suggests that large structures, considering the location and the corresponding wave properties, can play a role in tsunami attenuation.

7
Conclusion

Floating cities can be located in coastal zones that are prone to endure a tsunami. However, these structures have the potential to function as a barrier for the tsunami thereby attenuating the transmission of the wave. This is of utmost importance due to the coastal hazard of a tsunami. Especially the long length, large volume of water, local high currents, and inundation are hazardous. A reduced risk of highly damaging tsunamis through the use of floating structures is thus a very interesting point of research.

A floating city is a relatively large structure compared to existing coastal structures and therefore a potential for a reduction in transmission is present. To be able to find out if this is possible, this research features both a constructed simplified analytical model (also called the conceptual model) and a more complex model SWASH in observation of the interaction between the wave and a large floating structure. Typical dimensions of a floating city that are used in this research are based on the input of Design Company Blue21. The variable parameters, for both the conceptual model and SWASH, are the draft and the length of the platform. Both are analysed relative to a to a spatial parameter; the water depth or wave length.

The most optimal attenuation of the wave takes place when the structural length of the platform is increased, as longer structures induce more attenuation. Next to the effect of the structure itself, the positioning of the structure is also of large importance. This is not a structural design parameter but probably equally important in the design process. On a larger scale, the intensity of the wave will vary due to the surrounding local coastal features, such that the wave varies in shape per location. On a smaller scale, the local water depth is determinant in compressing the wave, therefore decreasing the wave length when the water depth decreases. Taking this into account, the positioning of the structure can influence the outcome of the wave attenuation. The most optimal conditions arise with the shortest wave and the longest platform, accordingly, the maximum wave attenuation that can be achieved by both models is 10%. Providing an answer to the first research question.

The goal of this research was to find a model that only uses the main parameters of a wave and a structure that are of interest, and provide a first global understanding of the situation. By comparing the conceptual model to SWASH, the effect of assuming hydrostatic pressure and a more simplified interpretation of the movement of water are tested. This comparison therefore serves as validation and proved that conceptual model presented a similar trend. Next to that, compared to SWASH, it is easier with the conceptual model to vary a larger range in parameters at the same time, thereby creating the opportunity to evaluate a situation more quickly. The conceptual model appears to work for which it is intended, modelling the resulting transmission between a floating structure and a linear tsunami. It does however have two limitations/assumptions of leaving out the non-hydrostatic pressure and a lower level of detail, which results in maximum of 5% deviation in both model results. With this the second research question is answered.

It is expected that modelling programs can be expanded and/or improved, so that more realistic floating structures can be modelled. However, it will remain difficult to accurately model a tsunami as it is complex in behaviour. Especially the combination of the tsunami with an extended full floating city structure requires future work. Yet, this research brought the field one step closer to evaluating the transmission of tsunami waves when interacting with a floating structure of certain dimensions.

8 Recommendations

The recommendations that this research provides mainly covers extensions of the conceptual model. Additionally, general recommendations with respect to the subject of tsunamis and floating cities are mentioned.

To compare the conceptual model and Swash for nonlinear waves. Explained during the section discussing the wave input, is the fact the type of input wave is somewhat difficult to decide on. Periodic waves are easily scaleable and in the basis form a linear wave signal. Especially when a tsunami is considered more offshore, it behaves linear. For this research the water depth did not vary. Therefore, no change in the wave shape should be present thus a linear wave signal is expected from the wave signal. In SWASH however the periodic waves could not be considered linear when in the order of meters. The wave height therefore needed to be significantly decreased. Especially when considering using SWASH with improved tsunami wave development representation, different wave signals should also be considered. Tsunami waves are are not periodic waves, but exist of a few waves maximum (due to reflection). To represent this wave better, for example a solitary wave signal can be used.

To make the outcome of the calculations more realistic, the degrees of freedom for the platform should be increased. This research only considers the allowed vertical movement of the structure. In reality the structure will experience not just heave but also other translation movements such as surge and sway. In addition the rotations of roll, pitch and yaw important to provide a complete representation of the movement of a platform. Changing these movement freedom aspects is done by changing the basis equations of the conceptual model. Therefore increasing this will also directly increase the complexity of the model. The inclusion of various degrees of freedom can however be done step by step and the way the platform is observed is also of importance. For example, at this point the model assumes a two-dimensional spectrum. Before changing this to three-dimensional, a first rotational movement can be added. This already makes a significant difference in representing a floating structure more realistically.

The next aspect that can be added to the conceptual model, is the fact that a floating city will consist of multiple platforms. Changing this is concerns the fact that a representation for connections should be found. These connections then should be implemented in the equation level of the model. Essentially, they will represent a limit to the movement that the platforms can experience relative to each other.

Another aspect that can help with that is include mooring lines. The structure(s) will be moored, either by pile mooring systems in smaller water depths or by (chained) mooring lines in larger water depths. This difference in type of mooring should also be considered. To be able to be certain about the type of mooring used, the location of the city should be known. Analysing the reaction of the mooring system therefore should be in close contact with the company responsible for the design.

Floating cities are still conceptual and for the concept to get closer to implementing, more research and also testing is required. In addition to the outcome of numerical models, to ensure validation is possible, evaluating wave development is necessary as detailed as possible as on the basis of a previous tsunami. In combination with the wave development, a configuration of a floating city can be tested. For tsunami it is impossible to do real life testing with full-scale waves. Reduced scale testing however still requires a considerable space and not possible in every wave laboratory. An example of a location where such testing can take place is the Hinsdale laboratory at the Oregon State University in Oregon, United States of America.

The following questions should also be considered. Is it even desirable for a floating city to be in an area that can be impacted by a tsunami? For the structure to be safe, it potentially should be located far offshore. Here a tsunami wave still is limited in height and might occur unnoticeable. The effect of transmission of the wave however is negligible in this area. Positioning it closer to shore will pose a problem though as this is the point where tsunamis develop into walls of water. This is however not included in this research; the effects on liveability or even the detrimental effect that a tsunami can have for coastal and marine areas. This area of research will always be somewhat daunting, fitting to such a wave.

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