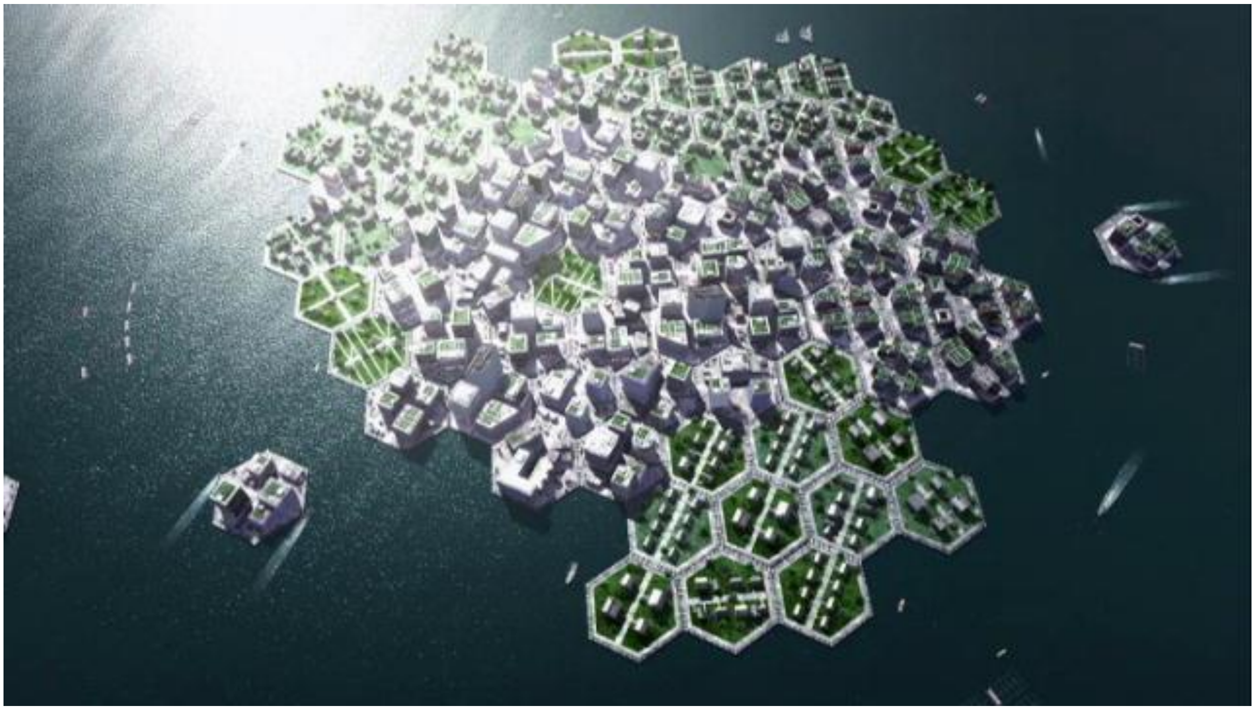
Realising a floating city

A feasibility study of the construction of a floating city



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Preface

This thesis is part of the Hydraulic Engineering MSc program at the faculty of Civil Engineering and Geosciences of the Technical University of Delft. The thesis is performed in cooperation with Deltasync; a multidisciplinary design, research and consultancy firm.

The thesis is about a feasibility study of the construction of a floating city. The main components necessary to realise a floating city are elaborated and worked out from a structural perspective.

I would like to thank all the members of my graduation committee for their guidance, advice, support and patience during the whole progress of the thesis.
I would also like to thank all the colleagues at Deltasync who helped me and gave me their opinion and advice during my short stay at the firm.
Finally I want to thank my family and friends for their support.

Kelvin Ko

Delft, June 2015

Summary

People are already living on water for centuries in some places around the world. However, the concept of building on water has been reintroduced with a new idea in the last two decades. The new idea is to realise a very large floating structure which is as big as a city. Instead of multiple independent floating houses forming a floating community or residential district, this new idea is to realise a complete city state which floats on the water, a so-called 'floating city'.

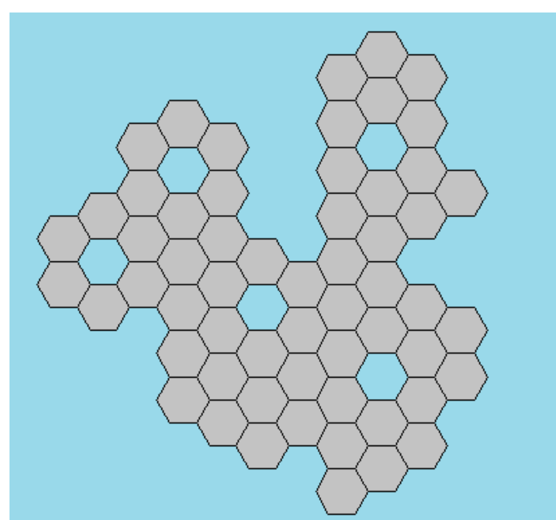
The main objective of this report is to give a general design of a floating city to determine the structural feasibility of such a concept. The challenge in this concept lies in the environment the floating community is in. The environment of the floating community determines which and what kind of forces are acting on the platforms. Strength and stability are heavily dependent on which forces are working on the platforms and the magnitude of these forces is also of great importance. It is common sense that such a floating city would survive better in a calm bay then in the open sea with huge waves and frequent storms. That is why this thesis will focus on the latter situation: a floating city in the open sea with a rough environment.

The main question in this thesis to be answered is defined as '*Is it possible and realistic to create floating cities from a structural perspective*'. To come to an answer for the main research question, several sub questions can be formulated:

- What kind of floating platforms are needed?
- How can platforms be connected to each other to form a floating city?
- How is the floating city to be moored to stay at one location?
- What is the behaviour of the platforms, connections and moorings when the floating community is loaded by (large) waves?

What kind of floating platforms are needed?

A design of the floating city is chosen in the form of modular hexagonal shaped platforms. The design with the hexagonal shaped platforms is very straightforward and the growth of this floating community is simply achieved by adding more platforms in all ways possible. Hexagonal shaped platforms are symmetric from all sides, so it is easier to configure the floating community in different ways without worrying about whether the platforms are going to fit to each other. Also, the more sides the platform has, the more sides there are to build houses near the water which is a plus for the criterion of water experience. A hexagonal shaped platform with sides of 60 m is the optimal size. The starting floating community consists of 60 platforms each with an area of 9353 m^2 to accommodate 15000 inhabitants in total. The total costs to just construct one platform are estimated to be €40 million. Each platform should house approximately 1500 inhabitants. The dimensions of the platform are shown in the table below.



Side length of hexagon	60 m
Construction height	14 m
Draught	10.89 m
Freeboard	3.11 m
Inner walls thickness	0.8 m
Outer walls thickness	1.0 m
Deck slab thickness	1.0 m
Bottom slab thickness	1.0 m

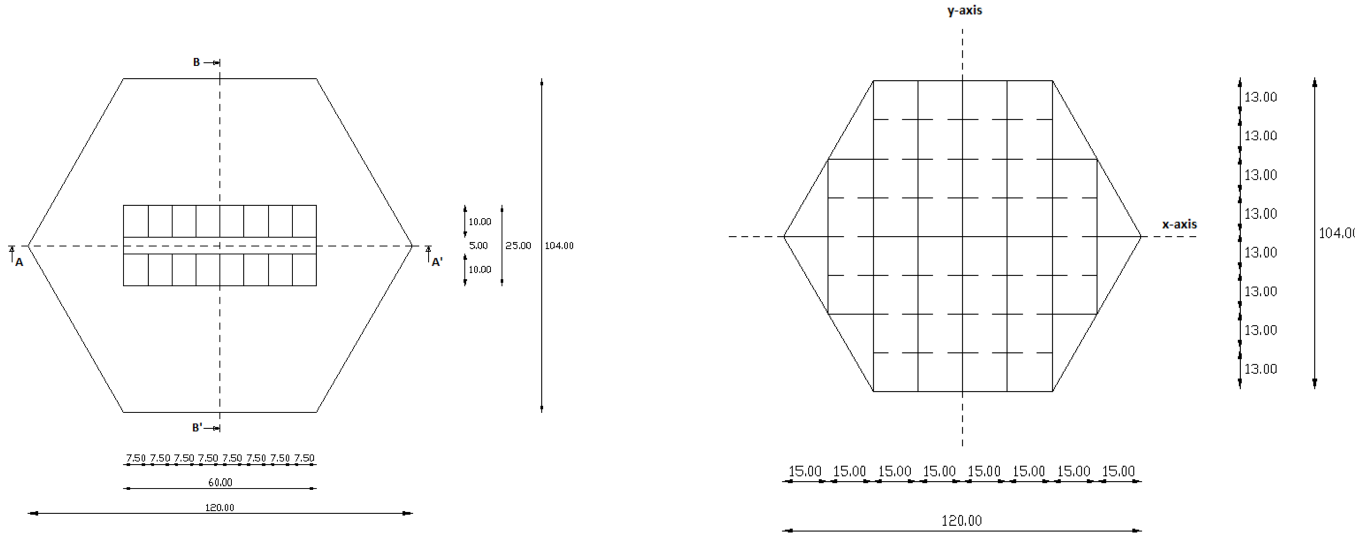


Figure 1: Footprint of the high rise building on the platform and inner walls plan

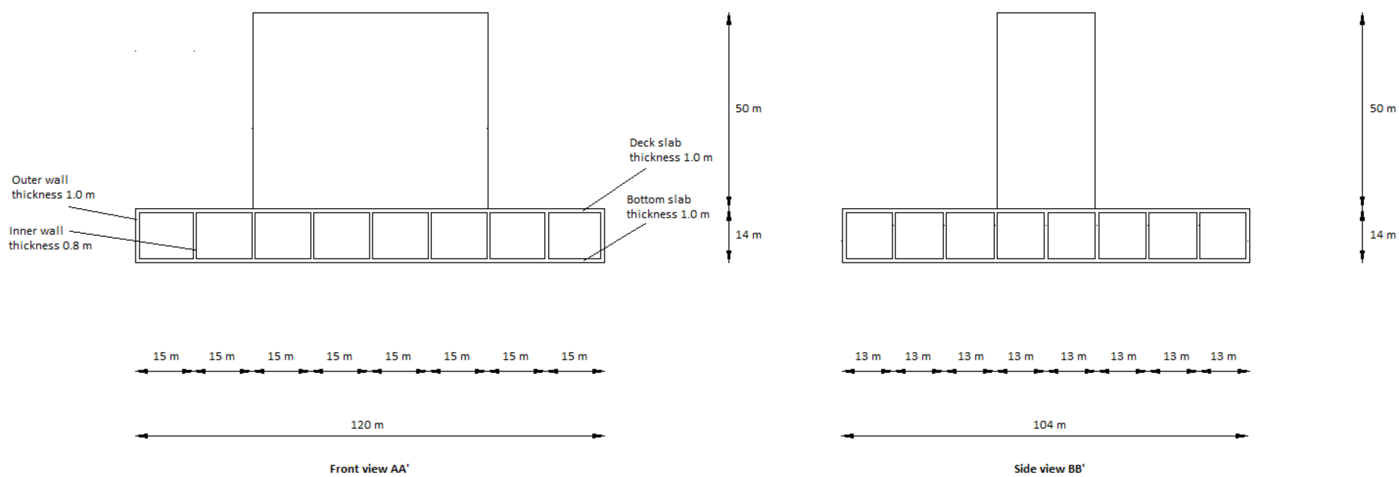


Figure 2: Front and side view of the platform

How can platforms be connected to each other to form a floating city?
A floating city can only be realised with modular floating structures. The platform is the base of the floating city and the floating community is realised by connecting all the modular floating platforms to each other. This way, the individual platforms will not move relative to each other, preventing collisions and/or platforms drifting away from the floating community. Several connection types can be distinguished, but a puzzle-type connection (or concrete toothed connection) is the easiest, cost effective and straightforward rigid connection type to be used. These connections are different shaped edges of the platforms which fit on the opposite platform and then pinned together through a bolt/pin.

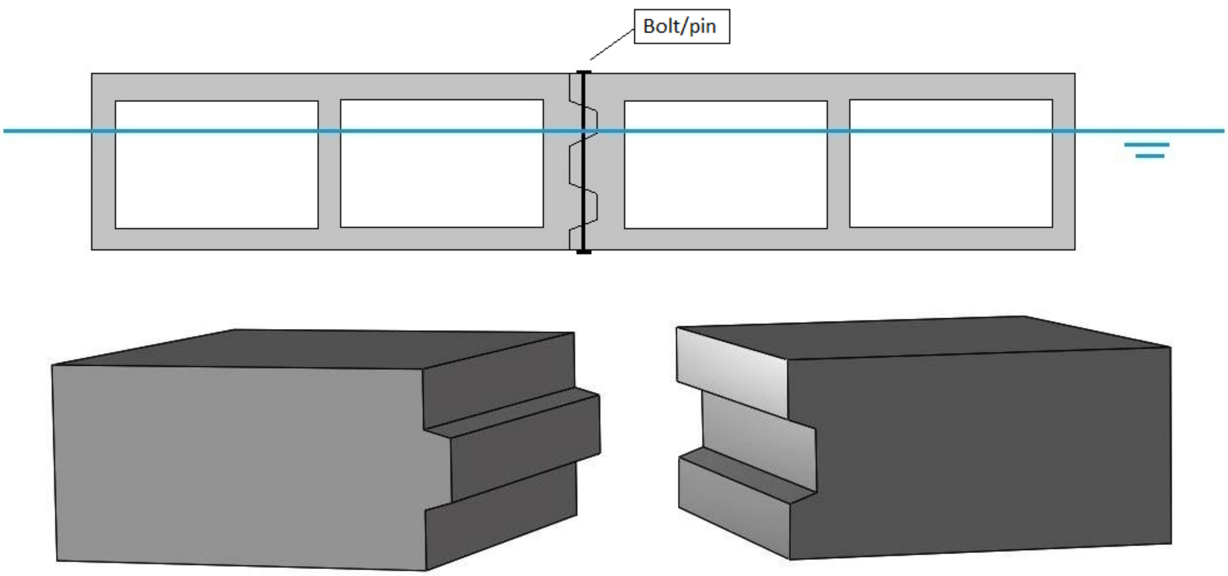


Figure 3: Puzzle-type connection

How is the floating city to be moored to stay at one location?
A reliable mooring system is needed to ensure that the floating city is staying at its location. It is chosen to use the cable/chain mooring system because this system can handle both horizontal and vertical displacements and forces very well. Specifically a taut-leg cable/chain system is chosen because this mooring line system arrives at the seabed at an angle and thus handles both horizontal and vertical forces well. This angle determines how well the vertical and horizontal loads are transferred to the anchorage. It is chosen to apply the mooring lines under an angle of 45°.

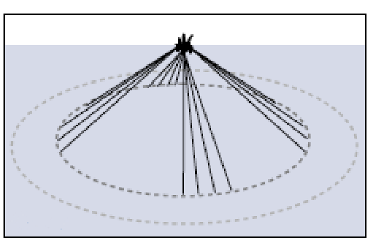


Figure 4: Taut-leg mooring system (Vryhof anchors, 2010)

The mooring lines are made of spiral strand ropes because these steel ropes have a lower deadweight for the same breaking load and a higher elasticity compared to other materials. The high strength to weight ratio makes the ropes easy to handle and result in lower vertical forces on the floating structure.

What is the behaviour of the platforms, connections and moorings when the floating community is loaded by waves?

The three elements platform, connection and moorings have to work with each other to realise the basics of a floating city. The platform, connection and moorings have a certain dynamic behaviour when a dynamic force/excitation is exerted on these elements. For example, earthquakes gives the moorings a dynamic excitation which will affect the movements of the platforms. Or wind/wave loads which are exerted on the platforms, making the moorings and connections bear the forces of the moving platforms. The latter dynamic situation with waves has been elaborated. A floating city is always loaded by waves which makes it the most basic dynamic problem.

The floating platform is schematized as a rigid, infinite stiff block founded on vertical and horizontal springs (hydrostatic forces) and diagonal springs (moorings). And the platform is excited by a sinusoidal motion which represents the vertical wave motion. First this analysis has been done for a single platform to give a better understanding of the analysis and then the same analysis is done with a series of platforms.

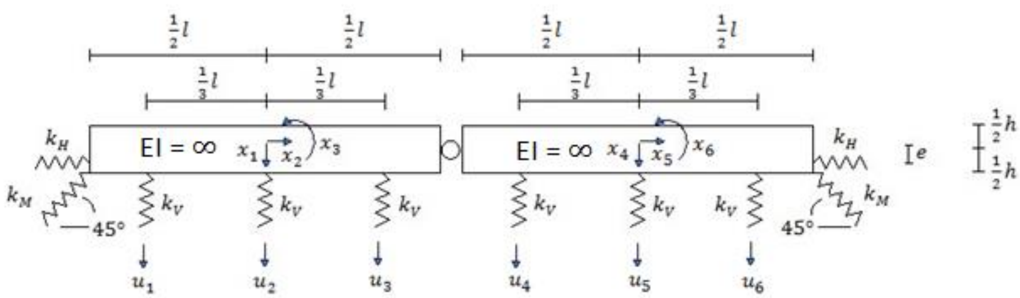


Figure 5: 2 mass-spring system model

By assuming different displacements of the platforms, all the forces in the springs can be expressed as a function of a certain displacement. By collecting all the forces in a logical manner, a so called equation of motion is obtained to solve the unknown displacements of the system. The equation of motion exists of a mass, stiffness and damping matrix originally, but the damping matrix is negligible when the frequency band of the occurring waves is sufficient far away from the resonance frequency of the structure.

The mass and stiffness matrix are solved with the program Maple. Comparing the results of the one and the two mass-spring systems, the outcomes of the occurring displacements and accelerations were the same for the first initial platform and the attached platform experiences displacements 10 times larger than the displacements of the first platform. From this statement, it can be concluded that a second platform/mass attached to the first platform/mass is not beneficial. However, because of the large dimensions of the platforms the displacements of the first platform are very small. Which means that the second platform experiences a displacement 10 times larger than this small displacement, which is still significant very small. This behaviour is actually the same as the characteristics of a whip. A whip experiences a very large displacement towards the end of the whip even when a small displacement is given at the beginning. The reason for this 'whip-like-behaviour' is because a hinged connection is used in the dynamic analysis. A hinge was purely used in the structural schematisation of the coupled platforms to calculate the forces occurring in the connection between the platforms. But in reality a rigid connection is used which means that two coupled platforms actually act as one large single platform. So expected is that the attached platforms will not really experience displacements 10 times larger.

Conclusion

The main question in this thesis to be answered is defined as '*Is it possible and realistic to create floating cities from a structural perspective*'.

The answer is that it is theoretically possible to realise floating cities with modular floating platforms rigidly connected to each other. The platforms are inhabitable under severe wave circumstances and they experience very small displacements as long as the connections between the platforms are very rigid constructed. However, to make sure rigid connections in a multiple mass-spring system are indeed experiencing lower connection forces due to smaller displacements, it is best to find this out with a small scale experiment/modelling program.

From the results and calculations in this thesis, it is reliable to connect up to 4 platforms in a linear formation for the chosen design of the hexagonal platform with sides of 60 m and a construction height of 14 m. This means that a floating community of 16 platforms (in a configuration of 4 by 4 platforms) can be realised and house approximately 4000 inhabitants.

The research in this thesis has come with the following crucial conclusions about 'Realising floating cities'.

- Hexagonal shaped platforms are the most reliable platform shape for constructing different floating city configurations.
- Although a hinged connection in a mass-spring system results in very small displacements, a fully rigid connection type is always preferred for realising a floating community.
- Mooring systems do not contribute to the displacements of the platforms. In other words, they do not reduce the displacements no matter how stiff the mooring line is. The moorings are there to prevent the platforms from drifting away due to repetitive displacements of the platforms.
- Comparing the results of the one and the two mass-spring systems, the outcomes of the occurring displacements and accelerations were the same for the first initial platform and the attached platform experiences displacements 10 times larger than the displacements of the first platform. From this statement, it can be concluded that a second platform/mass attached to the first platform/mass is not beneficial. However, because of the large dimensions of the platforms the displacements of the first platform are very small. Which means that the second platform experiences a displacement 10 times larger than this small displacement, which is still significant very small. This behaviour is actually the same as the characteristics of a whip. A whip experiences a very large displacement towards the end of the whip even when a small displacement is given at the beginning. The reason for this 'whip-like-behaviour' is because a hinged connection is used in the dynamic analysis. A hinge was purely used in the structural schematisation of the coupled platforms to calculate the forces occurring in the connection between the platforms. But in reality a rigid connection is used which means that two coupled platforms actually act as one large single platform. So expected is that the attached platforms will not really experience displacements 10 times larger.
- Because of the above conclusion and the fact that rigid connections are used in reality, a multiple mass-spring system can be solved as a 1 mass-spring system where the multiple platforms are schematised as a 'platform' with very large dimensions.

Recommendations

There are still a lot to find out and research about the subject of floating cities as not everything could be included in this thesis. The following aspects would be interesting for further research.

- A complete accurate cost analysis for a specific location should be done to determine whether land reclamation or floating cities would be a more cost effective solution. The costs of reclamation sand can make a big difference in the required water depth to make a floating city economic more feasible.
- A structural calculation for the platform is needed to maximise the strength of the platform. Structural calculation to determine how much reinforcement steel is needed and whether pre-stressing elements are needed etcetera.
- Load transfer from buildings and other live loads on top of the platform to the inner walls of the platforms should be investigated. Especially when the inside of the platform is used for other purposes (parking garage for example) which leads to a reduction and/or openings in inner walls.
- A more accurate structural calculation regarding the forces, moments and stresses in the platform connection is needed to really assure the reliability of the connections.
- Maintenance and the repair of the connections should be detailed looked into as the connections are very crucial to the floating community.
- A same dynamic analysis approach as in this thesis should be done to check the effect of earthquakes and typhoons on the floating platforms.
- Now it is clear that the floating city concept is structurally and dynamically feasible, the last question remains whether it is possible to effectively build it. A research on the construction method and the time management of the hexagonal platforms is essential to start realising the floating city concept.

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1 Introduction

1.1 General introduction

Floating structures are structures which stay afloat by relying on the buoyancy force of the water. The term floating structures as meant in this report can be used to define utility buildings, roads, harbours or other (urban) functions on the surface water. Floating structures are also used in the offshore industry (where they usually take form of large floating platforms) and are all well known, but floating houses and facilities are only realised on a very small scale.

The idea of floating structures is not a new revolutionary concept from the past decade. People are already living on water for centuries in some places around the world. However, the concept of building on water has been reintroduced with a new idea in the last two decades. The new idea is to realise a very large floating structure which is as big as a city. Instead of multiple independent floating houses forming a floating community or residential district, this new idea is to realise a complete city state which floats on the water, a so-called ‘floating city’.

As floating villages consisting of floating houses already exist throughout the ages, what sets a floating city apart from these floating communities except that a city is in theoretical sense larger than a village? One could simply think of even more floating houses gathered at one place and the whole floating community would be some sort of a city due to the quantity. But this is not the exact reasoning behind a floating city. A city has more facilities and utilities then just plain space for accommodation. An impression of a floating city is shown Figure 6. It is a concept for a floating city in the lake IJmeer in the Netherlands (Graaf, 2006).

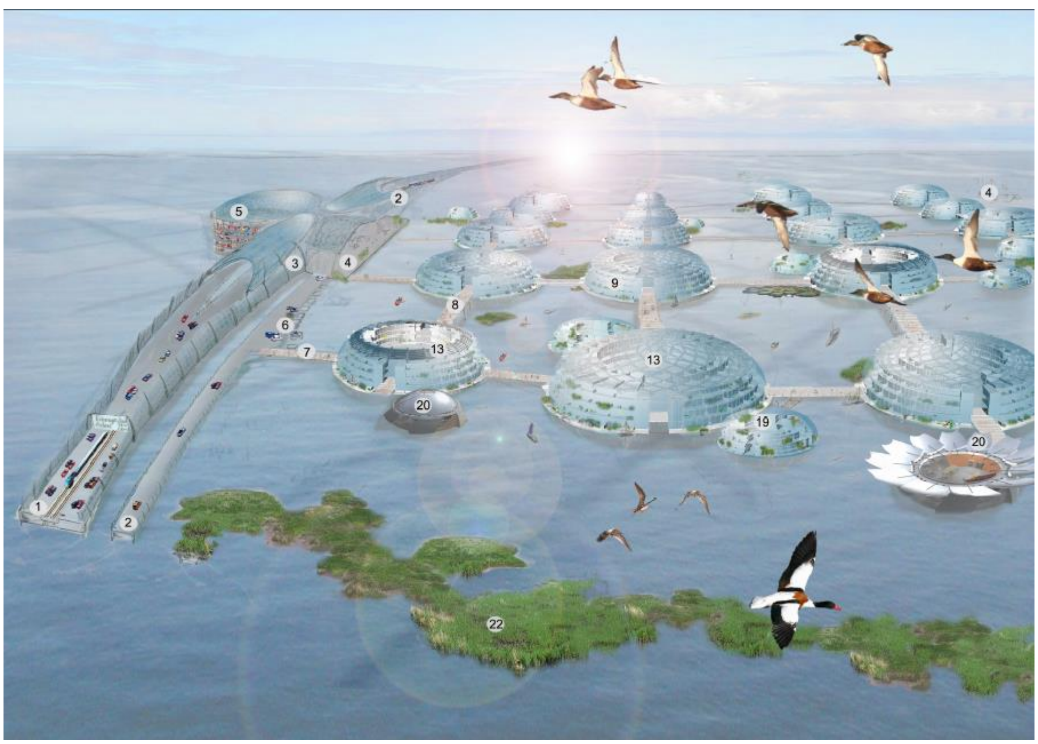


Figure 6: Impression of a floating city in IJmeer, the Netherlands (Graaf, 2006)

1.2 Future problems

It is estimated that only one-eighth of the surface of the earth is suitable for humans to live on. And roughly three-quarters of the earth surface is covered by oceans and water. The rest of the land area (one-eight) consists of deserts (14%), high mountains (27%), or other unsuitable terrain. However, there is still plenty of space left on the vast land to build cities or accommodate people for the coming centuries as we are only occupying roughly 5% of the earth surface. So why would we start to live on floating cities on the water surface? Reasons to live on water in the far future is encouraged by the following problems:

- Sea level rise due to climate change (intense rainfall)
- Lack of available building ground

Sea level rise due to climate change

The ice caps are melting as a result of the higher temperatures and the sea level is expected to rise. A rise of the sea level brings problems to the coast or the sea defences of a country. A rise of the sea level also means a rise in the water level of rivers. And the climate change brings more severe rainfall which leads to higher river discharges. The flood defences in a country (especially in a country below the sea level like the Netherlands) are more heavily loaded and need to be improved to minimise the risk of flooding. Instead of fighting against these water issues, one can also adapt to it and live with it. This can be accomplished by floating houses (and to a much bigger extend, floating cities), which are flexible on rising water levels.

Lack of available building ground

The lack of available ground to build houses and facilities on is another problem the society is facing. There is a demand for more living space due to the ever fast growing population. Some countries/cities do not have that available ground to build houses on, which is why they tend to extend to the sea with the help of land reclamations. But there are places in the world where land reclamation is less feasible. For instance, places where the water depth is too large or places where there is no or scarce sand available for land reclamation works (a well-known example is Singapore). A solution for these places where land reclamation is less feasible or expensive is, again, to live on the water with help of floating structures.

The concept of a floating city is not necessarily needed now, but it would provide more use in the future when sea level rise is really becoming a big problem. It also helps for overpopulated cities (near shores) to expand to the sea.

1.3 Main objective

The main question in this thesis to be answered is defined as '*Is it possible and realistic to create floating cities from a structural perspective*'.

To come to an answer for the main research question, several sub questions can be formulated:

- What kind of floating platforms are needed?
- How are the platforms going to be connected to each other to form a floating city?
- How is the floating city to be moored to stay at one location?
- What is the behaviour of the platforms, connections and moorings when the floating community is loaded by waves?

'What kind of floating platforms are needed?'
The floating city concept is dependent on the reliability of the floating platforms for a safe and comfortable living. That is why the strength and stability of these platforms are very important to start realising a floating city concept.

'How are the platforms going to be connected to each other to form a floating city?'
A city can be defined in several ways depending on its population and size. Cities mostly start out small and grow gradually. This is one of the reasons why it is chosen to work out a floating city which consists of multiple connected platforms as the floating city can 'grow' by just adding more platform to the floating community. The problem arises that these large platforms are difficult to connect to each other because of large internal forces caused by the environment and the platforms itself.

'How is the floating city to be moored to stay at one location?'
A mooring system is necessary to ensure that the floating structure is kept in position and prevented from drifting away under critical sea conditions and storms. A freely drifting floating structure may lead to damage to the surrounding facilities and infrastructures. It is also inconvenient to live on a constantly moving platform.

'What is the behaviour of the platforms, connections and moorings when the floating community is loaded by waves?'
If a modular floating community is really structural feasible, what will happen to the platforms, connections and moorings when they are loaded by external forces like waves? Will the connections and moorings withstand the internal forces? Are the motions on the platforms comfortable enough to live on it? In other words, is it still feasible and realistic to live on such a floating city?

The main objective of this report is thus to give a general design of a floating city to determine the structural feasibility of such a concept.

The challenge in this concept lies in the environment the floating community is in. The environment of the floating community determines which and what kind of forces are acting on the platforms. Strength and stability are heavily dependent on which forces are working on the platforms and the magnitude of these forces is also of great importance. It is common sense that such a floating city would survive better in a calm bay then in the open sea with huge waves and frequent storms. That is why this thesis will focus on the latter situation: a floating city in the open sea with a rough environment. Of course there are more severe situations imaginable like tsunamis, volcano eruptions and hurricanes, but these hazards seldom occur. The boundary conditions with such severe conditions should be looked into after a reliable general design of a floating city is realised.

1.4 Report layout

Regarding the structure of this report, the reader will first get into some background information about the floating city in chapter 2. This chapter will also provide boundary conditions and assumptions to start the design of a floating city. There is no specific location chosen for the floating city in this thesis, so most boundary conditions are fictional assumptions. In chapter 3, the possible designs for the floating city are evaluated and one design concept will be chosen to work out in this thesis. After it is clear what the total system of the floating city will look like, the floating city will be split into smaller subsystems. These subsystems are all worked out in chapters 4, 5 and 6. The subsystems which will be worked out are the floating platform itself, the platform interconnections and the mooring of the floating city. After each subsystem is explained and worked out in their respective chapters, the interaction of the three subsystems is worked out in chapter 7. Chapter 7 is in fact a detailed phase where the dynamic interactions and relations of the subsystems will be researched. And finally, chapter 8 gives a conclusion and some recommendations about the chosen design of the floating city concept.

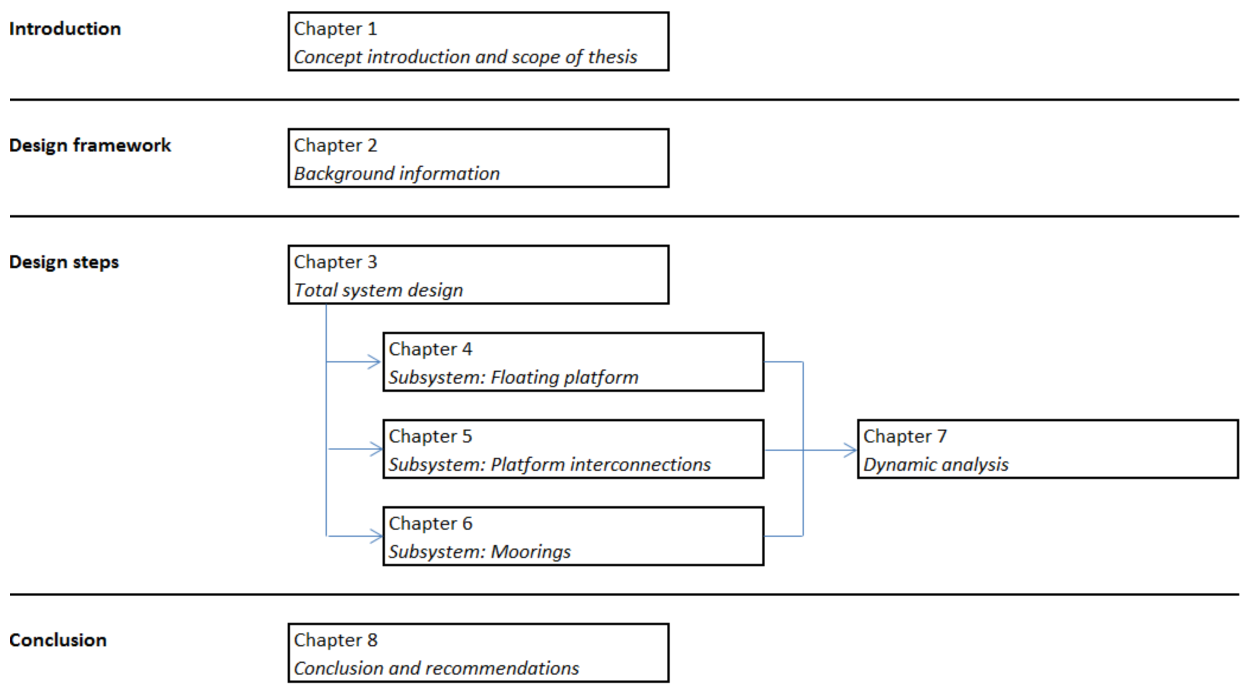


Figure 7: Report structure

2 Background information about floating cities

This chapter provides background information about floating cities. The issue of land reclamation versus a floating city is first shortly elaborated to give a clearer objective of why the floating city concept is necessary in the future. The floating city concept and the necessary structures for this concept are then shortly elaborated and the development of this concept till date is also provided. Aside from some general background information, information is also provided about the boundary conditions of such a floating city. With the boundary conditions, a design of the floating city can be made.

In short, the following paragraphs are being worked out in this chapter:

- *Land reclamation versus floating city*
- *Structures and facilities on a floating city*
- *Development of the floating city*
- *Boundary conditions*

2.1 Land reclamation versus floating city

While the floating cities are still in development and not yet realised. Land reclamations are nowadays a popular method as an alternative to gain more building ground. However, the costs for land reclamation will increase with increasing water depth. As the water depth increase, so does the material needed to fill up this depth increase, while floating structures remain their size regardless of the water depth. More disadvantages of land reclamations versus floating structures are for example:

(1) Floating structures are more environmentally friendly; it does not damage the marine eco-system or silt-up deep harbours or disrupt tidal/ocean currents.
(2) Floating structures are protected from earthquakes.
(3) Floating island cities are easier and quicker to construct than land reclamation projects.
(4) Reclaimed land must be wary of soil subsidence.
(5) Rise of the sea level ensures that land reclamation projects will be more expensive due to the larger depths to be filled with more material.

However, the disadvantages mentioned above have their doubts.

(1) It is not totally true that floating structures have no impact on the environment. Very large floating platform will block the sunlight, disrupting the marine eco-system.
(2) Although floating structures are indeed protected from earthquakes, the floating city must still be connected to the mainland for traffic purposes. The connections will be vulnerable for earthquakes. Furthermore, earthquakes can cause tsunamis, which is a threat for floating structures.
(3) The construction time of land reclamation projects are indeed quite long because of the many processes. This is because all the reclaimed land has to be subsided and settled before buildings and utilities can be built on the new acquired land. This is to prevent settlement of the buildings and utilities which will damage these structures. However, there are several methods to minimize settlements on soil bodies. The soil can for example be injected with special grout or compacted beforehand to increase the stiffness or reduce the time needed to subside. One must not forget that the technology for land reclamation is also improved throughout the years.
(4) Soil subsidence can be minimized or prevented through the methods mentioned above.

Even the mentioned increasing costs about land reclamation in deeper waters are still not justified exactly. It is estimated that land reclamation in water depths of 15 m or more leads to high costs. A list of big land reclamation projects is shown in Table 1 to give a better estimation of the total costs of such projects.

Project	**Country**	**Area**	**Total costs**	**Cost/unit**
Palm Jumeirah [1]	Dubai	25 km^2	\$12.3 billion	492 $\$/m^2$
Chūbu Centrair International Airport [2]	Japan	8.5 km^2	\$7.3 billion	859 $\$/m^2$
Kansai International Airport [3]	Japan	10 km^2	\$15 billion	1500 $\$/m^2$
Central and Wan Chai [4]	Hong Kong	320000 m^2	HK\$ 3620 million	11312 HK$\$/m^2$ (≈1458 $\$/m^2$)
Pulau Tekong [5]	Singapore	24.42 km^2	\$5 billion	205 $\$/m^2$
Changi Airport [6]	Singapore	13 km^2	\$1.9 billion	146 $\$/m^2$

Table 1: Land reclamation projects

Table 1 looks a little bit contradicting to what is said about Singapore where sand for land fill is very expensive. The projects in Singapore only indicate the costs of the land fill material. Chūbu Centrair International Airport, Kansai International Airport and Central/Wan Chai indicate the total costs of the project (costs including the super structures and facilities etcetera). For example, in the Netherlands sand is excavated nearby the place to be reclaimed leading to very low costs (the costs are around 3-10 €/m^3). [7]

[1] http://en.wikipedia.org/wiki/Palm_Jumeirah
[2] http://en.wikipedia.org/wiki/Ch%C5%ABbu_Centrair_International_Airport
[3] http://en.wikipedia.org/wiki/Kansai_International_Airport
[4] http://www.devb.gov.hk/reclamation/en/basic/plans_and_maps/project/index.html
[5] http://infopedia.nl.sg/articles/SIP_1009_2010-05-14.html
[6] http://cgssgeogchangiairport.blogspot.nl/2010/08/what-were-some-problems-or-challenges.html
[7] http://deltaproof.stowa.nl/Templates/pdf.aspx?rId=23#Kosten_en_baten

2.2 Structures and facilities on a floating city

A floating platform is not the only structure that is necessary to realize a floating city. There are several structures that help ensure the floating platform to perform well under all conditions and several facilities are needed in order to distinguish itself as a city.

In Figure 8 an impression of a floating city is given. Numbers (1) and (2) are highway bridges which connect two destinations on the mainland. The structure is a hollow vessel with a lowered road surface and an open top, where the sides act as noise barriers. The road surface must have enough buoyancy to support its dead weight, ensuring that the road will not sink even after sustaining damage. A floating city is moored along the highway bridge, surrounded by floating vegetation. This outer ring serves as a breakwater reducing the wave height in and around the city. The transport hub located on the floating bridge provides a parking facility (5) and a metro station (3), as well as a dock (6) for ferries. Within the city, residents can move around using floating pathways (7) (8), small and big ferries (6) and private boats (4).

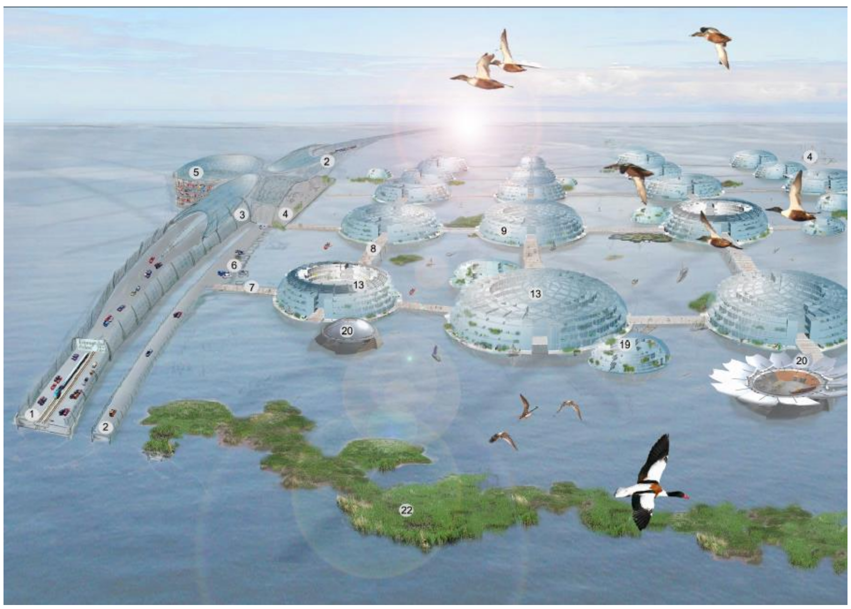


Figure 8: Impression of a floating city in IJmeer, the Netherlands (Graaf, 2006)

Based on Figure 8, the following structures and facilities are needed in a floating city:

- Buildings and houses
- A road/bridge connection to the mainland
- A mooring structure
- A breakwater around the floating city
- Interconnections between floating platforms which are accessible by people, vehicles and public transport.
- Parking facilities
- Port/harbour/ferry facilities
- Hubs for public transport, like a metro or train station
- Energy and gas stations
- Watering and sewerage systems
- Waste treatment facilities
- Stabilizing systems

2.2.1 Buildings and houses

Buildings and houses on a floating platform are included as the dead load of the floating structure. They give the largest amount of dead load aside from the floating platform itself. The dead load that is affordable to stay afloat is dependent on the type and draught of the floating structure. Buildings and houses also need to be distributed over the whole surface to avoid tilting and rotation. The heights of buildings are limited due to stability issues and the fact that high-rise buildings catch a lot of wind, making wind loads a very important aspect for the stability of the floating platform and the building itself. Another problem with high-rise building is that buildings on floating platforms have limited ways of being founded on the concrete or steel platform compared to buildings on the mainland. High-rise buildings on the vast ground are usually founded on very long piles to support the dead load of the building and in a lesser extent the over turning moments of the building. These pile foundations are not possible anymore or very limited on floating platforms.

2.2.2 Moorings

A mooring system is necessary to ensure that the floating structure is kept in position and prevented from drifting away under critical sea conditions and storms. A freely drifting floating structure may lead to damage to the surrounding facilities and infrastructures. It is also inconvenient to live on a constantly moving platform. Known mooring systems for floating platforms are: the dolphin-frame guide system, the cable and chains system, the tension leg method and the pier/quay wall method (see Figure 9).

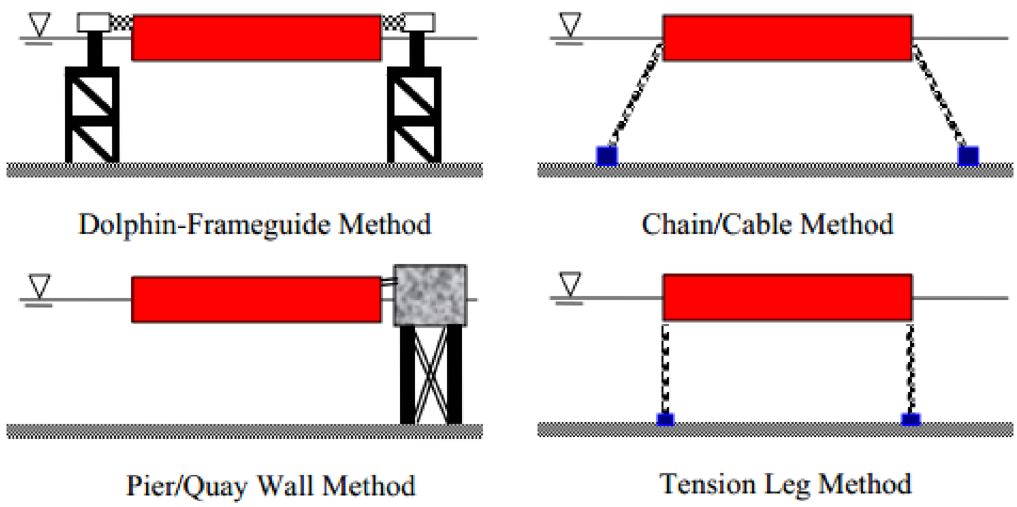


Figure 9: Example of some mooring systems [8]

There are a lot more mooring constructions imaginable and all are derived from the offshore industry. The dolphin-frame guide and the pier/quay wall method both are reliable to withstand horizontal and vertical displacements/loads from the floating structure. The chain/cable and tension leg method on the other hand can handle horizontal forces and displacements very well, while they perform less good when there is a lot of vertical movement. To better resist the vertical loads, the moorings have to be anchored very deep into the seafloor. As the focus on this thesis is on floating structures in deep waters, a good mooring construction is quite important. It is difficult to design a mooring construction for very deep waters as the attachment of the mooring on the seafloor is difficult to execute.

[8] http://www.eng.nus.edu.sg/core/Report%20200402.pdf

2.2.3 Breakwaters

It is common that floating structures are very prone to wave-actions, leading to undesired movements and rotations of the structure. In hydraulic engineering, breakwaters are designed to resist or dampen the wave-actions. Breakwaters can be a part of the floating city community to protect the floating structures from severe waves. There will be no focus on breakwaters in this thesis as it is a different structure and a possible subject for another thesis in itself.

2.2.4 Connections between platforms

Floating platforms have a maximum length and width. This is because of the ease of construction and the structural strength of the platform. Very large platforms can only be constructed on site because it is otherwise very difficult to tow the structure to the desired destination. With regard to the structural strength of the structure, longer elements suffer from large bending moments as the structure becomes heavier. In case of concrete structures, the stiffness can be improved by using more reinforcement. But this adds to the weight of the floating platform resulting in a larger draught and maybe even the incapability to float. To realize floating districts and cities, the floating structures have to be coupled with each other. The connections between multiple floating structures are very important in the design. A city is in the range of several to hundreds of square kilometer and known floating platforms till date range from 50-200 m in length. So, it is not even possible yet to make a large platform of 1 km^2 'in one go'.

2.2.5 Connection to the mainland

Connections are not only important as interconnections between multiple floating platforms. The connection to the mooring structure or to infrastructure leading to the mainland is also important. The floating city can be an independent city state in the middle of the sea or be an extension of a (overpopulated) city near the coastal zone. In both cases, the floating city must still be connected to the mainland for transportation and import/export reasons. It is not so convenient to have only seaborne and/or airborne transportation available to and from the floating city. In the case of an extension of a city near the coastal zone, it is even more favourable to have infrastructure to and from the floating extended city. When the floating city is an extension of an existing city near the coastal zone, then the distance between the city and floating extension is quite small. This distance will certainly be able to bridge with floating highways, floating bridges or even conventional bridges. In case of an independent floating city far from the coastal zone, conventional bridge constructions are less of a favourable option. Conventional bridges can cover great distances, but they are limited due to a high water depth, seabed soil weakness, occurrence of earthquakes etc. With an increasing and/or large water depth, the pillars of the bridge sometimes become impossible to construct or will be very costly to construct.

The choice of a floating bridge or conventional bridge lies in what kind of connection is favourable for the floating city. A floating bridge experiences displacements due to wind, wave and currents just as the floating city is susceptible to these environmental loads. The loads acting on the floating city have influence on the floating bridge and vice versa. In an extreme extent, movements of the floating city greatly affect the strength and stability of a floating bridge. Because of the length of the bridge, a small movement at one end will result in a bigger displacement at the other end of the bridge. Think of this phenomenon like the behaviour of a whip. With a conventional bridge on the other hand, the bridge is founded on the seabed and is a stiff structure. The bridge will experience no displacements due to wind, waves and currents (except for earthquakes). So the bridge more or less acts as a mooring structure limiting the displacements of the floating city.

The type of bridge to connect the floating city to the mainland is thus situational to the location and boundary conditions of the floating city. As there is no specific location chosen for the floating city, details about the connection to the mainland will not be elaborated in this thesis.

2.2.6 Parking facilities

As the surface of the floating city is quite limited and mainly intended for buildings and infrastructure, there will be a possible space shortage for open parking spots. It is more efficient to gather all the cars in a parking building. As parking buildings on the mainland, they can be partly/fully above or below ground level. Buildings above ground level are no problem as regular buildings are also constructed this way. The problem lies in underground parking. Only floating platforms with internal space available like caissons are able to realise underground parking lots.

2.2.7 Port/harbour/ferry facilities

A floating city is still largely dependent on the water traffic as this is the most flexible way of travelling from the mainland to the floating city and vice versa. Even within the floating city itself it is handy to travel by means of boats and ferries as to reduce the dependency of infrastructure for traveling purposes. Ports are mainly needed for the import of goods, as a floating city will not have very much to export out to other places (floating cities lacks agriculture for example).

2.2.8 Infrastructure and public transport

The infrastructure on the floating city must include public transport facilities to make transportation in the city as easy as possible like in cities on the mainland. The surface of a city is in the range of at least 100 km^2. Examples of cities in Europe are in the range of 105 km^2 (Paris), 219 km^2 (Amsterdam) or 892 km^2 (Berlin). These surfaces cannot be travelled by foot or bike alone. That would take too long to reach a destination within the community. So the infrastructure and public transport are a must in the design of a floating city. The floating platforms need to be designed to withstand the dynamic loads of traffics on the surface (or maybe even in the floating platform if internal spaces are available).

2.2.9 Energy and gas stations

Inhabitants of the floating city need energy and gas for living purposes. Gas can be provided via pipelines from the mainland. But this gives a lot of difficulties given that these pipelines are very prone to the external forces from the environment or the floating city (e.g. waves, movements and torsion of the floating platforms). Energy can luckily be generated on the floating city itself. For example, this can be done by generating energy trough solar panels, windmills and water wheels. Energy can also be generated by using pumps which starts to work when vertical water movements occur. All these methods to generate energy are environmentally friendly, but their efficiency rate is quite low.

2.2.10 Watering and sewerage systems

As a floating city is in fact literally living on the water, the inhabitants still needs systems for clean water usage and sewer systems to dump the filthy water. These facilities are more easily implemented when there are internal spaces available in the floating platforms, as these facilities lie below ground level in mainland cities. Sewer water need to be stored somewhere for cleaning processes and my not be dumped directly into the open water where the floating city is located. These facilities can also be on the mainland, but then again, issues about the pipelines being prone to external forces and moments cause difficulties to realise this.

2.2.11 Waste treatment facilities

Waste treatment facilities are not really a must on board of a floating city. Just like in Hong Kong, all the waste is transported by means of vessels to remote places for waste processing and recycling.

2.2.12 Stabilizing elements

Stabilizing elements are structural elements which contribute to the stability of the floating structure. Such structures can be for example water-ballast-tanks or aircushion supported pontoons to minimize the rotation and tilt effects of floating structures. With the improving technology of nowadays, very accurate sensors can be used to measure the tilting displacements and then these stabilizing elements can counteract by using the exact amount of air or water to compromise the tilt. There is still no study done to such an element and there is actually no prove whether it will work for a large scale platform.

2.3 Development of the floating city

Although an actual floating city is not realised yet, there is some development and knowledge about the elements of a floating city.

2.3.1 Development of large floating platforms

As the floating city is in fact a very large floating platform, knowledge about the floating platform can be achieved by other floating structure reference projects, see **Appendix 1: Reference projects**.

Very large floating structures till date can achieve lengths of 300 m and heights of 20 m. For example the floating breakwater in Monaco has a total length of 352 m and a construction height of 19 m. Such large platform/pontoons are usually made of reinforced concrete. The larger the platforms/pontoons, the heavier the structure will be, thus leading to a very large draught.

Floating platforms can be made in a dry dock and then be towed to their destination. But there are also techniques which enable the construction of such a floating platform on the still water level. The construction of a floating platform directly on the water is till date only applied to small scale floating platforms (platforms made with EPS).

2.3.2 Development of interconnections

The interconnections between modular floating platforms had some difficulties to realise. Till date, mostly small scale modular floating structures are using interconnections. Maintenance of the connections is difficult if the draught of the platform is too large. This means that the connection is not easy accessible for maintenance purposes. If it is possible, the modular platforms have to be disconnected to maintain the interconnections, which is more convenient with smaller scale floating structures. For this reason, it is favourable to use interconnections which are easy to connect and disconnect, see the projects of (Koekoek, 2010) and (Rooij, 2006).

Also, with larger structures come larger forces which the connection must withstand. Because of the large forces, deflections and movements of the platforms occur which are not favourable. That is why the connections between the platforms are constructed as a rigid structure, preventing movements in most directions. It is shown in different projects that rigid connections are more favourable compared to hinged connections, again see the reports of (Koekoek, 2010) and (Rooij, 2006). Hinged connections are only favourable when the separate floating structures are allowed to have independent movements from each other.

2.3.3 Development of moorings

Moorings are well developed in the offshore industry. Floating structures in the offshore industry are being realised in water depths of thousands of meters. Mooring lines for such large water depths are no difficult issues in the offshore industry. For reference, the Perdido oil platform is situated in a water depth of 2.450 m with cable mooring lines and still functions well till date.

Moorings can be simply divided into the mooring line and the mooring anchor. Different mooring anchors are being developed to withstand larger forces and displacements. Each project with moorings has different boundary conditions which needs a different type of mooring anchor. There are mooring anchors which restricts movement only in horizontal direction or vertical direction or even both at the same time. Development of mooring lines lies in the different material that is being used. Most mooring lines are made of thick steel chains. But nowadays, mooring lines made of synthetic material can achieve the same strength as steel chains which are more durable and less heavy in weight.

2.4 Boundary conditions

The boundary conditions are given for specific locations. As the thesis concerns a general design for floating cities, there is no location and thus no absolute boundary conditions given. However, a design process cannot start without the boundary conditions. This section will elaborate the choice of some boundary conditions to start the design process with. Also, the challenge of the floating city concept depends on the environment the floating city is in. A floating city faces greater challenges when the floating city is situated in the open sea compared to a calm bay for example.

2.4.1 Water depth

The floating city concept in this thesis is focussed on oceanic/coastal waters where the water depth is very large to make this concept feasible compared to land reclamation. The costs for land reclamation will increase with increasing water depth. As the water depth increase, so does the material needed to fill up this depth increase, while floating structures remain their size regardless of the water depth.

The average cost of concrete (including the reinforcement) is around €400 per m^3. Or in other words, the cost per meter depth is €400 per m^2. And this is just pure cost for the material. The labour costs for one platform are not low either and there are a lot more additional costs for constructing one platform. Assume that the average cost of concrete becomes €800 per m^3 including labour and additional costs (double the material cost) and reclamation sand (in the Netherlands) can be purchased for around €10 per m^3. The minimum depth of the location for the floating city must then be $\frac{800}{10} = 80\ m$ to be cost effective compared to land reclamation. This is just a rough estimation and is not very accurate. The costs for one platform of the floating city can be calculated after the exact amount of material needed is known. With this estimation, the fictitious boundary condition regarding the water depth is set to 100 m just to be sure that the floating city concept is economic more feasible compared to land reclamation.

2.4.2 Waves

The wave height is one of the most important parameters for the design of a floating structure. The wave height determines the wave load on the structure and the dimensions of the structure must resist these loads. Figure 10 shows results of wind waves on oceanic waters (waters with large water depths). The average wave height in Figure 10 is about 4 m with a wave length of 76.5 m and an average wave period of 8.6 seconds. These parameters are chosen to start the design with.

Conditions Necessary for a Fully Developed Sea at Given Wind Speeds, and the Parameters of the Resulting Waves					
Wind Conditions			Wave Size		
Wind Speed in One Direction	Fetch	Wind Duration	Average Height	Average Wavelength	Average Period and Speed
19 km/hr (12 mi/hr)	19 km (12 mi)	2 hr	0.27 m (0.9 ft)	8.5 m (28 ft)	3.0 sec 9.3 ft/sec
37 km/hr (23 mi/hr)	139 km (86 mi)	10 hr	1.5 m (4.9 ft)	33.8 m (111 ft)	5.7 sec 19.5 ft/sec
56 km/hr (35 mi/hr)	518 km (322 mi)	23 hr	4.1 m (13.6 ft)	76.5 m (251 ft)	8.6 sec 29.2 ft/sec
74 km/hr (46 mi/hr)	1,313 km (816 mi)	42 hr	8.5 m (27.9 ft)	136 m (446 ft)	11.4 sec 39.1 ft/sec
92 km/hr (58 mi/hr)	2,627 km (1,633 mi)	69 hr	14.8 m (48.7 ft)	212.2 m (696 ft)	14.3 sec 48.7 ft/sec

Figure 10: Examples of wind waves [9]

It could be suggested that a tsunami wave is an extreme load case for the floating city concept. But tsunamis are only destructive when the tsunami wave reaches the shore. Because of the so called shoaling effect, the enormous water mass of the tsunami will turn into a high wave of several ten meters because

[9] http://en.wikipedia.org/wiki/Wind_waves

of the decreasing water depth. In the middle of the sea or ocean, where no shoaling occurs, a tsunami is more like a water level elevation. As the floating city concept is most likely being situated in deep oceanic waters, a water elevation should give no problems to the floating city. One of the advantages of a floating city concept is that it can freely adapt to any water level elevation.

2.4.3 Wind

High wind speeds can be very destructive. The speed of the wind (or wind velocity) acts as pressure against a structure. The intensity of that pressure is called the wind load. Wind speed increases with structural height. However, wind velocity is most unpredictable closer to the ground, because it is affected by interacting with objects on the ground. Wind loads can be simplified as static loads when the wind speed is constant and acting over a great surface. However, wind loads are considered dynamic loads when the wind speed is fluctuating and where the wind can go around the structure. For example, a pole will start to resonance when the frequency of the wind is close to the natural frequency of the pole.

Wind causes huge horizontal loads provided the floating structure has a large freeboard where this wind load can act on or the (high-rise) buildings and facilities on top of the floating structure. It depends on the location of the floating structure how to calculate the wind loads on buildings. As in the Netherlands (Europe) there is a section in the Eurocode (Eurocode EN-1991-1-4) on how to determine the wind loads on different types of buildings. Wind load acting on buildings and facilities on a floating structure are not simply being resisted by the mooring structures just like with drag from currents. Wind causes uplifting forces on the buildings which are to be resisted by the foundation/connection of the building with the floating platform. Also, as the wind load act on a certain height on these buildings, this causes a tilt and rotation of the floating structure.

Wind contributes to the origin of wind waves. The chosen wave height of 4 m exists if there is a wind speed of 56 km/hr. According to the Beaufort scale, a wind speed of 56 km/hr corresponds to Beaufort number 7 (high wind, moderate gale).

Cat.	Winds [km/h]		Effects
0	0-2	Calm	Land- Smoke rises vertically Water- Like a mirror
1	2-6	Light Air	L- Rising smoke drifts W- Small ripples
2	7-11	Light Breeze	L- Leaves rustle W- Small wavelets, wind fills sail
3	12-19	Gentle Breeze	L- Light flags extend W- Large wavelets, sailboats heel
4	20-30	Moderate Breeze	L- Moves thin branches W- Working breeze, sailboats at hull speed
5	31-39	Fresh Breeze	L- Small trees sway W- Numerous whitecaps, time to shorten sails
6	40-50	Strong Breeze	L- Large tree branches move W- Whitecaps everywhere, sailboats head ashore, large waves
7	51-61	Moderate Gale	L- Large trees begin to sway W- Much bigger waves, some foam, sailboats at harbour
8	62-74	Fresh Gale	L- Small branches are broken from trees W- Foam in well marked streaks, larger waves, edges of crests break off
9	75-87	Strong Gale	L- Slight damage occurs to buildings W- High waves, dense spray, visibility affected
10	88-102	Whole Gale	L- Large trees uprooted, considerable building damage W- Very high waves, heavy sea roll, surface white with spray and foam, visibility impaired
11	103-117	Storm	L- Extensive widespread damage W- Exceptionally high waves, small to medium ships obscured, visibility poor
12	117+	Hurricane	L- Extreme destruction W- Waves 40+', air filled with foam and spray, visibility restricted

Figure 11: Beaufort scale[10]

[10] http://www.spc.noaa.gov/faq/tornado/beaufort.html

2.4.4 Currents

Currents underneath the floating structure cause drag which lead to movement of the floating structure. Currents perpendicular to the draught of the floating structure will give a constant horizontal load which also cause the floating structure to move. These movements are to be resisted by the mooring structures to prevent the floating structure from drifting away. This is the same case as horizontal wave loads causing the floating structure to move. The difference is that (breaking) waves give an impact while drag from currents is along the whole underside and draught of the structure. Except for movement issues, the pressure of the current against the hull of the floating structure can also become quite large if the surface where the current is working on is large. The hull of the floating structure must also withstand this pressure.

Currents can arise due to a difference in water levels on the sides of the floating structure as water flows from the side with high potential energy to the lower part. If the underside of the floating structure is made of loose floating elements like aircushions, then there is risk of these elements being damaged or displaced due to the current. Overall, it depends also on the location whether currents are a big deal for the floating structure. In some locations, ocean currents can get quite high. For example, the Gulf Stream in the Atlantic Ocean can reach current surface speeds of 2.5 m/s. In storm conditions it is likely that the structure will deal with currents and wind that have the same direction. This means that high water pressure and wind pressure can occur simultaneously.

About 10% of the water in the world ocean is involved in surface currents. Surface currents are water flowing horizontally in the uppermost 400 meters of the ocean surface, mainly driven by wind friction. Larger ocean currents due to salinity and temperature differences occur at a larger depth and are not of influence for the floating city. It is difficult to estimate the current velocity based on only the wind velocity. So a random velocity of 2.5 m/s is chosen (like in the Gulf Stream in the Atlantic Ocean).

2.4.5 Summary of boundary conditions

Boundary conditions are given for specific locations. As the thesis concerns a general design for floating cities, there is no location and thus no absolute boundary conditions given. The choice of some boundary conditions to start the design process with are elaborated in the above paragraphs and summarised in the table below.

Boundary	Value
Wave height	4 m
Wave length	76.5 m
Wind speed	56 km/h
Current velocity	2.5 m/s
Water depth	100 m

3 Floating city configurations

This chapter discusses the different designs for floating cities and results in a chosen design to work out in this thesis. The ideas and designs are from the Seasteading Institute in collaboration with Deltasync (Czapiewska et al., Seasteading implementation plan, 2013). Seasteading Institute is a company in the United States which specializes in researches and designs of floating communities.

In this chapter, the objectives and requirements of a floating city concept are first explained. After it is clear what kind of objectives play a role, the critical objectives and requirements are chosen to base a design of a floating city concept on. A preliminary design of the floating city can be done with the chosen objectives and requirements. And finally a short summary of the whole chapter is given.
In short, the following paragraphs are being worked out in this chapter:

- *Objectives of a floating city*
- *Prioritization of objectives*
- *Preliminary design of platform shape*
- *Summary and conclusion*

3.1 Objectives of a floating city

To come up with a design for a floating city community, several objectives and requirements need to be stated first. There are six objectives which the floating city design must require more or less, which are: movability, dynamic geography, sea keeping, water experience, growth and safety. The selection for these objectives is obtained from the Deltasync report in collaboration with Seasteading. (Czapiewska et al., Seasteading implementation plan, 2013)

3.1.1 Movability

It may be useful if the floating city is movable. This has several reasons; a floating community can move to another location if the current location would be no longer suitable to live in; or the floating community can assure to move away from dangerous phenomena's such as hurricanes or cyclones. When it is considered to realise a moving floating community, the design qualities in terms of movability are the speed, safety and convenience of the movement. A good speed is required to limit the time needed to reach another location, but the movement must still be convenient enough for the inhabitants on the floating community. The different possibilities to move a floating structure are directly linked to their size. A large structure has a relatively simple mooring system and fewer connections between other floating elements and can thus be decomposed quickly to move on. Floating structures on a smaller scale have more connections between the floating elements and the ocean floor.

There are different possibilities to move a floating community:

- Self-propelled floating platforms
- Towed by ships
- Transported with (semi-submersible) ships

Self-propelled floating platforms are floating platforms which has an own propelling system for maximum free movability. Each platform can move on their own and independent of each other. The advantage of such a system is that the platforms are easy and fast to move when necessary. Also the mooring systems would be quite simple considering the platform can always correct its own position. The disadvantage is that a large propulsion system is required to propel larger and heavier structures, which will also need a lot of energy.

Figure 12: Self-propelled system (Czapiewska et al., Seasteading implementation plan, 2013)

Floating structures which are designed in such a way that they can easily be towed by tugboats also have the advantage of an easy and fast moving process. Disadvantage of this idea would be that there must always be a tugboat available and a large amount is needed to tow a complete floating community. Also, only very large structures are recommended to be towed because of the vulnerability to dynamic movements such as sway, roll and pitch. These dynamic movements occur less with increasing dimensions of the structure.

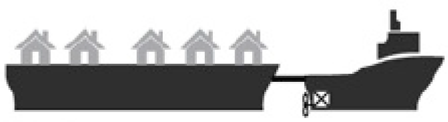


Figure 13: Towed floating platforms (Czapiewska et al., Seasteading implementation plan, 2013)

Floating structures can also be transported by semi-submersible ships. Because of the large dimensions it is not possible to transport the structures by regular ships (because this means that the floating structure must be lifted up to place on the ship). With semi-submersible ships, a variety of platform sizes can be transported at once. Also, the total structure of the floating community stays intact; the platforms do not need to be totally decomposed till every single platform. However, there are some disadvantages to the use of semi-submersible ships. Again, a lot of ships are required to tow a complete floating community (although less ships needed compared with the idea of using tugboats). Another disadvantage is that the size of the floating platform is restricted to the size of the ship.

Figure 14: Semi-submersible ship (Czapiewska et al., Seasteading implementation plan, 2013)

3.1.2 Dynamic geography

Except for the obtained freedom from a political point of view, a floating community can achieve more freedom at a city level, on the community level or on individual level. The freedom of moving inside the floating community with one's own house as an individual, or even moving away from the community with a group of inhabitants is referred to as 'dynamic geography'. The dynamic geography is important for the spatial configuration of the floating platforms to form a floating community. There are a few types of configurations to achieve a floating city, but only two of them are suitable for maximum dynamic geography. Types of configurations for a floating community can be like:

- Islands
- Branches
- Composite structures
- Large structures

The island-type configuration consists of floating platforms connected to each other through bridges or jetties. This way, each floating platform acts as an individual island and the structures can be disconnected easily from each other to move around. The disadvantage of this type of configuration is that forces and loads on one floating platforms can influence the stability of another nearby platform connected through a bridge or jetty. As a bridge or jetty acts as a hinged connection, loads and forces on one floating platform act as eccentric loads on the other platform. The island-type configuration grants maximum freedom in dynamic geography.

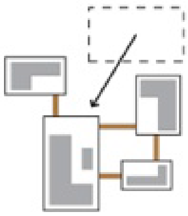


Figure 15: Island-type configuration (Czapiewska et al., Seasteading implementation plan, 2013)

The branch-type configuration looks almost the same as the island-type configuration, except that the platforms are now connected to each other directly instead of with bridges and jetties. This way, the eccentric forces on the adjacent platform will have less effect because the connected platforms will more or less act as a whole structure. However, it is more complicated to move one platform away from a group because of the denser layout. Also, the floating structures need to be uniform shaped to be able to fit together. The branch-type configuration also grants great freedom in dynamic geography.

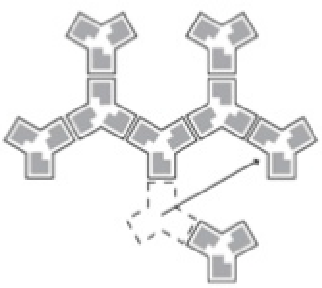


Figure 16: Branch-type configurations (Czapiewska et al., Seasteading implementation plan, 2013)

A composite structure is a floating community existing of several floating platforms directly connected to each other. Semi-large platforms are connected in such a way that they form a larger platform. The difference with the branch-type configuration is that the platforms are not easy to disconnect anymore. And the connected platforms mostly have to move as one structure if movement to another location is desired. Another disadvantage of this type of configuration is that a lot of connections are needed to keep the platforms together.

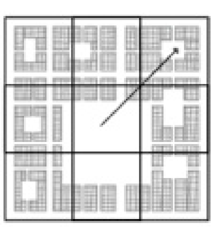


Figure 17: Composite-type configuration (Czapiewska et al., Seasteading implementation plan, 2013)

Instead of using semi-large platforms to create a large platform, it is also possible to use a single large platform as a floating community. However, if it is required to have freedom in movability on individual level this concept is not viable.

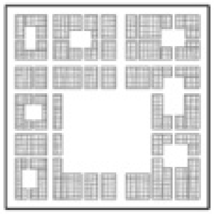


Figure 18: Single large platform (Czapiewska et al., Seasteading implementation plan, 2013)

As said, the two most suitable options are the islands and branch-type configurations. Both structures consist of a small amount of houses. Where the islands are connected by bridges or jetties, the branches are connected using a hinged connection. Because of this, both structures can be disconnected easily and are free to move around.

3.1.3 Sea keeping

Sea keeping is referred to the ability to keep the floating community suitable to live on. Suitable means that it has to be safe and comfortable to live on the floating structures. The floating community has to be able to adapt for survival on high seas and extreme conditions should such phenomena's take place. The stability of the platforms and the moorings play a big role to achieve a good sea keeping condition for a floating community. The stability of the platforms is dependent on the shape of the platform, the used material and the type of floating structure. How to achieve stability with different types of floating platforms can be found in **Appendix 2: Types of floating structures**.

To further increase the sea keeping of a floating community, a breakwater can be considered around the floating community to reduce the wave actions behind the breakwater. However, to fully protect the floating community on open sea, the whole floating community has to be surrounded by such a breakwater structure. The most economical way of such a breakwater structure is if the breakwater is shaped in a circular form around the floating community. This means that the configuration of the floating community has to be more or less circular to fit into the ring of breakwater.

3.1.4 Water experience

The experience of the water in a floating community can be subdivided into two categories: visual and physical experience. Visual experience is about the ability to see the water and physical experience is about activities on the water such as swimming, sailing, diving etc. Physical water experience is also about the ability to use the water as a means of living and transportation within the floating community. Visual water experience is more for the fact to realise that you are living on a floating community. If for example a floating community would exist of a single large platform, then the people in the centre of the platform wouldn't even realise they are living on water. Evaluating the different configurations, only the island and branch-type configurations would have maximum water experience. Smaller platforms make it easier to experience the water environment because of the flexible and open configurations.

One can see the complexity of the transportation within the floating community from a favourable or less favourable point of view. On one hand, the island and branch-type configurations offer fewer roads directly to other floating platforms. While on the other hand, to optimize the infrastructure of the floating community, ferries and boats are used to offer direct transportation from one platform to the other. The use of less land-based vehicles and more ferries and boats could give a positive effect on the emissions of CO_2.

When a design for a floating community is preferred with a lot of water experience, the enclosed water areas between the floating platforms can also be opted to use for single floating houses or facilities. These single floating houses would gain the maximum freedom of movability within the floating community.

3.1.5 Growth

Roughly two types of structures can be distinguished from the previous paragraphs: large floating structures which are developed at once and modular structures which are easier to configure in shape and size. A modular structure like the island or branch-type configuration can gradually grow in the course of time. Growth can be achieved by steadily adding more platforms on the outer side of the existing floating community.

It is much more difficult to expand a large floating structure. To expand a large floating structure, one can add another equally large platform adjacent to the existing platform, effectively doubling the capacity of the floating community. This is not called gradually growth anymore and the investment in such an expansion must be thought of thoroughly. Another option would be to connect smaller platforms to the large platform with bridges or jetties. But this way, the sea keeping stability of the smaller platforms is less favourable because of large eccentric forces and loads from the large floating structure. Small rotations and movements of the large structure will result in large rotations and movements of the smaller units.

The growth of the floating city in general is associated with the population and the dependency of resources from the main land. As a small floating community, it is best to build such a concept within protected waters with a calm environment. Such a small floating city would then be dependent on the resources of the main land. A larger floating city is capable to survive a more violent environment such as the open sea. The floating city much be large enough to accommodate its own facilities for resources, the floating city would then be independent of the main land.

3.1.6 Safety

Safety is the most important requirement for the design of a floating community. Safety means to provide a reliable floating structure and a living environment where people can safely move around. To ensure the reliability of the floating structure, it is best to protect the floating community from environmental hazards like large waves, storms and hurricanes. For example, a breakwater-structure surrounding the floating community would dampen most wave actions. And to avoid heavy hurricanes or other environmental hazards, the option exists to move with the floating community to a safer location. However, these hazards have to be foreseen beforehand and the course of the hazard has to be predicted either. If moved to another location where the hurricane would eventually end up, then the effort is wasted.

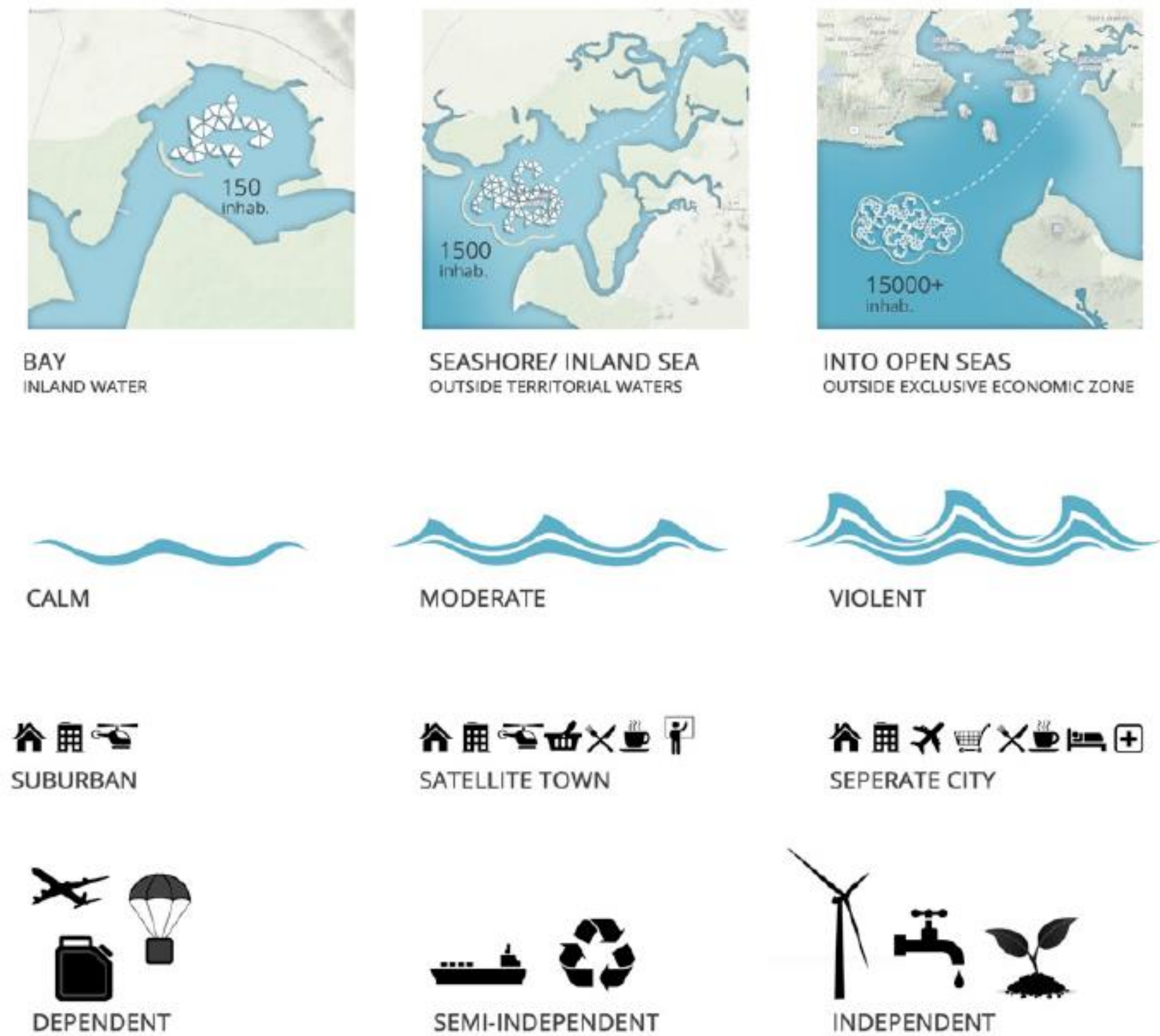


Figure 19: Growth of a floating city (Czapiewska et al., Seasteading implementation plan, 2013)

3.2 Prioritization of objectives

Summarizing the objectives in the previous section, it can be concluded that the objectives movability and sea keeping are important factors for determining the safety of the floating community. From the point of view of sea keeping, the size of the floating platform depends on the significant wave characteristics. The smaller the platform size, the more prone it is to waves causing sway and surge movements. On the other hand, if the platform is too large, large moments in the structure occur due to the deadweight (called hogging and sagging moments), which will lead to extra material investments in order to strengthen the structure.

The dynamic geography, water experience and growth development are less important, but they play a key role in determining the layout of the floating community. The dynamic geography of having freedom to move around on individual level is actually unnecessary to base a design on in these beginning design concepts. This aspect could be considered for future floating cities, it is now more important to be able to realise such a scale of a floating community.

The reason to actually consider the objective of more water experience is because of the fewer connections between the floating platforms. Less water experience means that the platforms in the floating community are denser on each other. This means that a lot of platforms are adjacent to each other, resulting in more connections. Growth can be achieved by steadily adding more platforms on the outer side of the existing floating community.

Viewed from the point of safety, it is indeed favorable to avoid dangerous phenomena's such as hurricanes and cyclones. However, a location has to be chosen where these phenomena's actually never occur or at least just once in a few hundred years. It is not as simple as being said to move such a large structure a few kilometers from its original position. It will even become more and more difficult to move the whole floating community as it grows larger. The more connections and platforms are involved the longer it takes to decompose the platforms to safely transport them away (before the hurricane, tsunami wave etc. arrives). The layout of the floating city should therefore not be too dependent on the objective movability. The design of the floating community must be such that it can withstand common severe conditions. The option to move to another location must be the last resort in very dangerous situations. In other words, the frequency of moving around should be kept as low as possible. However, the movability of a floating platform is always considered if the platform is constructed on another location then the destination of the floating community. So basically, the objective movability is more or less a standard design objective for the construction of the floating platform and the ability to move the floating community to a safer location is an extra added feasibility. For the movability in normal (wave) conditions, any platform size can be towed, but transporting the platforms in more severe (wave) conditions can only be achieved with larger platforms. Semi-submersible ships can move very large-scale floating platforms, but the maximum size of a platform is limited to the dimensions of the ship itself.

A selection of the possible types of structures/configurations is made concluding from the objectives discussed. As discussed, the options of using semi-submersible ships or towed platforms are the best options from the objective of movability. As very large structures are not preferred from the point of view of water experience, dynamic geography and growth strategy; the dimensions of the platforms are relatively small, but large enough to keep up with severe waves during transportation. And because of the relative smaller platforms, a breakwater structure to improve the sea keeping of the floating community is also added to improve the sea keeping of the floating community. This means that the floating community should more or less be shaped in a circular configuration. As it is clear that large structures are less preferred, this means that modular components are used as these grant a better water experience and growth strategy. Between the modular type structures, the branch-type configuration is preferred over the island-type configuration as the branch type configuration has an overall better sea keeping ability.

Summarised, the floating community should have a branch-type configuration that can be composed into one larger structure and can eventually be placed behind a breakwater. The selection is summarised and illustrated in Figure 20.

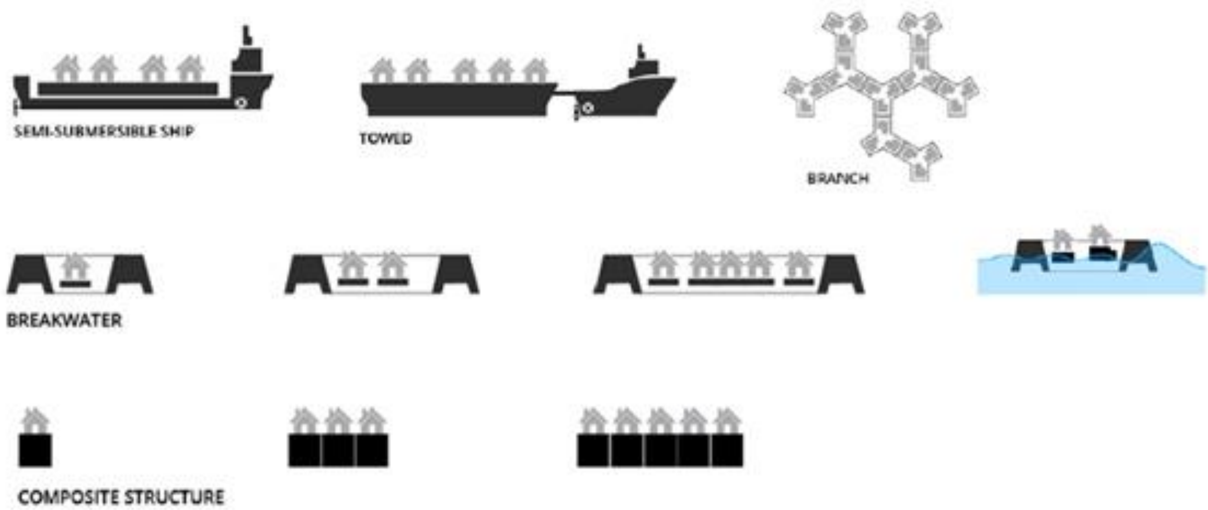


Figure 20: Selection of possibilities for the design of the floating community (Czapiewska et al., Seasteading implementation plan, 2013)

3.3 **Preliminary design of platform shape**

Aside from the objectives discussed in section 3.1, the design of the floating community should also be based on several other considerations:

- The individual floating structures should be uniform shaped to keep down the construction costs. Repetition of an element offers an increasing learning cycle in the construction and thus to a lowering of the required man-hours, see Figure 21. The uniform shapes also simplify the configuration possibilities.

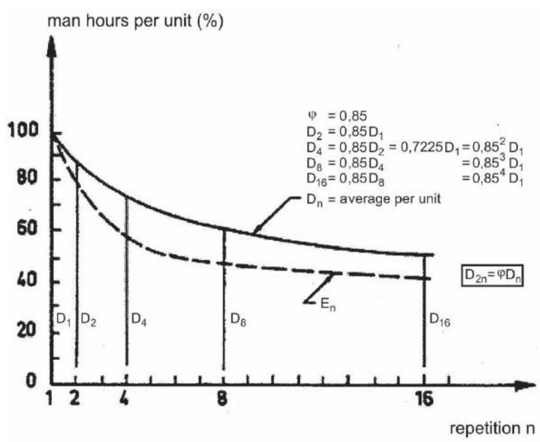


Figure 21: Learning cycle of a repetitive construction method (CIE4170 lecture notes)

- The configuration of the platforms should enable circular layouts in order to efficiently fit behind a breakwater structure if ever needed (a circle has the shortest perimeter for a given area).
- The platforms should be connected in such a way that a dimensionally stable cluster is created. A cluster of small platforms will behave more or less like a big platform and thus the whole floating community would have a good sea keeping ability in general. When the platforms are connected linearly to each other, a vertical displacement of one platform could result in a very large displacement on the last platform (just like how a whip behaves).
- The shape and the configuration of the platforms should be chosen such that as less as possible connections between the platforms are used as these connections are very costly.

A system was developed that meets the above criteria and the design objectives by Deltasync in collaboration with the Seasteading Institute. Their design is based on two basic shapes: a square and a pentagonal shaped platform. Their result is illustrated in Figure 22. The reasoning to use these shapes is because a pentagonal-shape allows the creation of circular clusters. Circular clusters are possible because two opposing edges are oriented at an angle of 36 degrees, so it requires 10 pentagonal-shaped platforms to create a complete circle. To have some more creativity, one or more rectangle-shaped platforms can be placed in between the pentagonal-shaped platforms to change the radius of the circle or to create a different curvature.

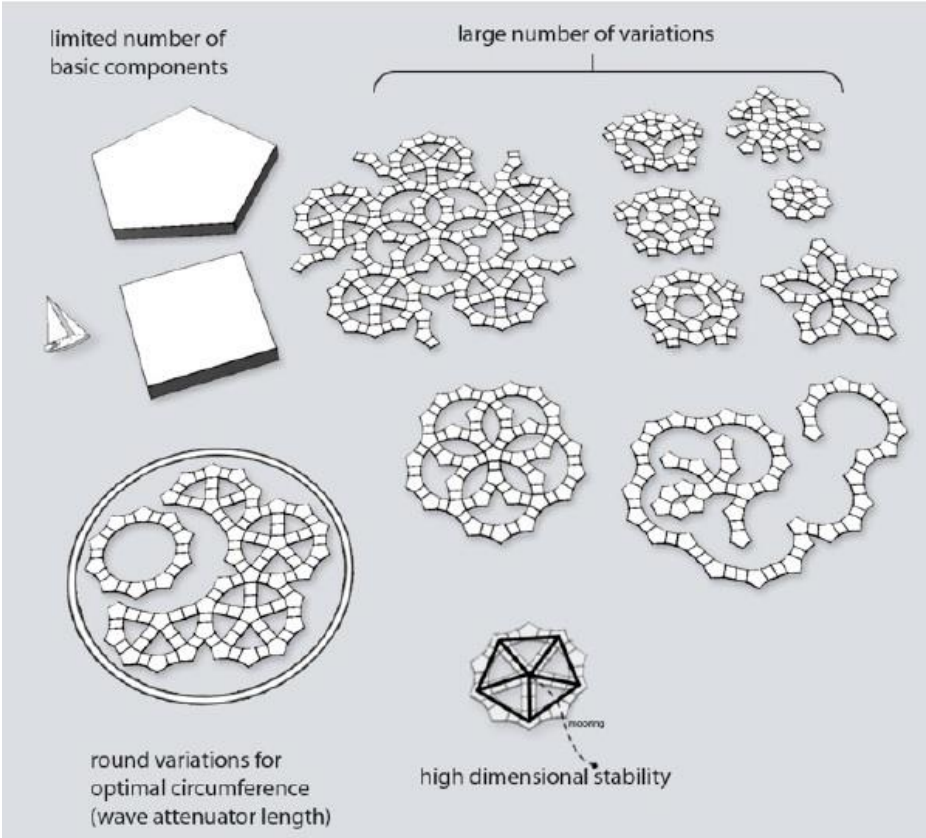


Figure 22: Design of a floating city by Deltasync and the Seasteading Institute (Czapiewska et al., Seasteading implementation plan, 2013)

However, the designs shown in Figure 22 are not all possible. The layouts of the configurations are just simple sketches to present the idea. When the layouts are drawn on scale, many of the configurations will not fit in each other. The only viable configurations from Figure 22 are presented below.

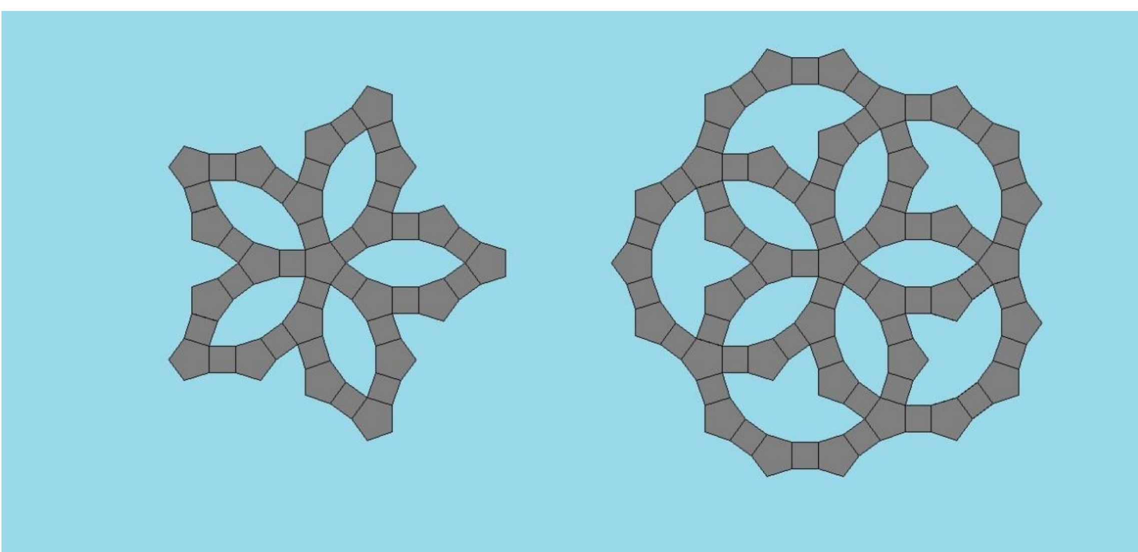


Figure 23: Possible configuration with rectangle and pentagonal-shaped pontoons

Both of the layouts in Figure 23 have in common that there is a lot of water experience available. The layout on the right has slightly more open water space than the layout on the left. Note that the layout on the right is actually an extended version of the layout on the left. It is one of the objectives to have enough water experience in the floating community, but the layout on the right has a little bit too much space for water, leading to an ineffective use of platform space. Therefore, the layout on the left is chosen as a basic design.

3.3.1 Design alternatives

Not all designs in Figure 22 of the report of Seasteading (Czapiewska et al., Seasteading implementation plan, 2013) are viable. So, there is still not an optimal design available for the configuration of a floating community. In this paragraph, a small form-study is done with the following requirements:

- The individual floating structures should be uniform shaped.
- The configuration of the platforms should enable circular layouts.
- The platforms should be connected in such a way that a dimensionally stable cluster is created.
- The shape and the configuration of the platforms should be chosen such that as less as possible connections between the platforms are used.
- The shape of the individual platform should enable easy configuration for future growth.
- There must be enough water experience in the floating community.
- The form of a single floating platform must be such that the single floating platform is statically and dynamically stable on its own.

First, the design with pentagonal and rectangle-shaped platforms is evaluated. The growth possibility of this design is shown in Figure 24. This design maintains a circular layout suitable to be put behind a breakwater. The configuration of the platforms is quite complicated as two basic shapes are used. Not many different configurations can be used except for the one shown in Figure 24. Also, the configuration of these two basic shapes leaves quite some space for water experience, thus the water experience is maybe a bit too much here. A fully grown floating community with this layout would have a lot of open water spaces. The space usage looks very ineffective. Although, the closed off water areas within the floating city could be used for single floating houses. A positive point about this design is that each platform uses a maximum of three sides to connect with other platforms (except for the platform in the middle, which uses five sides).

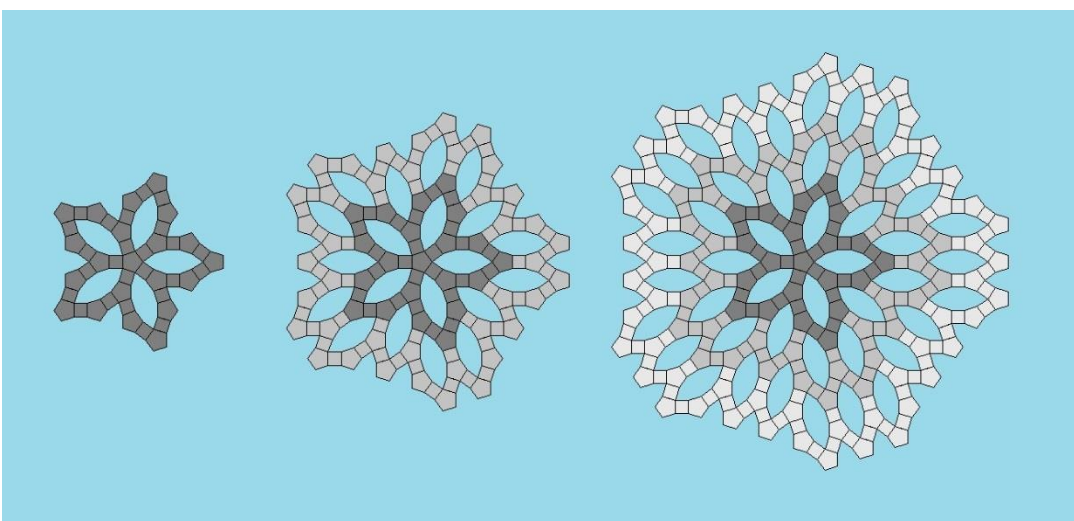


Figure 24: Design 1, pentagonal and rectangle-shaped platforms

If the pentagonal-shaped pontoon is out of the question, the most basic shape there is left is the rectangle-shaped platform. These platforms are easy to construct, but they do not have a lot of freedom in possibilities for a good configuration of a floating city. A lot of platforms and connections are needed to realise a dimensionally stable cluster. And the clusters it can form are always more or less rectangle shaped, so it does not fit too well behind a circular breakwater structure. Most platforms need three to four sides to connect to another platform to form a dimensionally stable cluster. The use of connections and platforms can be decreased by slightly altering the shape of a single platform. Instead of using rectangles, the rectangles can be shaped into a cross-shape to get the same layout as with only rectangle-shaped platforms, see Figure 26. This way, fewer connections are used because of the bigger platforms. However, the configuration is one-dimensional and is also rectangular shaped, rendering it less efficient to use it behind a circular breakwater structure. Another important point is that the cross shaped platform on its own is very prone to pitching and rolling movements.

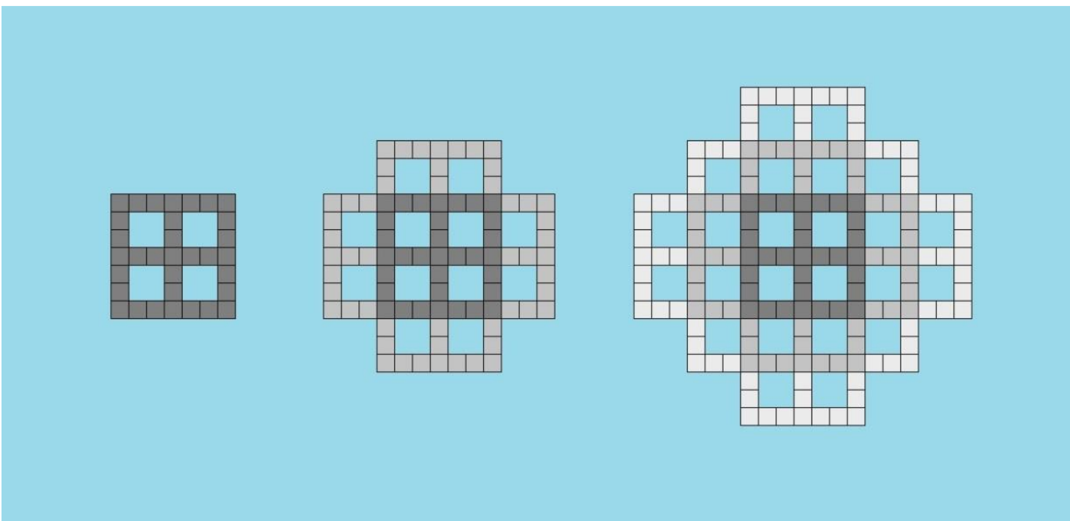


Figure 25: Design 2, rectangle-shaped platforms

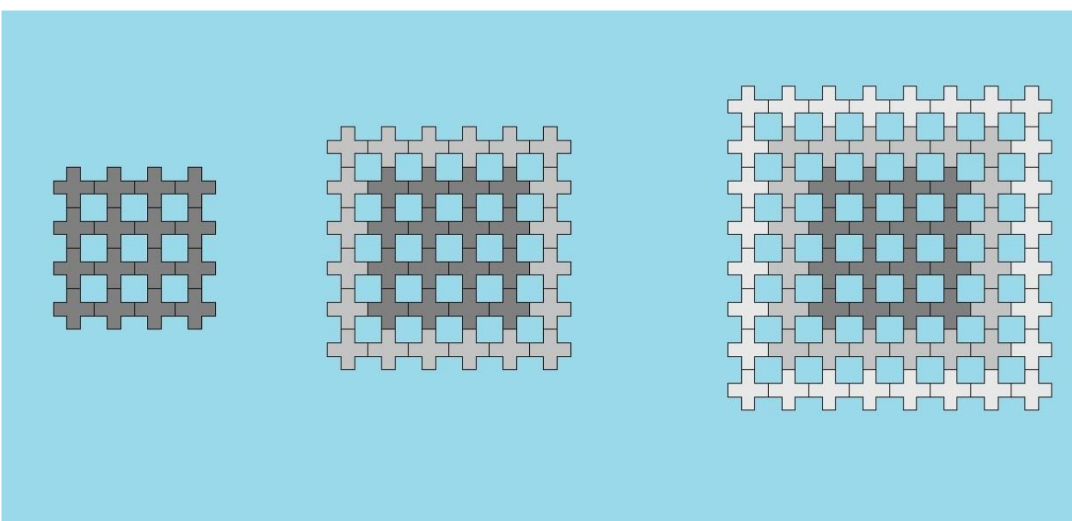


Figure 26: Design 3, cross-shaped platforms

We have already considered rectangle and pentagon shapes as a floating platform. The forms that are left are the triangles and shapes with more corners. Triangles are not efficient to use as floating platforms because the space usage on top of the platform is ineffective. There can almost nothing be constructed on the corners of a triangle. And from the point of easy configuration, two triangles would end up as a rectangle (more or less, dependent on the angle of the triangle). To get a dynamically stable cluster, a lot of triangles and thus connections would be used.

There rest only one more shape to be considered and that is a hexagonal shape. Hexagonal-shaped platforms are symmetric compared to the pentagonal-shaped platforms. Thus making it easier to construct and making symmetric layouts. Compared to design 1 in Figure 24, hexagonal-shaped platforms have a great number of layout possibilities although only one form is used. And the ability to create circular clusters is also easier to achieve with hexagonal-shaped platforms. Where the pentagonal-shaped platform uses 10 platforms to create a circle, the hexagonal-shaped platform only uses 6 platforms. The only disadvantage of using this shape is that on some platforms it is required to use more connections. Because of the many sides a hexagonal has, there are more platforms adjacent to each other to keep a dimensionally stable cluster as the floating city expands.

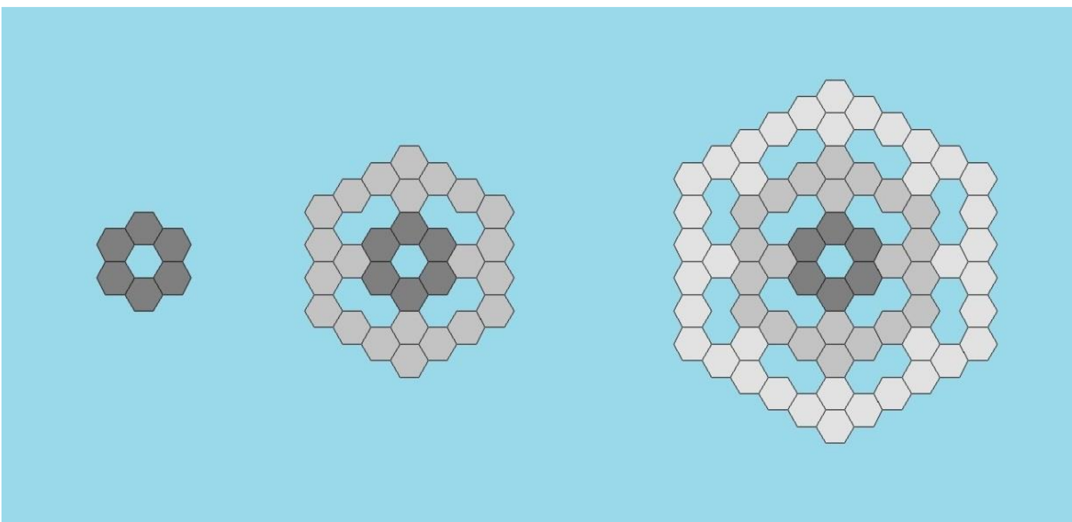


Figure 27: Design 4, hexagonal-shaped platforms

3.3.2 Multi-criteria evaluation

To choose the most suitable design, a few criteria must be concluded which the designs should fulfil. Each criteria has an own value of importance for the design, this is implemented in a weight factor for the criterion. And so, each design will be given a score for each criteria and the design with the highest score will be chosen. This method is also known as the multi-criteria evaluation.

The score given for each criterion is in the range of 1 till 5, where a score of 1 contributes to bad quality concerning the criterion and a score of 5 contributes to a very good quality concerning the criterion. The weight factor for each criterion is in the range of 1 to 4.

The following criteria are used in the multi-criteria evaluation to choose a suitable design:

- Sea keeping
- Number of connections needed
- Number of different platforms needed
- Efficient space usage
- Growth
- Circular layouts
- Dynamic geography
- Water experience

Table 2 presents the MCE and the result is that the hexagonal shaped platforms are the most suitable option. For the grading and MCE process, see **Appendix 4: Multi-criteria evaluation**.

	Weight factor	Square shape		Pentagon shape		Hexagon shape	
Sea keeping	4	5	20	3	12	5	20
Growth	3	5	15	3	9	3	9
Circular layouts	3	1	3	5	15	4	12
Number of connections	3	1	3	4	12	3	9
Different platforms needed	2	5	10	1	2	5	10
Efficient space usage	2	5	10	4	8	3	6
Dynamic geography	1	5	5	1	1	5	5
Water experience	1	3	3	4	4	5	5
Total score			**69**		**63**		**76**

Table 2: MCE

If opted from an architectural view, the hexagon shaped platforms and the possible layouts with these platforms are quite ‘boring’ and straightforward. Because of the symmetrical form, the layouts would all become more or less symmetrical too. Although the criteria was that less different forms of platforms was a better option for production purposes, the hexagon shaped platforms are very good compatible with the square shaped platforms to give more ‘exiting’ layouts if preferred.

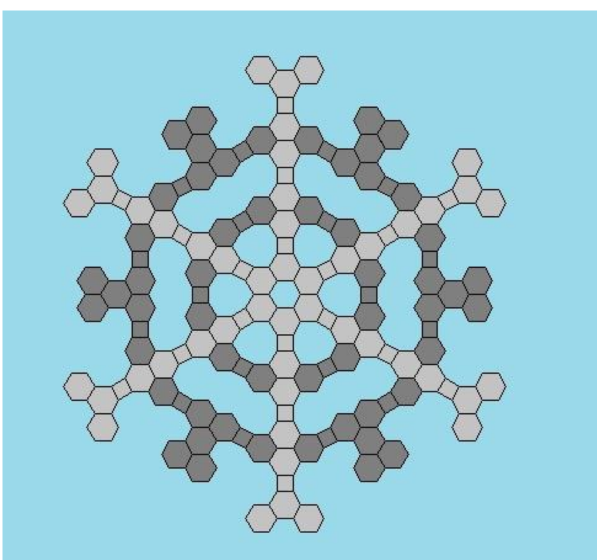


Figure 28: Example of layout made with hexagons and squares

3.4 **Summary and conclusion**

To come up with a design for a floating city community, several objectives and requirements need to be stated first. There are six objectives which the floating city design must require more or less, which are: movability, dynamic geography, sea keeping, water experience, growth and safety. Other requirements to base a design of the floating city on are:

- The individual floating structures should be uniform shaped.
- The configuration of the platforms should enable circular layouts.
- The platforms should be connected in such a way that a dimensionally stable cluster is created.
- The shape and the configuration of the platforms should be chosen such that as less as possible connections between the platforms are used.
- The shape of the individual platform should enable easy configuration for future growth.
- There must be enough water experience in the floating community.
- The form of a single floating platform must be such that the single floating platform is statically and dynamically stable on its own.

This chapter has come to an answer for the sub question *'What kind of floating platforms are needed?'*. With the above objectives and requirements, a design of the floating city is chosen in the form of modular hexagonal shaped platforms. The design with the hexagonal shaped platforms is very straightforward and the growth of this floating community is simply achieved by adding more platforms in all ways possible. Hexagonal shaped platforms are symmetric from all sides, so it is easier to configure the floating community in different ways without worrying about whether the platforms are going to fit to each other. Also, the more sides the platform has, the more sides there are to build houses near the water which is a plus for the criterion of water experience.

The dimensions of the hexagonal shaped platform are calculated in the next chapter 'Single floating platform design'.

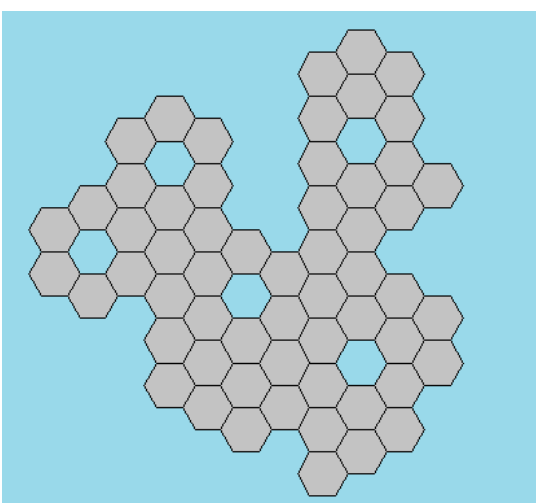


Figure 29: Example of modular hexagonal shaped platforms constructed as a floating city

4 Single floating platform design

This chapter elaborates the design of the chosen hexagonal shaped platform. The dimensions of the platform are first roughly estimated and a plan for the inner walls and compartments is also presented. With the known dimensions, the loads on the platform can be defined which leads to different load cases. With the load cases, the stability and strength of the platforms are checked which leads to the definition of the draught of the platform. And last, a quantitative calculation of the cost of the platform is given. In short, the following paragraphs are being worked out in this chapter:

- *Platform size*
- *Inner walls and compartments*
- *Load cases*
- *Static stability*
- *Strength check*
- *Cost of one platform*
- *Summary and conclusion*

4.1 Platform size

A city can be defined in several ways depending on its population and size. For example, a metropolis is a large city or urban area which is a significant economic, political and cultural centre for a country or region, and an important hub for regional or international connections, commerce and communications. Examples of such cities throughout the world are like New York City, Beijing, Tokyo, Paris, London etcetera. Cities mostly start out small and grow gradually until they have the capacity of the so-called metropolis. It is unknown whether the floating city concept will eventually become such an important and large city, but it should not be an impossible goal. Anyhow, to start realising a city, a starting capacity has to be chosen from which it can gradually grow. The capacity of a city is usually defined by the population or population density. As one of the goals of a floating city is to decrease the overpopulation in big and dense cities, the top 10 cities with the highest population density throughout the world is shown in Table 3 (note that these are cities near coastal zones).

From the cities shown in Table 3, the average population is 7 million inhabitants. Of course this is too big to realise at once, so the general design of the floating city will start with a population of 1/500 of 7 million, roughly 15000 inhabitants. This is a fair number to start with as a city centre.

City	Inhabitants per km^2	Total inhabitants
Chennai	26903	4.7 million
Mumbai	20698	12.4 million
Macau	20069	582000
Monaco	18068	36000
Jakarta	15400	10 million
Casablanca	9342	3 million
Lagos	7938	8 million
Singapore	7669	5.2 million
Shanghai	6845	17.8 million
Hong Kong	6540	7.1 million

Table 3: Population of overpopulated cities [11]

[11] The figures are from www.wikipedia.org and range from the period between 2012 and 2014.

The pentagon shaped platforms from the report of Seasteading in collaboration with Deltasync (Czapiewska et al., Seasteading implementation plan, 2013) were estimated to have sides of 60 m. This dimension will be used as a starting point for the hexagonal shaped platform.

The area of a hexagon is calculated as follows:

$A = \frac{3}{2} * z^2 * \sqrt{3}$ Where, A = area of the hexagon [m^2]
z = one side of the hexagon [m]

So if z = 60 m, then the area of the platform would be:

$$A = \frac{3}{2} * 60^2 * \sqrt{3} = 9353\ m^2$$

This area is used for housing, offices, infrastructure, green and recreation and other facilities. The area usage of most basic cities is shown in Figure 30.

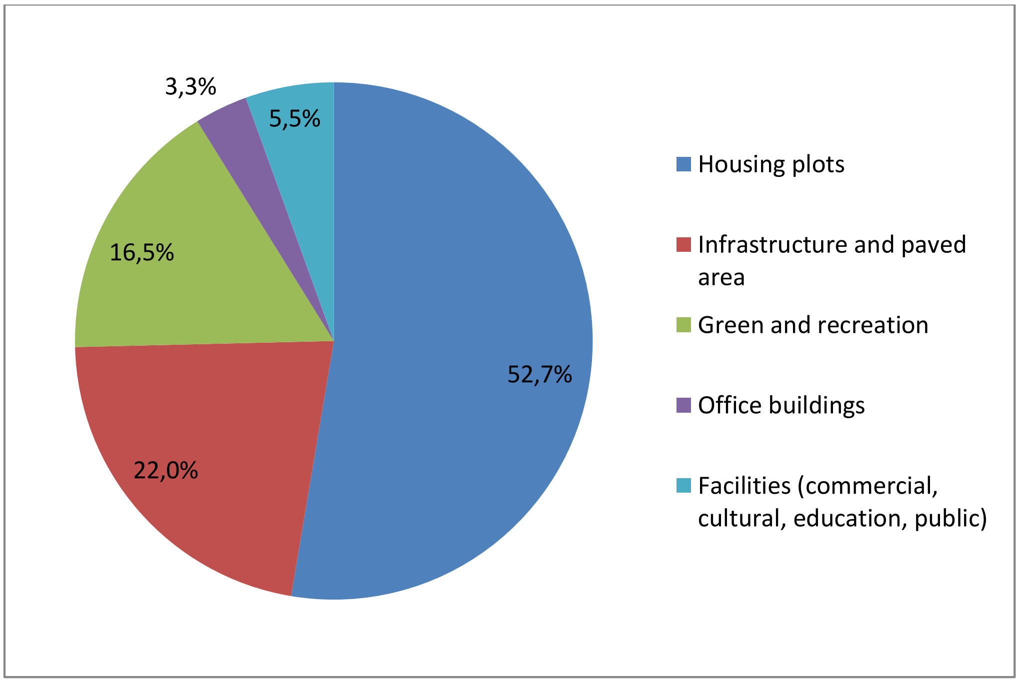


Figure 30: Land use of cities [12]

According to Figure 30, approximately 50% of the area is used for housing. This means that an area of $9353 * 0.50 \approx 4677\ m^2$ is available for housing on a single platform.

Assumed is that each inhabitant has 75 m^2 available for living space and the housing on the platform are 1, 2 or 3 layered houses. So approximately for each 75 m^2 there are 2 residents ≈ 37.5 m^2/resident (living above and below each other). Each platform would have approximately $4677/37.5 \approx 125$ inhabitants.

It is opted to achieve 15000 inhabitants as a start for the floating community. 15000 inhabitants would result in $15000 * 37.5 = 562500\ m^2$ of area needed for housing. The total amount of platforms to start

[12] **Data is achieved from Deltasync.**

the floating community would then be $562500/4677 \approx 120$ platforms. This is quite a large amount of platforms to start building the floating community with. More platforms result in a longer construction time before the floating city centre is realised.

The 125 inhabitants on the platform share an area of 9353 m^2 with each other. This means that the population density on the platform would be:

$$\frac{125}{9353*10^{-6}} = 13364\ inhabitants/km^2.$$

According to Table 3, Chennai has a population density of 26900 inhabitants/km^2. So it is a possibility to opt for a larger population density for the floating city. For the floating city, a larger population density is favourable because this results in fewer platforms for the same amount of inhabitants. A reduction in the amount of platforms greatly reduces the costs of the floating city project. Let us assume that the floating city would opt for the population density like in Chennai. Chennai has almost two times as much inhabitant per km^2 compared to the population density of the current platform. This means that the number of inhabitants on the current platform can be raised from 125 to 250 inhabitants. The total amount of platforms was estimated to be 120 platforms for 15000 inhabitants, but now the amount of platforms can be cut by half as 15000 inhabitants should fit on 60 platforms with 250 inhabitants on each platform. However, to maintain enough living space for the double amount of inhabitants while the area of the platform remains unchanged, the inhabitants have to live in higher buildings.

Concluding, a hexagonal shaped platform with sides of 60 m is used resulting in 60 platforms each with an area of 9353 m^2 to accommodate 15.000 inhabitants in total. The population density would be 26728 inhabitants/km^2.

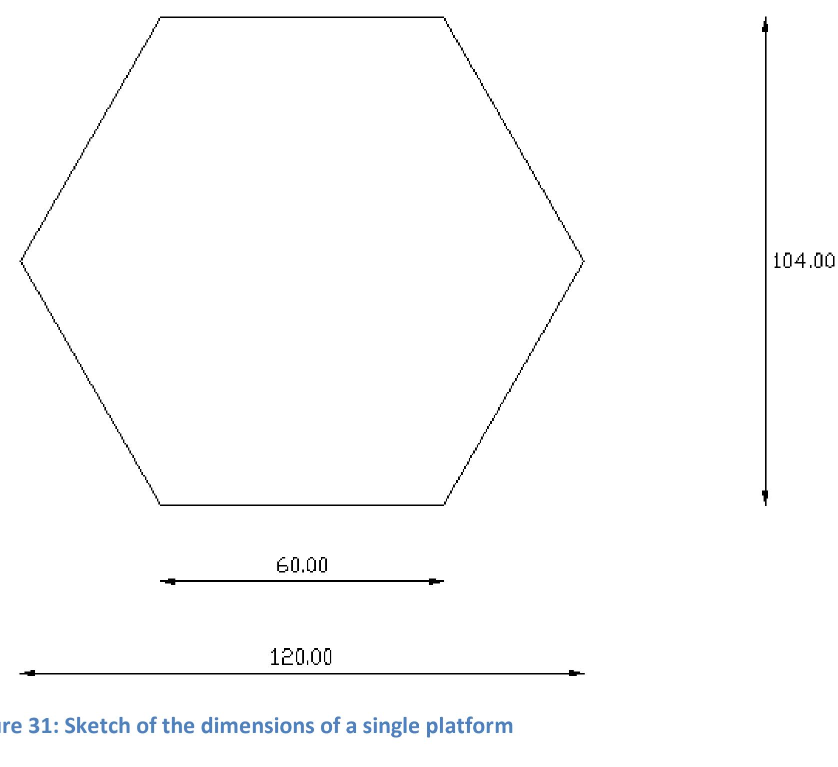


Figure 31: Sketch of the dimensions of a single platform

The platform is 120 m in its longest direction. As a rule of thumb, the height of the platform would be 1/20 of this length, thus 6 m.

4.2 Inner walls and compartments

Before the static stability can be measured, it has to be made sure that the platform is floating. The floating capacity is determined by the weight of the platform and its size. To determine the weight of the platform, the amount of concrete must be calculated. This includes the inner walls which are necessary to shorten the spans to reduce bending moments in the top and bottom slabs. The inner walls in the platform can be divided as seen in Figure 32. This is just one of the many possibilities to arrange the inner walls. It is chosen for each chamber to have a span of 10 – 20 m as too large spans results in larger bending moments and therefore a thicker deck slab. As a first estimation, the inner walls all have a thickness of 0.5 m and all the outer walls have a thickness of 1 m (including top and bottom slabs).

One can image that the space inside the platform can be efficiently used for storage or as an 'underground' parking facility etc. When the chambers of the platform is used for such purposes, there should be openings in the inner walls to allow traffic, people, pipelines, wires etc. to pass. Such openings in the inner walls lead to a decrease in the weight of the platform and thus contribute to a positive effect of the floating capacity. However, the stability and strength of the platform will also decrease.

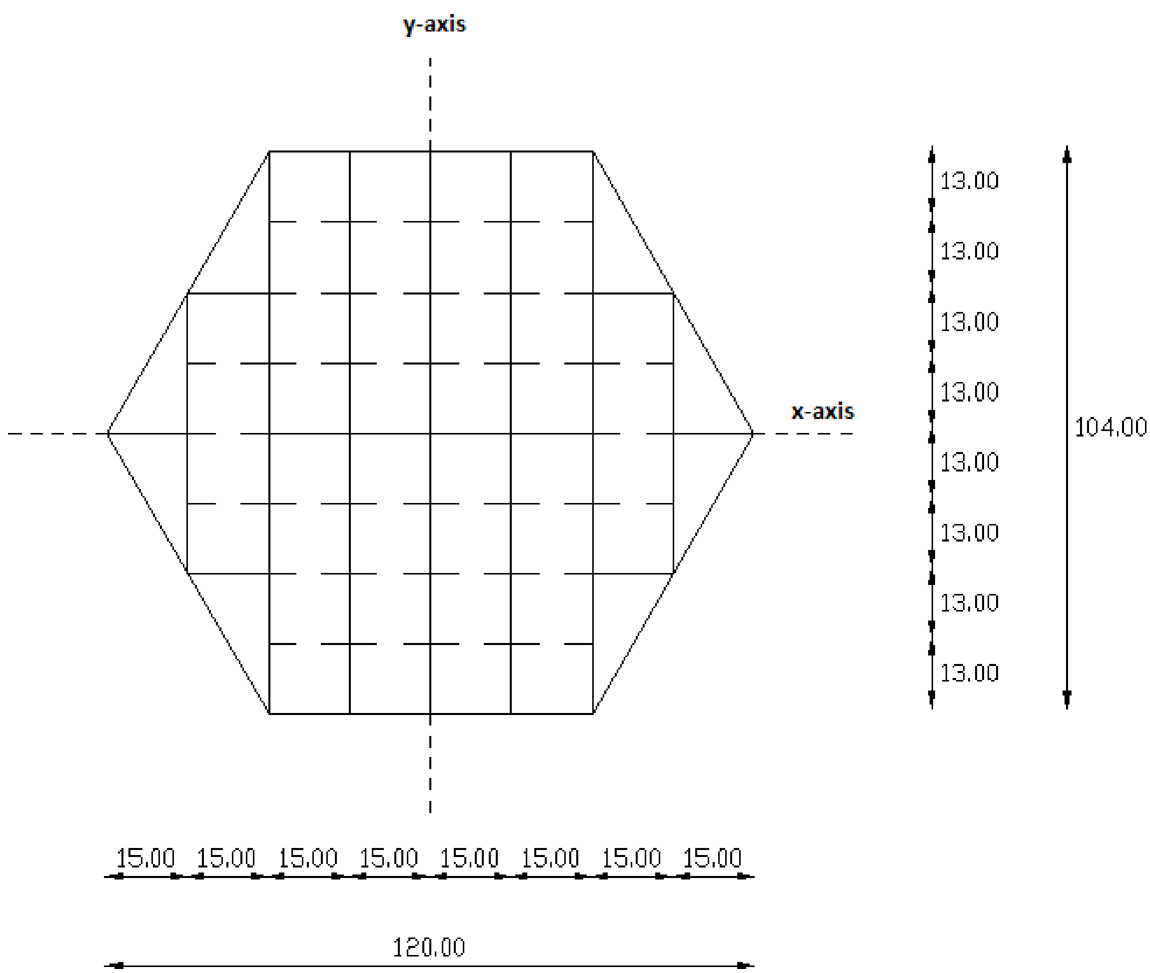


Figure 32: Inner walls of the platform

The openings in the inner walls are largest when the space is used as a parking facility. This is because a car needs the most space through an opening compared to humans, pipelines or wires. If the design of the platform with an 'underground' parking facility suffices the strength and stability requirements, then the other designs with openings in the inner walls for humans, pipelines or wires will easily suffice the strength and stability requirements too.

There are two options to realise an 'underground' parking facility: the self-parking and the mechanical-parking garages. The self-parking garage is the most common and traditional parking garage where you park your car all by yourself. The mechanical-parking garage is more like an automatic storage facility for your car; your car is parked with the help of machines. A self-parking garage requires more space, because space is needed to manoeuvre your car to the parking spot; extra width in the traffic lane is needed (especially for two-ways traffic) and space is needed for the entrance and exit. On the other hand, a mechanical-parking garage utilises the space to its maximum as everything is arranged by machines, there is no need for extra space for an entrance or exit and the width of the traffic lane is at its minimum. The car is parked in a lift on the surface and the lift will then automatically park the car in an empty parking spot underground. The parking facility is not accessible for trespassers. See Figure 33 for an impression of this concept.

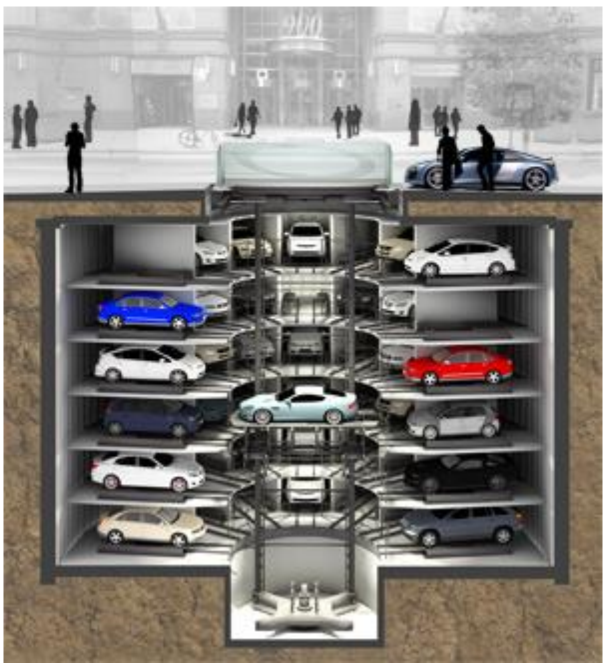


Figure 33: Mechanical-parking garage [13]

Because of a shortage of space (and the problem of removing as less as possible walls) the mechanical-parking garage would be the best solution to utilise the space within the platform. The size of such a parking garage is not standard and can be different in each design, but considering the setup of the inner walls according to Figure 32, it is not efficient if the parking garage would take up to more than 4 chambers (in length). As the whole length of the platform is 120 m, it is inefficient to park your car at 120 m distance from where you left your car. It is inefficient because the time for the machinery to pick up your car and to transport your car all the way to you would take too long.

The openings in the inner walls are all 5 m in width and the height is the same as the inner height of the platform (thus total height of platform minus the thicknesses of the top and bottom slab). A width of 5 m is chosen because the dimensions of a parking spot are 5 m by 2.5 m on average. It would be more logical

[13] http://www.perfectparkusa.com/system-overview.html

and efficient to choose the 2.5 m for the openings in the inner walls, but the design for now is to take the most unfavourable situation. If the design suffices the strength and stability requirements, then other designs which are in a more favourable and efficient situation would suffice too. Each chamber has dimensions of 15 m by 13 m, the most logical division of the parking spots can be seen in Figure 34. How many cars can be stacked on each other depends on the height of the platform, but each parking spot should have 2 m height available on average. So with the current (inner) height of the platform, 4 m, there can be 2 layers of parking spots in each chamber.

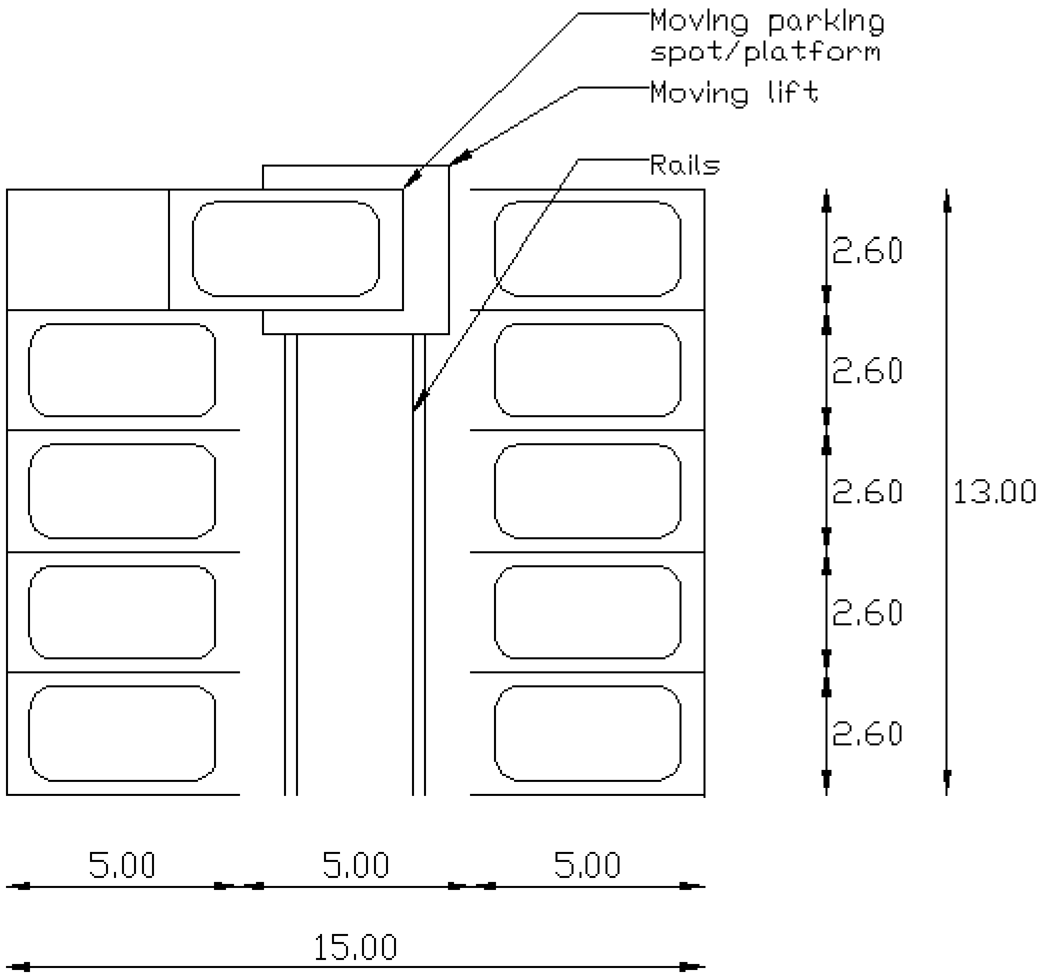


Figure 34: Division of the parking spots in one chamber (two floors possible, each 2 m high)

4.3 **Load cases**

For this thesis, two different load cases are set up: a case with high-rise buildings and a case with low-rise buildings. One platform has to accommodate 250 inhabitants. To maximize space usage, it is best to opt for high-rise buildings were all inhabitants live in. Of course this is a very extreme case as there is enough space on one platform to utilize low-rise buildings.

4.3.1 Load case 1

Assume all the 250 inhabitants would live in one flat/apartment. And assume each floor can house approximately 16 inhabitants with 75 m^2 of living space for each resident. The amount of floors in the apartment would then be $\frac{250}{16} = 15.6 \approx 16$ floors. Assuming each floor has a height of 3 m, the total height of the building would be $16 * 3 = 48\ m \approx 50\ m$. An example of the footprint of such a high building is seen in Figure 35. The building footprint is $25 * 60 = 1500\ m^2$, but other designs for the building with different dimensions are also possible. The most standard building is taken to give a general idea about the stability and strength of the platform in this thesis. It is known for sure that the platform would tilt if a large eccentric force (dead weight of the building) acts on the platform. So that is why the building is placed in the centre of the platform.

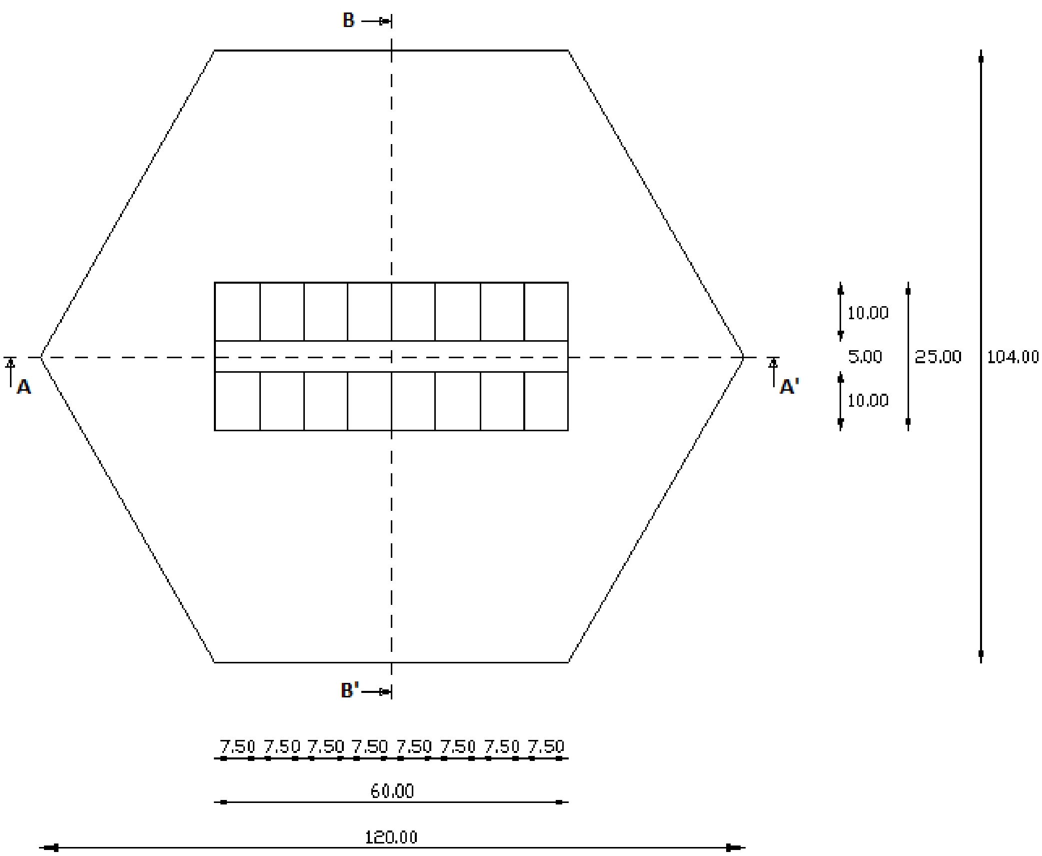


Figure 35: Footprint of the high rise building on the platform, plan view

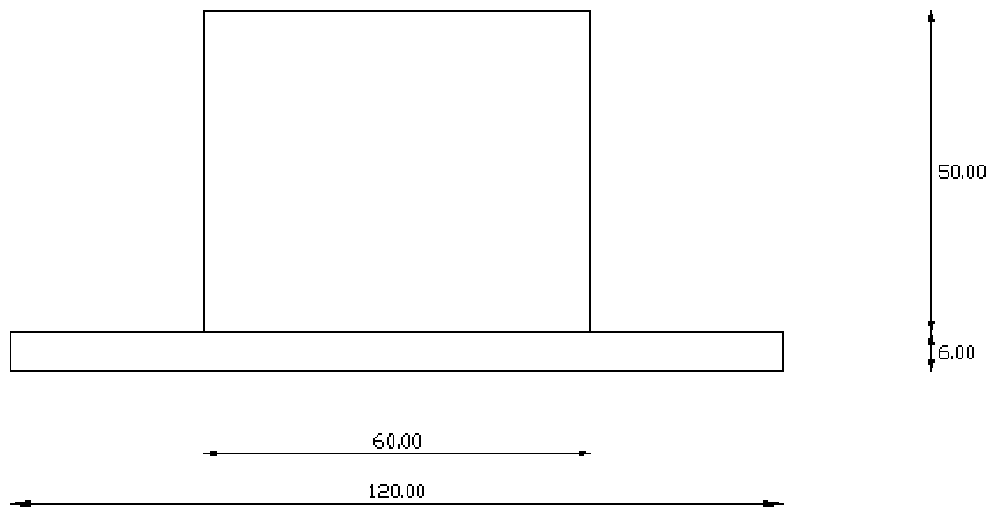


Figure 36: Cross-section AA'

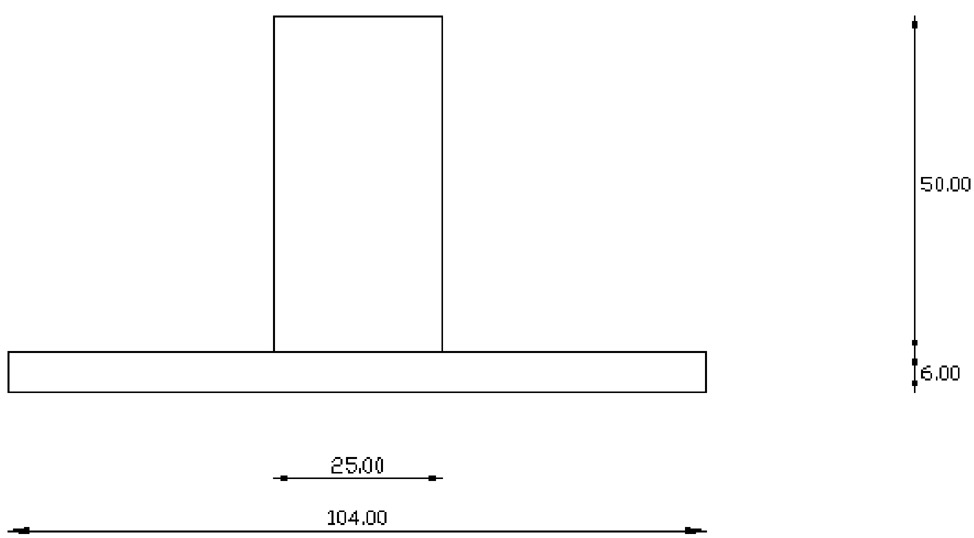


Figure 37: Cross-section BB'

Cross-section BB’ is governing for stability calculations because a smaller width of the platform results in a smaller shifting of the centre of buoyancy when the platform rotates. The more the centre of buoyancy shifts and can shift with a certain rotation, the higher the metacentre will be, so the more stable the floating structure will be. In other words, the stability increases a lot by enlarging the width of the floating structure. Thus a smaller shifting of the centre of buoyancy gives a significantly smaller metacentric height and that is why the stability calculations should focus on this cross-section.

4.3.2 Load case 2

The total area available for housing was estimated to be 50% of the platform space, thus 4677 m^2. With an apartment with a footprint of 1500 m^2, there is still a lot of space left for housings. So it is actually not very necessary to build such a high building, but it is certainly an option if preferred or needed.

Another option would be to utilise the maximum area available on the platform and see how high the buildings then would be. Assume 50% of the platform space (4677 m^2) is fully used for housings. It does not matter how the houses and buildings are arranged, but the idea is to have a distributed load over the entire platform with apartments of the same height; see the arched area in Figure 38. Again, the cross-section with the smallest width is chosen because this cross-section is governing for stability calculations.

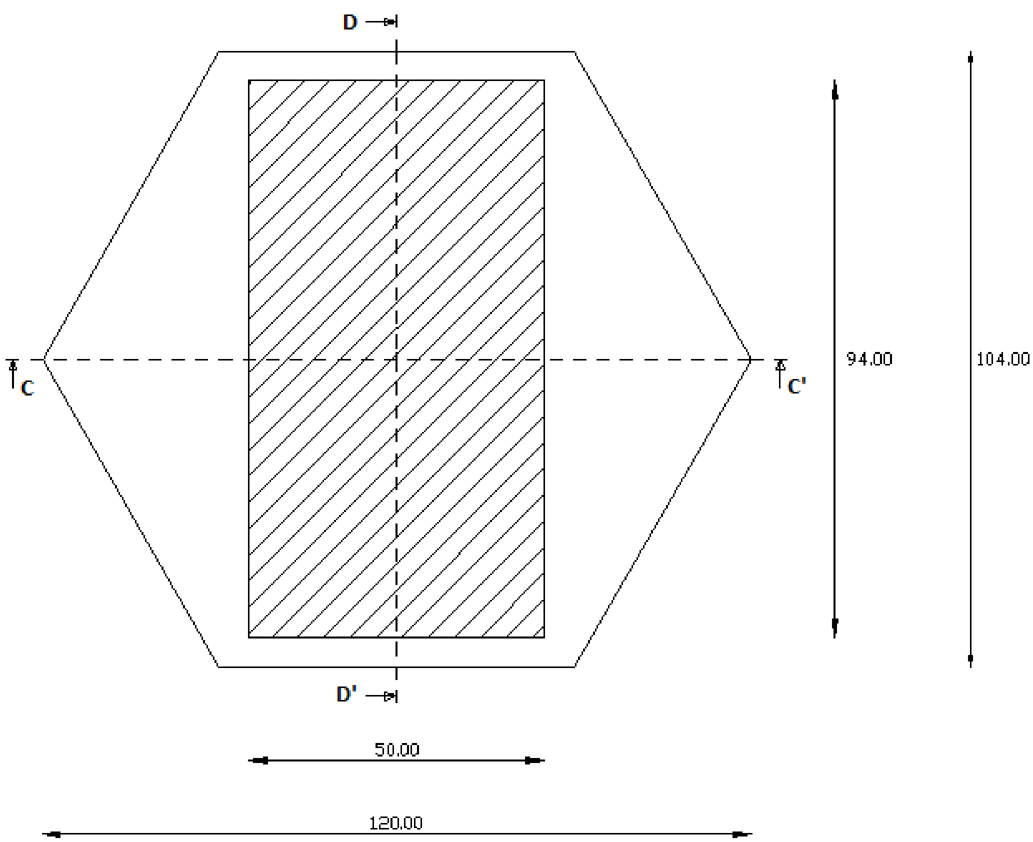


Figure 38: 50% of the platform area for housing, plan view

4677 m^2 of housings over a full length of 94 m (5 m on each side for sidewalks etc.) results in a $\frac{4677}{94} \approx 50\,m$ wide strip on the platform. The amount of inhabitants living on one floor would be $\frac{4677\,m^2}{75\,inhabitants/m^2} \approx 62\,inhabitants$. The average amount of floors of all the housings to accommodate all 250 inhabitants would be $\frac{250}{62} \approx 4\,floors$, with each floor having a height of approximately 3 m the average height results in $4 * 3 = 12\,m$.

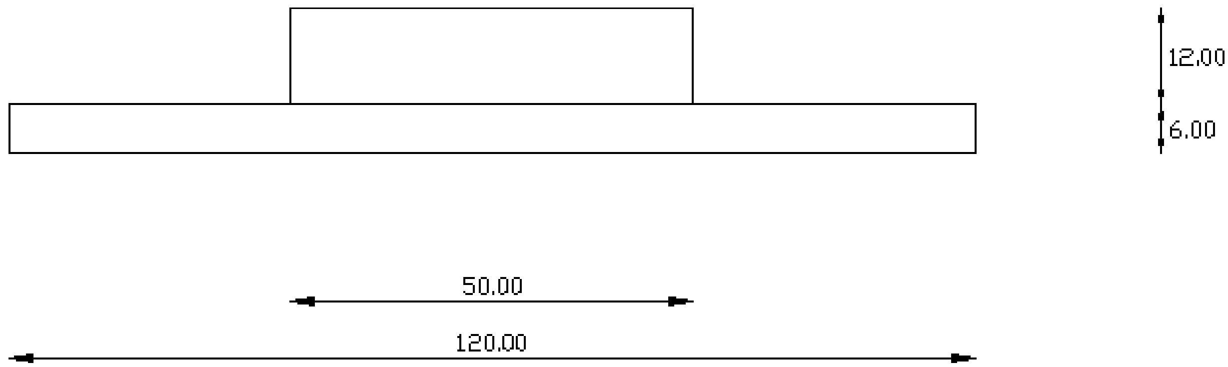


Figure 39: Cross-section CC'

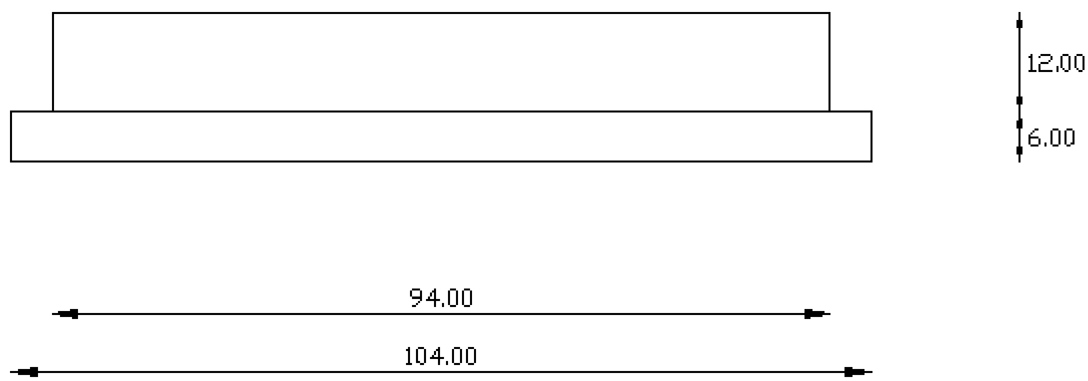


Figure 40: Cross-section DD'

4.3.3 Load definition

The possible loads acting on the floating platform are divided into dead and live loads. Dead loads are loads which will not change (very much) over time and live loads are loads which change under different circumstances.

The dead load of the floating city consists of the following loads:

- Dead weight platform
- Dead weight super structure

The live load of the floating city consists of the following loads:

- Load of the inhabitants
- Storage load
- Traffic load
- Wave load
- Wind load
- Current load

All live loads except for the traffic, wave and current load and extraordinary live loads such as collisions and explosions etcetera are not included in the stability calculations. The traffic load is excluded because the magnitude of this load is small compared to the other loads. Also, the design of the infrastructure is important to estimate the load. The wave and current load are horizontal loads which cause small momentum regarding the platform, so these loads can be neglected in the stability calculations.

Case 1

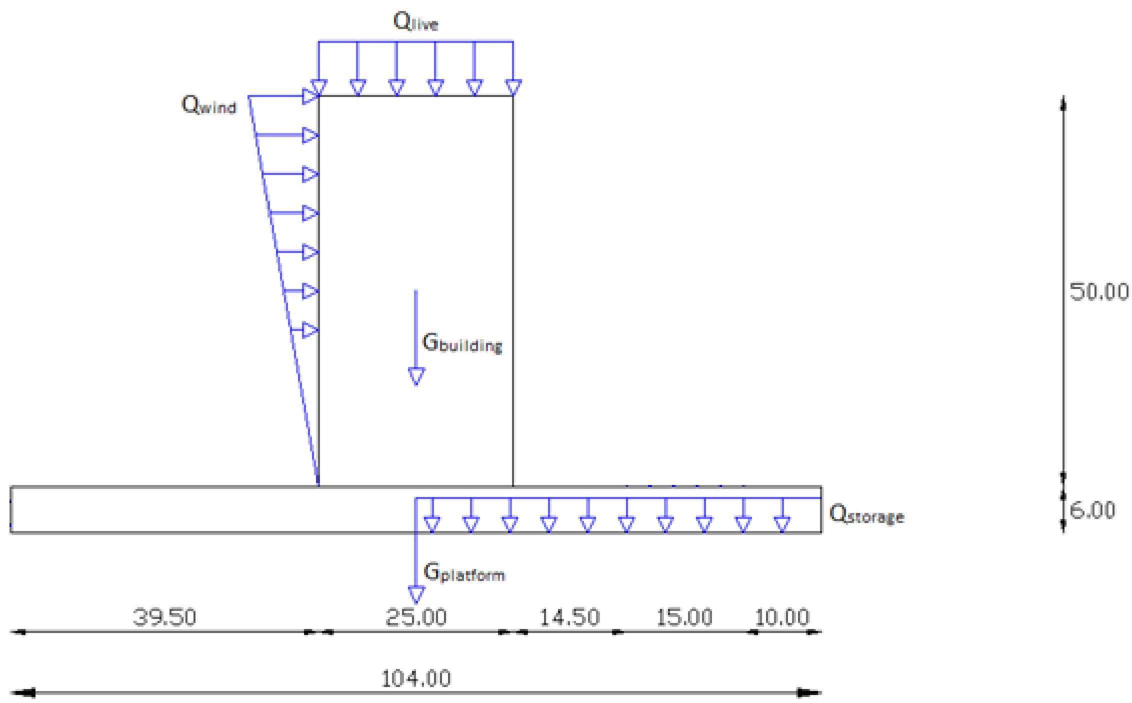


Figure 41: Load case 1 with high rise building

Load type	**Load**
Dead weight superstructure $\mathbf{G_{building}}$	91500 kN
Maximum wind load $\mathbf{Q_{wind}}$	6 kN/m
Load of inhabitants $\mathbf{Q_{live}}$	3660 kN/m
Storage load $\mathbf{Q_{storage}}$	2400 kN/m

Table 4: Known loads in load case 1

The storage load is randomly taken at one side of the platform such that maximum tilting occurs in combination with the prevailing horizontal wind load. The high storage load is because waste and sewerage water is taken as storage in the compartments in the platform. Waste and sewerage water need to be stored in the platform for cleaning processes and my not be dumped directly into the open water where the floating city is located.

The decrease of the wind pressure is more like an exponential function, but for simplification reasons a linear decreasing function is assumed.

The values of the loads are elaborated in **Appendix 5: Load definition**.

Case 2

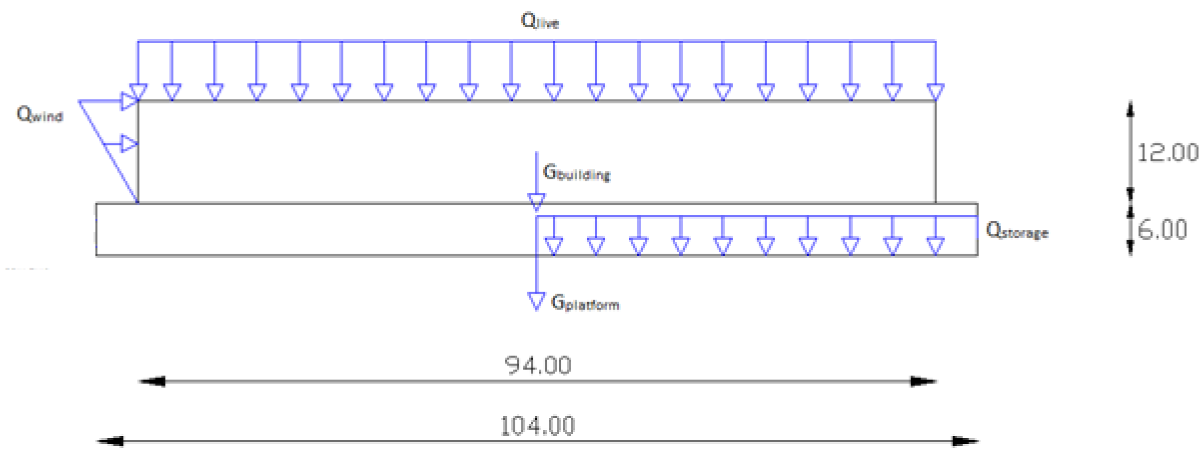


Figure 42: Load case 2 with low-rise buildings

Load type	**Load**
Dead weight superstructure $\mathbf{G_{building}}$	89300 kN
Maximum wind load $\mathbf{Q_{wind}}$	5 kN/m
Load of inhabitants $\mathbf{Q_{live}}$	950 kN/m
Storage load $\mathbf{Q_{storage}}$	2400 kN/m

Table 5: Known loads in load combination case 2

Also in case 2, the storage load is randomly taken at one side of the platform such that maximum tilting occurs in combination with the horizontal wind load.

Of course it is less likely to have just one high-rise building for all the inhabitants on a platform or to have all the houses be distributed into one rectangular area. Urban architecture plays a big role to determine the exact dead loads causes by the super structures. The cases mentioned are more or less extreme situations. When the strength and stability requirements suffice for the extreme cases, then other cases would likely to suffice the requirements too.

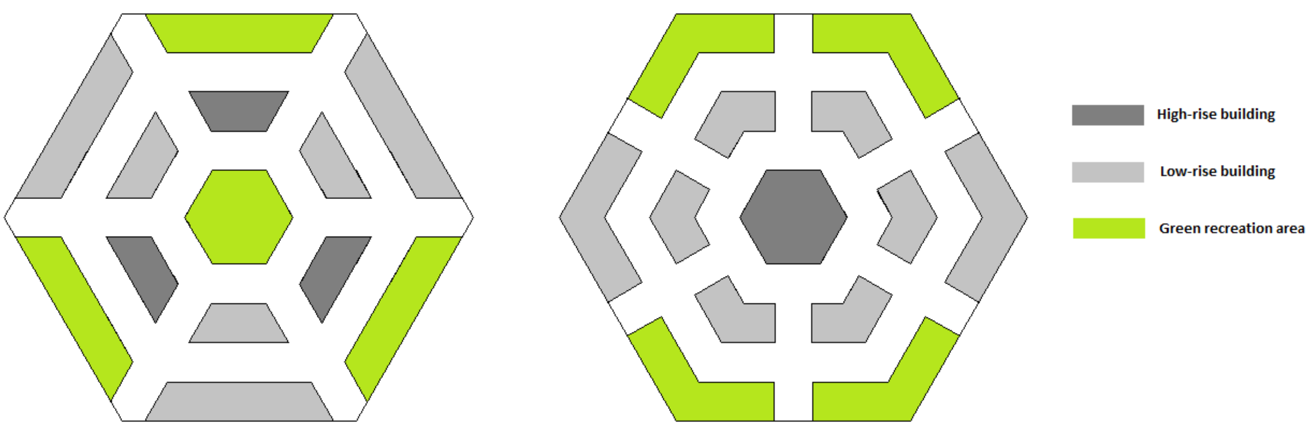


Figure 43: Sketch examples of urban architecture for one platform

4.4 Static stability

Now the load cases and dimensions of the platform are known, it has to be checked whether this size of platform is stable when subjected to loads. The dimensions in Figure 32 are the centre-to-centre distance as the walls all have a certain thickness. For a first loop of calculations, the inner walls are assumed to be 0.5 m thick and the outer walls are assumed to be 1 m thick. The deck and bottom plate of the platform is also assumed to be 1 m thick. The calculations of the static stability can be found in **Appendix 6: Static stability calculations**.

4.4.1 Equilibrium of vertical forces

Vertical forces establish an equilibrium if the buoyant force equals the weight of the floating platform including all the additional loads on the platform. If the platform is able to float, then the desired vertical equilibrium is reached. The vertical equilibrium gives a result on how high the construction height of the platform must be.

With the assumed thicknesses, the concrete volume of the platform and thus the weight of the platform can be calculated. The draught of the platform is calculated by adding the weight of the platform and the additional vertical loads and then dividing through the buoyant force.

$$D = \frac{F_v}{F_{buoyancy}} = \frac{F_v}{A * \rho_w}$$

Where,	D	= draught	[m]
	F_v	= total vertical load	[kN]
	$F_{buoyancy}$	= buoyant force	[kN/m]
	A	= area of the hexagon	[m^2]
	ρ_w	= density of water	[kN/m^3]

Case 1 draught calculation

A first estimation of the construction height was 6 m. This construction height results in a draught of 9.02 m and thus a 'freeboard' of -3.02 m. The draught of the platform exceeds the construction height, which means that the platform is completely under water and it will sink. Therefore, the construction height needs to be increased. Table 6 shows the draught and freeboard of different construction heights. In this table, it can be seen that the draught fulfils the requirement when the construction height is larger than 10 m. However, the freeboard is then 0.04 m and the freeboard must also be of sufficient height for extra safety, additional loads and to keep the deck dry and safe from wave attacks.

Construction height [m]	Draught [m]	Freeboard [m]
6	9.02	-3.02
7	9.26	-2.26
8	9.49	-1.49
9	9.73	-0.73
10	9.96	0.04
11	10.19	0.81
12	10.43	1.57
13	10.66	2.34
14	10.89	3.11

Table 6: Construction height, draught and freeboard relation of case 1

Case 2 draught calculation

The load of case 2 is slightly lower than in case 1, but the height of the platform assumed first (6 m) would definitely not suffice in this case too. The results on the draught and freeboard with different construction heights are seen in Table 7.

Construction height [m]	Draught [m]	Freeboard [m]
6	8.54	-2.54
7	8.78	-1.78
8	9.01	-1.01
9	9.24	-0.24
10	9.48	0.52
11	9.71	1.29
12	9.95	2.05
13	10.18	2.82
14	10.41	3.59

Table 7: Construction height, draught and freeboard relation of case 2

The draught of the platform is slightly smaller in load case 2, so this load case is actually preferred. However, the difference with load case 1 is significant small and high-rise buildings are an interesting option for the floating community to accommodate many inhabitants. So it is opted to use load case 1 with the high-rise building as the governing load case throughout this thesis.

A special note, the freeboard must actually be large enough to keep the deck dry from waves. With a wave height of 4 m, the freeboard must actually be at least 4 m. But this would economically be not feasible as the platform would gain too much weight and material and thus increasing the costs. On top of the platform, provision need to be taken to keep the waves from the deck, like barriers for example.

4.4.2 Equilibrium of moments

The platform is tilting because of the horizontal loads and the asymmetric storage load. And when the platform is tilted, the dead and live load of the super structure moves out of the symmetry-axis (z-axis) and thus contributes to the rotation of the platform. However, the centre of buoyancy also shifts and should be counteracting the moments caused by the external loads and the loads of the super structure. Horizontal loads also include the wave load and the current load. But because these loads act on the platform, the distance of these loads to the centre of gravity (arms) are small and thus negligible.

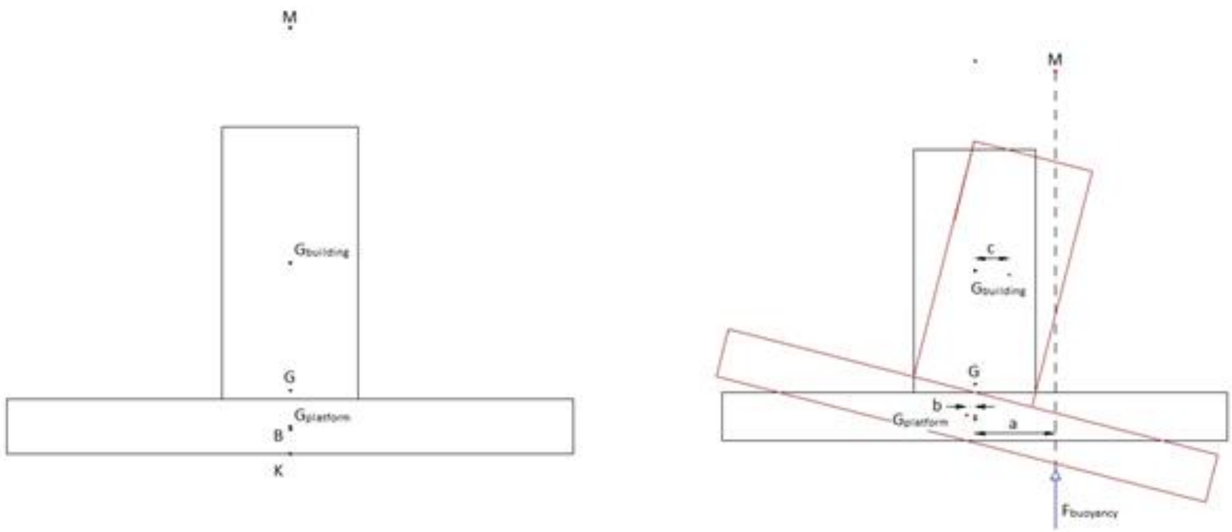


Figure 44: Sketch of the metacentric height and the displacement of the centre of buoyancy

A measure of the resistance to tilting is given by the 'metacentric height'. The distance of point G to point M (the line segment GM) is called the metacentric height. If the metacentric height is positive, it indicates that the floating element is stable. The larger the metacentric height is, the more stable the structure is.

The platform is considered to be statically stable when the metacentric height equals 0.5 or more. Note that horizontal loads are not included in the calculation of the metacentric height. The metacentric height is about the static stability due to the weight of the platform and the super structure on top of it. Both the dead load and the live load of the buildings are taken into account.

	Case 1	**Case 2**
KB	5.45 m	5.09 m
KG	13.37 m	8.51 m
BM	68.84 m	73.68 m
GM (h_m)	60.92 m	70.26 m

Table 8: Static stability calculation results

The distance between the centre of buoyancy and metacentre (BM) in both cases is very large. This is because the platform has very large dimensions. Larger dimensions results in a larger shift of the centre of buoyancy when the platform is tilted. A momentum balance can be made of the platform when it is tilted:

	Case 1	Case 2
Arm a	34.90 m	40.26 m
Moment buoyancy	36457017 kNm	39284634 kNm
Arm c	14.69 m	601 m
Moment building weight	-2687610 kNm	-822.271 kNm
Arm storage load	26.00 m	26.00 m
Moment storage load	-3244800 kNm	-3244800 kNm
Arm wind load	33.97 m	37.82 m
Moment wind load	-7642 kNm	-1702 kNm
Total moment	30516964 kNm	35215860 kNm

Table 9: Moment calculation

Because of the tilting, the water pressure on both sides of the platform would increase and decrease because of the change of the draught on each side. But the rotation φ is very small, so these changes in the draught are neglected and the resulting moment caused by the horizontal water pressure equals zero. The negative signs in Table 9 indicate that the moment is an overturning moment and the moments with a positive sign are restoring moments.

In both cases, the total moment is nearly equal to the moment due to buoyancy. The moment due to buoyancy is far greater than the other moments because of the large metacentric height. The platform will quickly restore itself to its initial position when it is forced in tilting.

4.4.3 Extreme case for static stability

As can be seen in Table 9, the largest overturning moments are due to the (asymmetric) storage load in the first place and then the overturning moment due to the building in second place and the overturning moment due to the wind load is the least impressive.

Typhoons

The (random) chosen wind speed of 56 km/hr corresponds to Beaufort number 7 (high wind, moderate gale). It can occur that the floating city is going to be realised in a region where higher wind speeds occur more frequently or even in the worst case a region with typhoons and hurricanes. Typhoons and hurricanes are categorised with the Saffir Simpson scale instead of the Beaufort scale, see Figure 45.

Cat.	Maximum Sustained Wind (1-min mean)		Effects
	[kt]	[km/h]	
One	64-82	118-152	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal road flooding and minor pier damage
Two	83-95	153-176	Some roofing material, door, and window damage to buildings. Considerable damage to vegetation, mobile homes, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of centre. Small craft in unprotected anchorages break moorings.
Three	96-113	177-208	Some structural damage to small residences and utility buildings with a minor amount of curtain wall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris. Terrain continuously lower than 5 feet ASL may be flooded inland 8 miles or more.
Four	114-135	209-248	More extensive curtain wall failures with some complete roof structure failure on small residences. Major erosion of beach. Major damage to lower floors of structures near the shore. Terrain lower than 10 feet ASL may be flooded requiring massive evacuation of residential areas inland as far as 6 miles.
Five	135	>248	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Major damage to lower floors of all structures located less than 15 feet ASL and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5 to 10 miles of the shoreline may be required.

Figure 45: Saffir Simpson scale[14]

If for example a typhoon with wind speeds of 250 km/h strikes the floating city, the wind load on the high-rise building would then be: $Q_{wind} = \frac{1}{2} * 1.225 * \left(\frac{250}{3.6}\right)^2 * 0.7 * 60 = 124060\ N/m^2 \approx 124\ kN/m$

The overturning moment with this wind load is then: $33.97 * \left(\frac{1}{2} * 50 * 124\right) = 106156\ kNm$ (these load calculations are explained in **Appendix 5: Load definition**). The restoring moment due to the buoyant force is in the order of 10^7 while this overturning moment is still in the order of 10^5. So it can be concluded that such an extreme wind load would not endanger the static stability of the platform. However, this overturning moment is actually being exerted on the foundation of the building. So it is more likely that the building will collapse due to this wind load rather than affecting the stability of the platform. And in turn, the collapse of such a building causes damage to the platform.

A similar calculation can be done for eccentric loads of buildings. Assume that the high-rise building is placed at the edge of the platform; this will result in an overturning moment of approximately $(2 * 91500) * 52 = 9516000\ kNm$ (52 m is halve of the platform length). This moment is in the order of 10^6 and is still not a risk for the static stability because the restoring moment of the buoyant force is in the order of 10^7. However, the platform maintains statically stable, but the platform will likely remain in a tilted position (the platform can be tilted and still be statically stable). This can be solved by adding

[14] http://www.nhc.noaa.gov/aboutsshws.php

ballast on the other side of the platform to compensate the eccentric load and get the platform horizontal again.

Higher buildings

The overturning moment due to the extreme wind load increases with increasing building heights. The question then is, what is the maximum height of the building such that the floating platform remains statically stable?

The current load case of the high rise building concerns a 50 m high building, which consists of 16 floors, each floor with a height of 3 m. For each floor we add to the building, the total building load increases which affects the draught of the platform. Also, with increasing building height the wind load increases too which affects the overturning moment of the platform. In the table below, the results of calculations of different heights for buildings with a typhoon wind load is presented.

Amount of floors	20	30	40
Building height	60 m	90 m	120 m
Draught	11.33 m	12.43 m	13.52 m
Freeboard	2.67 m	1.57 m	0.48 m
KB	15.66 m	23.09 m	31.87 m
KG	5.67 m	6.21 m	6.76 m
BM	66.18 m	60.35 m	55.46 m
GM (h_m)	56.19 m	43.47 m	30.35 m
Arm a	32.19 m	24.91 m	17.39 m
Moment buoyancy	34977688 kNm	29677905 kNm	22542188 kNm
Arm c	16.24 m	20.58 m	24.14 m
Moment building weight	-3653892 kNm	-6790245 kNm	-10499231 kNm
Arm storage load	26 m	26 m	26 m
Moment storage load	-3244800 kNm	-3244800 kNm	-3244800 kNm
Arm wind load	38.34 m	50.91 m	62.13 m
Moment wind load	-118864 kNm	-157829 kNm	-192589 kNm
Total moment	27960131 kNm	19485031 kNm	8605566 kNm

Table 10: Maximum building height during typhoon

The building can be 120 m high which still results in a positive overturning moment (the restoring moment due to buoyancy is still greater). However, for the current shape and size of platform, the draught becomes very large resulting in a small freeboard. The total overturning moment becomes negative when a building of 141 m is applied (47 floors). But this results in a draught of 14.29 m which means that the platform is 0.29 m under the water level (platform will slowly sink).

Note that the moment due to building weight increases faster with increasing building height compared to the moment due to wind load. This has several reasons. First, the wind load is assumed to be a linear function for simplification reasons. The total moment due to wind load would be larger if the original function for the wind load is taken.

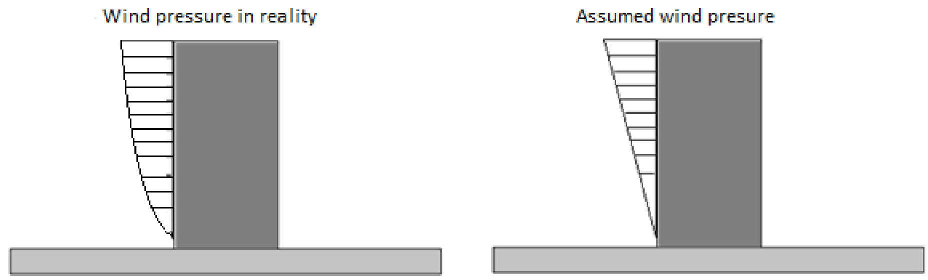


Figure 46: Wind load in reality versus assumption of the wind load acting on a building

Second, the shape of the building is constant with increasing height. If the building would be more slender with increasing height, the upper floors will cause a smaller over turning moment. The centre of gravity for slender structures are lower compared to structures with a constant shape.

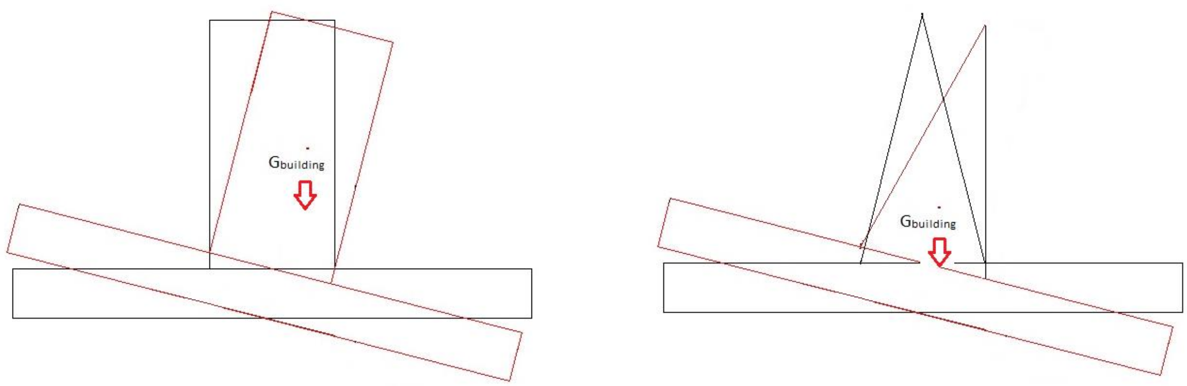


Figure 47: Bulky building versus slender building

Due to these reasons, there is no absolute value of the maximum building height one can place on the platform. It always depends on the shape and dimensions of the platform and the building. In this case, for a hexagonal platform with sides of 60 m, the maximum acceptable building height would be 120 m (building with a base of 60 m by 25 m).

4.5 Strength check

The platform sizes and the draught are calculated and defined in the previous paragraphs. Only the thicknesses of the walls and the slabs remain uncertain. For a first loop of calculations, the outer walls were assumed to be 1 m thick and the inner walls 0.5 m. The inner walls have a centre to centre distance of 13 m, see Figure 32. A simple representation of the top/bottom slab is to schematize the slab as a beam fixed at both sides. When a distributed load is exerted on the beam, the forces and moments at each end of the beam can be calculated with a rule of thumb as seen in Figure 48.

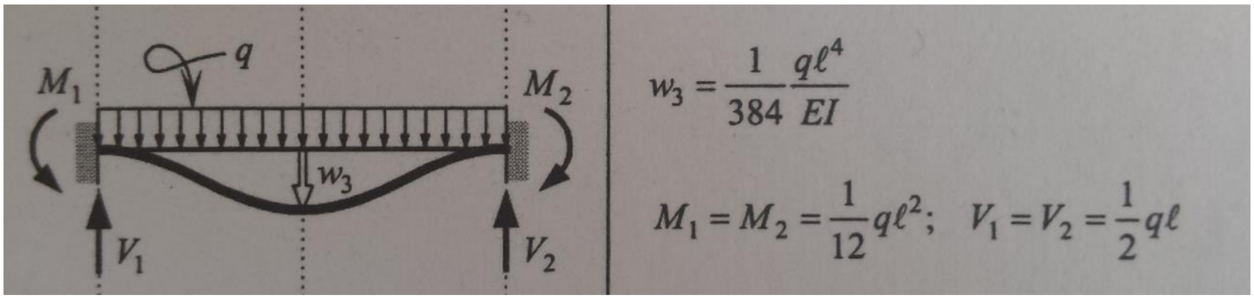


Figure 48: Rule of thumb for beam with fixed ends (Hartsuijker)

Bottom slab:
The main load on the bottom slab is the upward water pressure. The deadweight and additional loads which are working downward are neglected as these loads compromise the upward water pressure, leading to smaller forces and momentums.

$$q_{water} = draught * \rho_{water} = 10.89 * 10.25 = 111.63\ kN/m/m$$
$$M_1 = M_2 = \frac{1}{12} * q_{water} * l^2 = \frac{1}{12} * 111.63 * 13^2 = 1572\ kNm$$
$$M_{mid} = M_1 - \frac{1}{8} * q_{water} * l^2 = 1572 - \frac{1}{8} * 111.63 * 13^2 = -786\ kN$$

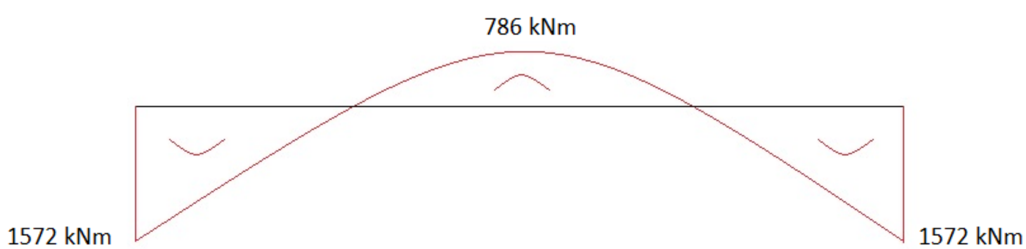


Figure 49: Momentum distribution over bottom slab

To determine the required thickness of the slab with the calculated maximum moment, Table 11 is used.

$$\frac{M_{max}}{w * t^2 * f_{cd}} = 150 \text{ (≈ 1% reinforcement ratio, C35/45 concrete)}$$

$$t = \sqrt{\frac{M_{max}}{w * 150 * f_{cd}}} = \sqrt{\frac{1572}{1.0 * 150 * 30}} = 0.59\ m$$

Top slab:

The top slab has to endure all the variable loads on top of the platform. This includes loads from buildings and traffic etcetera. The largest load is due to a high rise building as in load case 1.

$$q_{building} = \frac{2*91500}{60*25} = 122\ kN/m/m$$
$$M_1 = M_2 = \frac{1}{12} * q_{building} * l^2 = \frac{1}{12} * 122 * 13^2 = 1718\ kNm$$
$$M_{mid} = M_1 - \frac{1}{8} * q_{building} * l^2 = 1572 - \frac{1}{8} * 122 * 13^2 = -859\ kN$$

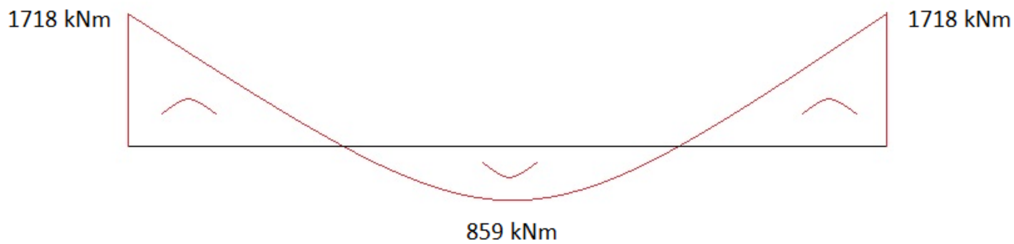


Figure 50: Momentum distribution over top slab

$$\frac{M_{max}}{w*t^2*f_{cd}} = 150 \text{ (≈ 1% reinforcement ratio, C35/45 concrete)}$$

$$t = \sqrt{\frac{M_{max}}{w*150*f_{cd}}} = \sqrt{\frac{1718}{1.0*150*30}} = 0.62\ m$$

The first estimation of 1.0 m thickness for the top and bottom slabs were slightly over estimated, but this should be fine as there will be more loads to be considered which leads to larger moments in the slabs. The moments at the fixed ends are also (more or less) the moments transferred to the inner and outer walls. The outer walls of 1.0 m thick suffice the strength requirement. The inner walls were taken as 0.50 m as a first estimation. The requirement for the wall thickness is 0.62 m, so the inner walls should be made slightly thicker. A thickness of 0.8 m should suffice for the inner walls.

$\frac{M_d}{bd^2 f_{cd}}$	ψ	k_x	k_z	ρ [%]				
				C20/25	C28/35	C35/45	C45/55	C53/65
10	0,010	0,013	0,99	*0,03*	*0,05*	*0,06*	*0,08*	*0,09*
20	0,020	0,027	0,99	*0,07*	*0,10*	*0,13*	*0,15*	*0,18*
30	0,030	0,240	0,98	*0,10*	*0,15*	*0,19*	*0,23*	*0,27*
40	0,041	0,055	0,98	*0,14*	0,20	0,25	0,31	0,37
50	0,051	0,068	0,97	0,18	0,25	0,32	0,39	0,46
60	0,062	0,083	0,97	0,21	0,30	0,39	0,47	0,56
70	0,073	0,097	0,96	0,25	0,35	0,45	0,55	0,66
80	0,084	0,112	0,96	0,29	0,41	0,52	0,64	0,75
90	0,095	0,127	0,95	0,33	0,46	0,59	0,72	0,85
100	0,106	0,141	0,94	0,37	0,51	0,66	0,81	0,95
110	0,117	0,156	0,94	0,40	0,56	0,73	0,89	1,05
120	0,129	0,172	0,93	0,44	0,62	0,80	0,98	1,16
130	0,140	0,187	0,93	0,48	0,68	0,87	1,06	1,26
140	0,152	0,203	0,92	0,52	0,73	0,94	1,15	1,36
150	0,164	0,219	0,91	0,57	0,79	1,02	1,24	1,47
160	0,176	0,235	0,91	0,61	0,85	1,09	1,34	1,58
170	0,188	0,251	0,90	0,65	0,91	1,17	1,43	1,69
180	0,201	0,268	0,90	0,69	0,97	1,25	1,53	1,80
190	0,214	0,285	0,89	0,74	1,03	1,33	1,62	1,92
200	0,227	0,303	0,88	0,78	1,10	1,41	1,72	2,04
210	0,240	0,320	0,88	0,83	1,16	1,49	1,82	2,16
220	0,253	0,337	0,87	0,87	1,22	1,57	1,92	2,27
230	0,267	0,356	0,86	0,92	1,29	1,66	2,03	2,39
240	0,281	0,375	0,85	0,97	1,35	1,75	2,13	2,52
250	0,295	0,393	0,85	1,02	1,43	1,83	2,24	2,64
260	0,310	0,413	0,84	1,07	1,50	1,93	2,35	2,78
270	0,325	0,433	0,83	1,12	1,57	2,02	2,47	2,91
280	0,340	0,453	0,82	1,17	1,64	2,11	2,58	3,05
290	0,356	0,475	0,81	1,23	1,72	2,21	2,70	3,19
300	0,372	0,496	0,81	1,28	1,80	2,31	2,82	3,34
310	0,388	0,517	0,80	1,34	1,87	2,41	2,94	3,48
320	0,405	0,540	0,79	*1,40*	*1,96*	*2,51*	*3,07*	*3,63*

Table 11: Reinforcement ratio chart (CT3330 lecture notes)

4.6 Cost of one platform

With the known dimensions of the platform, the costs of the material needed to construct one platform can be estimated. The hexagonal platform with sides of 60 m has a bottom and deck slab thicknesses of 1.0 m; outer walls of 1.0 m; inner walls of 0.8 m and a construction height of 14 m. This results in a total volume of 33332 m^3 concrete. The average cost of concrete (including the reinforcement) is around €400 per m^3. For such a big structure, the labour costs are usually double the material costs. Assume that the average cost of concrete becomes €1200 per m^3 including labour and additional costs. The total costs to just construct one platform would become €40 million.

It is opted to achieve 15000 inhabitants as a start for a floating community. These 15000 inhabitants are roughly distributed over 60 platforms (each of 9353 m^2, resulting in a population density of 26000 inhabitants/km^2). The construction costs of only the platforms for a starting floating community of 15000 inhabitants would then be €2400 million = €2.4 billion. This is one average 4000 €/m^2. Compared to the costs of several land reclamation projects as seen in Table 1 in section 2.1, the total costs of this starting floating city concept is way more expensive. Even compared to land prices in countries like Hong Kong (570 \$/m^2)[15] and Singapore (650 \$/m^2)[16] this floating platform is very expensive.

Project	Country	Cost/unit
Palm Jumeirah	Dubai	492 \$/m^2
Pulau Tekong	Singapore	205 \$/m^2
Changi Airport	Singapore	146 \$/m^2

Table 12: Price comparison with land reclamation projects

The floating city could only be economic more feasible compared to land reclamation when it is situated in waters with a large water depth. Reclamation sand in the Netherlands can be purchased for around €10 per m^3. The minimum water depth for the floating city in the Netherlands must then be $\frac{1200}{10} = 120\ m$ to be cost effective compared to land reclamation. But on the other hand, reclamation sand in Singapore is more expensive like €20 per m^3. The minimum water depth for the floating city in Singapore must then be $\frac{1200}{20} = 60\ m$ to be cost effective compared to land reclamation.

These are just estimations of in what range the costs of such a floating platform are like. The costs of a complete floating city are on a whole different scale. A specific location based cost analysis should be done to determine whether a floating city would be more cost effective compared to land reclamation. The costs of reclamation sand can make a big difference in the required water depth to make a floating city economic more feasible.

[15] http://www.bloomberg.com/news/articles/2014-09-17/hong-kong-developers-raise-cash-to-buy-land-real-estate
[16] http://www.stproperty.sg/articles-property/singapore-property-news/land-costs-outpaced-rise-in-home-prices/a/135948

4.7 Summary and conclusion

A hexagonal shaped platform with sides of 60 m is the optimal size. The starting floating community consists of 60 platforms each with an area of 9353 m^2 to accommodate 15000 inhabitants in total. The total costs to just construct one platform are estimated to be €40 million (4000 €/m^2). Each platform should house approximately 1500 inhabitants and as an extreme load case, these inhabitants are living in a 50 m high building in the middle of the platform. The load of the building in combination with the dead weight of the platform results in a construction height of 14 m, a draught of 10.89 m and a freeboard of 3.11 m. The load on the platform can increase to an extra 183000 kN (which is comparable to two high rise buildings of 50 m high) and the freeboard would still be 1.23 m which is sufficient safe.

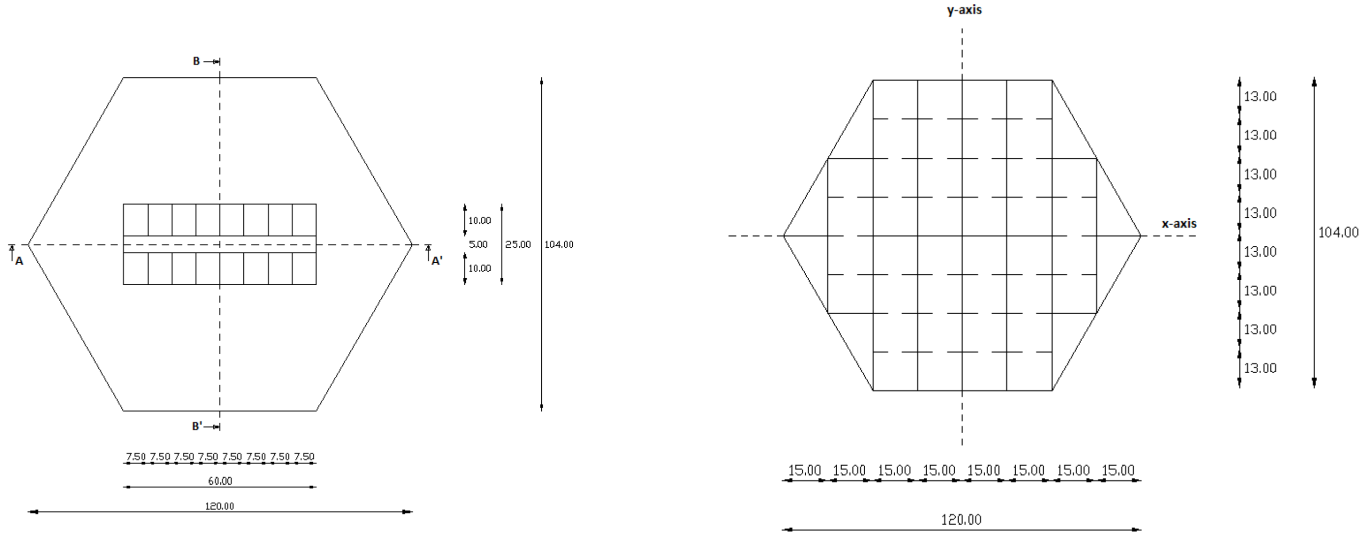


Figure 51: Footprint of the high rise building on the platform and inner walls plan

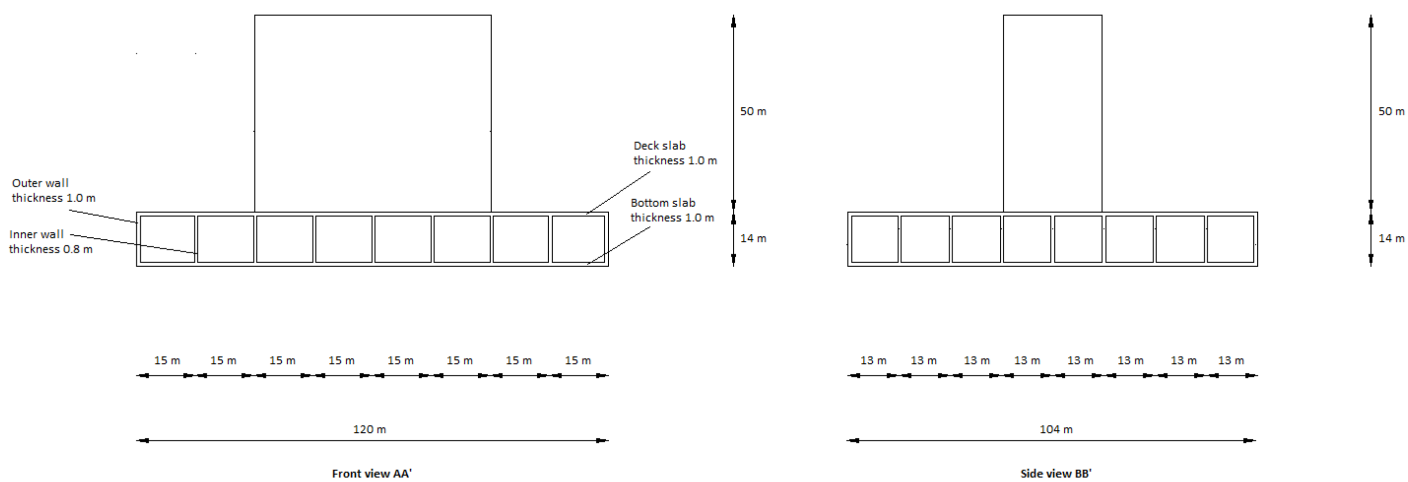


Figure 52: Front and side view of the platform

Side length of hexagon	60 m
Construction height	14 m
Draught	10.89 m
Freeboard	3.11 m
Inner walls thickness	0.8 m
Outer walls thickness	1.0 m
Deck slab thickness	1.0 m
Bottom slab thickness	1.0 m

Table 13: Final dimensions of the hexagonal platform

Because of the large surface area of the platform (9353 m^2), the platform is statically very stable. The moment due to buoyancy is far greater than the other moments because of the large metacentric height. The platform will quickly restore itself to its initial position when it is forced in tilting. Even in extreme cases; like hurricanes and when the high rise building is placed near the edge of the platform (eccentric load), the platform still remains statically stable.

There is no absolute value of the maximum building height one can place on the platform. It always depends on the shape and dimensions of the platform and the building. In this case, for a hexagonal platform with sides of 60 m, the maximum acceptable building height would be 120 m (building with a base of 60 m by 25 m).

5 Platform interconnections

It is clear that a floating city can only be realised with modular floating structures. The platform is the base of the floating city and the floating community is realised by connecting all the modular floating platforms to each other. This way, the individual platforms will not move relative to each other, preventing collisions and/or platforms drifting away from the floating community. The total design of the floating platform is discussed in the previous chapter, now this chapter elaborates the possibilities to connect the platforms to each other. This chapter first discusses the different types of connections between the platforms and their functions and a suitable type of connector for the floating city concept is chosen at the end of this chapter. In short, the following paragraphs are being worked out in this chapter:

- *Problems and challenges of existing connections*
- *Criteria and requirements*
- *Connection types*
- *Summary and conclusion*

5.1 Problems and challenges of existing connections

The use of connections between floating structures nowadays is still quite limited and gives several problems and challenges concerning the construction and execution phases. Connecting floating structures on the water surface gives rise to the following problems:

- The lack of accessibility to the connectors that is located between the elements and/or below the water level.
- An uneven draught of the floating structures; this will result in connection elements not being in the same position. If these position inequalities are large, the draught should be adjusted by ballasting and trimming of the floating structures. However, small position inequalities will always remain.
- Large motions due to wave actions also make the execution difficult. The window of time to secure the connection is small.
- Collision of the platforms during execution.
- Strength and fatigue failures due to high sea load and load of the platforms self (deadweight).

The second and third mentioned problems can be solved with connections with a self-alignment function. The last two problems can be solved by using pre-stressing and/or using an elastic material in between the connected faces.

5.2 Criteria and requirements

Requirements the connector must or should fulfil are:

- Strength
- Rigidity
- Robustness
- Durability
- Easy execution
- Self-alignment
- Pre-stressing
- Detachable
- Amount of material/costs

5.2.1 Strength

Connections will introduce, transfer and distribute connection forces which it must withstand. The forces in the connection are caused by the deadweight of the platforms, variable load on the platforms, wind, current and wave loads. The connection must not fail under these loads and should keep the platforms connected to each other under any conditions.

5.2.2 Rigidity

Connections should restrict the undesired relative motions of the coupled platforms as explained in the beginning of this paragraph. The displacements and rotations are the degrees of freedom a platform has. One platform has 6 degrees of freedom:

Translations

- Surge; movement in x-direction
- Sway; movement in y-direction
- Heave; movement in z-direction

Rotations

- Roll; rotation around x-axis
- Pitch; rotation around y-axis
- Yaw; rotation around z-axis

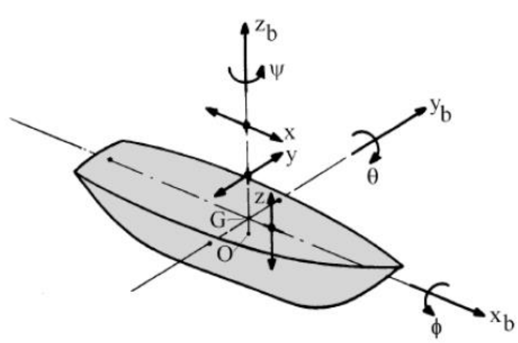


Figure 53: Degrees of freedom of a single floating object (CT3330 lecture notes)

For two adjacent floating platforms, the translations and rotations are defined as relative movements.

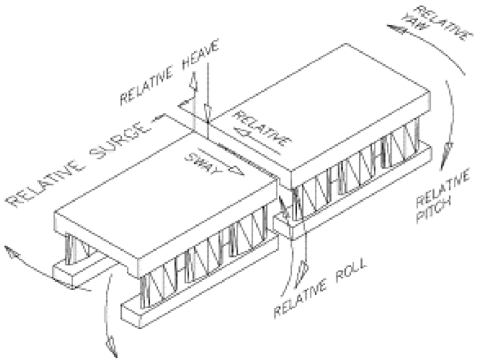


Figure 54: Relative movements between two floating structures (Koekoek, 2010)

All these relative movements lead to different failure modes of the structures on (infrastructure) or between (lines, pipes, connector) the two floating platforms. It is best to restrict all the possible relative movements, but this will lead to large transfer loads in the connections.

5.2.3 Robustness

Connections should not fail easily under the loads it must withstand. The connections should be safely designed to bear loads from the ULS condition (Ultimate Limit State).

5.2.4 Durability

Connectors should bear the connection forces and motions for a long life time. Fatigue and corrosion should be limited by applying the right material or protections and frequent inspection and maintenance is required.

5.2.5 Easy execution

The connectors should be easy to construct and executed. It is very important for an easy and convenient execution procedure when a large amount of platforms have to be connected to each other. This saves time and money. However, one of the problems of realizing such connections between floating platforms is that the execution is most of the time very difficult because of movements due to waves and the lack of accessibility of parts between the floating platforms and/or below the water surface. To fulfil this criteria, the connection should have a self-alignment function.

5.2.6 Self-alignment

The term self-alignment interprets that two floating platforms will get and stay in the right position while applying or executing a connection. Self-alignment is usually made possible by making use of shaped edges which will interlock to each other when the platforms are pressed together. The interlocking edges keep the platforms temporarily together while the connection is being executed.

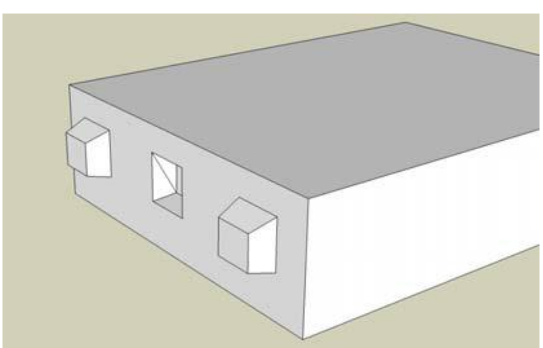


Figure 55: Ridges and cavities for self-alignment (Koekoek, 2010)

5.2.7 Pre-stressing

If necessary, it might be possible to apply connections with a pre-stressing function. Pre-stressing within the connections results in the floating platforms to be pressed together. This technique gives the following benefits for the connection:

- Preventing small relative movements (rigidity)
- Preventing/postponing fatigue problems
- Self-alignment.

By pre-stressing two platforms together, the relative movements can be prohibited and the connection is made more rigid. Pre-stressing can also work effectively against fatigue of the connections. By pre-stressing, certain regions of the connection will experience only tension stresses while opposite regions experience compression stresses only. This means that stress changes from tension to compression, which will lead to fatigue, will not occur. Lastly, pre-stressing also have slightly results for self-alignment. While pre-stressing the connection, the two floating platforms will be pulled together.

5.2.8 Detachable

The platforms should be connected and disconnected with comparable ease. The platforms sometimes need to be disconnected from each other for maintenance purposes or if the layout of the floating community is about to be changed.

5.2.9 Amount of material/costs

An optimum has to be found between the costs and good usability of a connector. The amount of the costs will mainly depend on which materials are used and the amount of the materials. When movable or mechanical elements or other systems are present in the connection, the costs will increase significantly. Thus the costs mainly depend on the simplicity of the connection. The more simple the connection, the less it will cost.

The requirements concerning the strength, rigidity and robustness are standard requirements for all connections to achieve their function. The requirement of durability and material/costs depends on the choice of material for the connection. The remaining requirements (easy execution, self-alignment, pre-stressing, detachable) are depending on the type of connection. With these requirements, the different types of connections are graded to come at the most suitable connection type for the floating city. Unlike in chapter 3, where a Multi-criteria evaluation is used to choose the best solution, there will be no MCE grading be applied here. This is because in fact all connections which are going to be discussed are possible, but it depends on the preference of the future client and the environment of the floating city.

5.3 Connection types

The problems and requirements concerning connectors discussed in the previous paragraph does not apply to all the connection types which are currently available. Each type has its own advantages and disadvantages and these are to be shortly elaborated in this paragraph and will lead to the most suitable connection type for the floating city concept. Detailed information about the connection types can be found in **Appendix 7: Connection types**.

5.3.1 Main types of connections

First, there are two main types of connections possible for floating structures:

- Connections which leaves space between two adjacent platforms
- Connections which does not leave space between two adjacent platforms

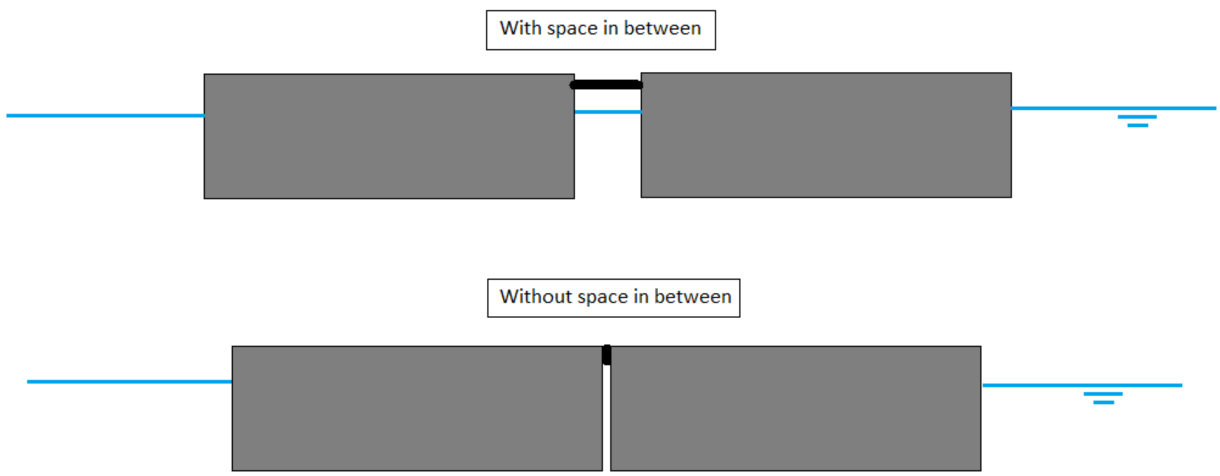


Figure 56: Two main types of connections

The connections which leaves space between two adjacent platforms are more like a bridge connection. The connections mostly do not restrict movements in the vertical direction (heave motions). When heave motions are not of great concern for the floating platforms, this type of connection is preferred as the heave motions of one platform will not affect the heave motions of the adjacent platform, so the two platforms can freely move in vertical direction completely independent from each other. This is because the connection does not transfer any vertical forces as the connection is in fact a beam with two hinges at each end. The main failure mechanism of the connection will be because of torsion, which is induced by relative roll and yaw motions.

Aside from the structural aspects, the use of connections with intermediate space between platforms also have aesthetic reasons. Like if each platform got a different owner, then the connection sort of acts like a border between the two territories. Due to the distance between the platforms, it is more difficult to move from one platform to the other. Specially designed infrastructure or bridges are always needed, which leads to larger investments for a large scale floating community. The infrastructure and bridges will be more expensive than regular structures because they have to withstand the internal forces due to the motions of the platforms too.

The connections without intermediate distance between the platforms are able to restrict movements in all directions, making these types of connections very rigid compared to connections with intermediate distance between the platforms. These connections are already designed to take on high internal loads and are therefore easier to be made rigid compared to the other type of connection. As a rigid connection is the most favourable for the floating city concept (all movements are undesired for maximum living comfort ability), it is chosen to only elaborate the connections without intermediate distance between the platforms.

5.3.2 Sub-types of connections

Depending on the desired movement restriction(s), there are different sub-types within the two main type connections. There are six degrees of freedoms for the connections to restrict, each of these degrees of freedom can be either rigid, compliant or fully released. This makes a total combination of 6 times 3 is 18 sub-types of connections possible. Although there are theoretically 18 possible combinations of movement restrictions, it is considered to always prevent the relative surge and sway motions. The relative surge and sway motions are the most basic motions and they need to be resisted to prevent the platforms from drifting away from each other. Note that the connections must prevent the relative surge and sway motions, thus the horizontal displacements of the platforms relative to each other. The moorings attached to the platforms are there to resist the overall surge and sway motions of the whole floating community as will be explained in chapter 6.

The most common sub-types of connections used in practice are the following:

- Fully flexible
- Vertical free (allowing relative heave)
- Hinged connection
- Fully rigid connection

When movements are restricted, large forces and moments are introduced into the platform and the connection. The choice/requirements of restricting certain degrees of freedom also greatly depends on the structural design of the connection and the platform.

5.3.2.1 Fully flexible connection

A fully flexible connection in fact does not restrict any major movements. This means that such connections have no structural value when certain movements are undesired. Undesired movements are usually prevented by the moorings when fully flexible connections are used. These connections are mostly used for transportation of cars and pedestrians (like a bridge) or ducts and cables etcetera. Fully flexible connections are common sub-types within the main category of connections with an intermediate distance between the platforms.

5.3.2.2 Vertical free connection (allowing relative heave)

By allowing relative heave motions between platforms, the vertical internal forces are greatly decreased in the connections and the platform. Relative heave motions are frequently occurring due to waves and/or unequal vertically imposed loads. When heave motions are not of great concern for the floating platforms, this type of connection is preferred as the heave motions of one platform will not affect the heave motions of the adjacent platform, so the two platforms can freely move in vertical direction completely independent from each other. Also because of the decrease in the internal vertical forces, the connection can be constructed lighter and simpler.

Again, vertical free connections are usually a good option when an intermediate distance between the platforms is preferred or allowed.

5.3.2.3 Hinged connection

When relative heave is undesirable but relative pitch is allowed, a hinged connection is used. A hinged connection has the structural property to only transfer shear and normal forces and no moments. A pure hinged connection allows relative pitch, but with more degrees of freedom it is also possible to allow certain roll and/or yaw movements to further decreasing the internal forces. An example of a hinged connection is the McDermott MOB connection system.

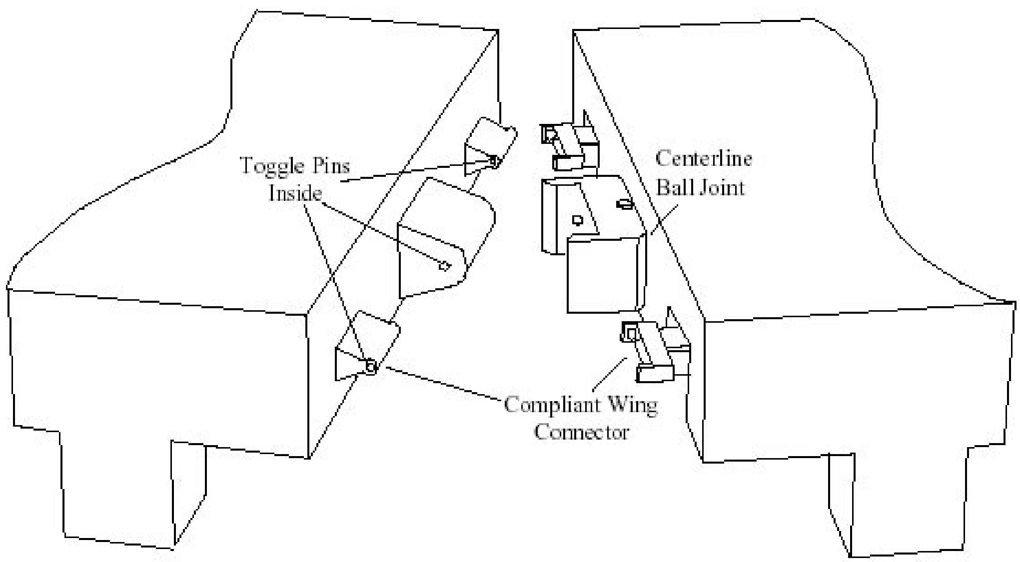


Figure 57: McDermott hinge connection (Koekoek, 2010)

Although the McDermott MOB connection is a hinged connection and is categorized as a connection without intermediate distance between the platforms, there is still a significant gap between the platforms because of the presence of the connection itself. This could be dangerous for the inhabitants on the floating community so this is seen as a disadvantage of this system. Another disadvantage would be that this connection uses quite expensive materials and labour as the connection must be specially fabricated.

Pros:

- Good structural strength
- Easy execution
- Detachable

Cons:

- No self-alignment possible
- High material costs

Deriving from the McDermott MOB connection system, a simpler hinged connection can be made with a row of horizontal or vertical steel hinges. When two or three rows of steel hinges are used, more relative motions will be restricted. A combination of horizontal and vertical steel hinges results in a fully rigid connection. Disadvantage of this system is that the steel hinges are quite prone to corrosion and need to be maintained regularly.

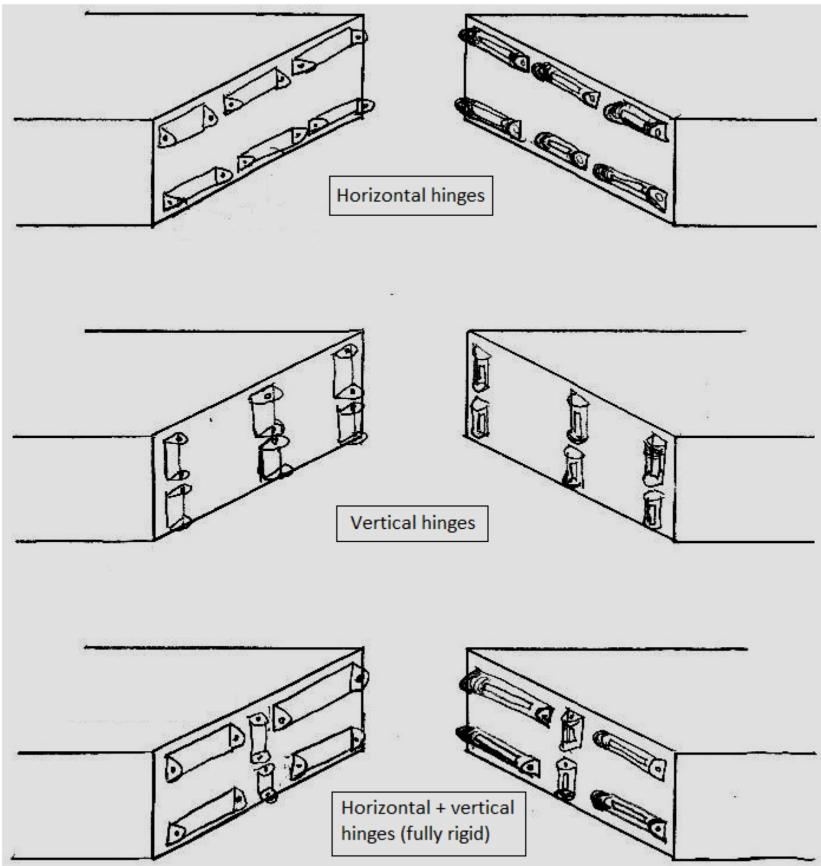


Figure 58: Steel hinged connection (Rooij, 2006)

Pros:

- Good structural strength
- Detachable

Cons:

- Not very durable, prone to corrosion
- Execution is quite difficult
- No self-alignment possible

5.3.2.4 *Fully rigid connection*

When all relative movements are undesired, a fully rigid connection is to be used. Rigid connections prevent relative motions, but they also contribute to the decrease of the overall movement of the platforms. This is because the coupled floating platforms can be approximated as a single platform when rigidly connections are used. The combined length of the platforms will more likely be larger than the wavelength. If the length of the structure is greater than the wavelength, the heave response becomes significant smaller.

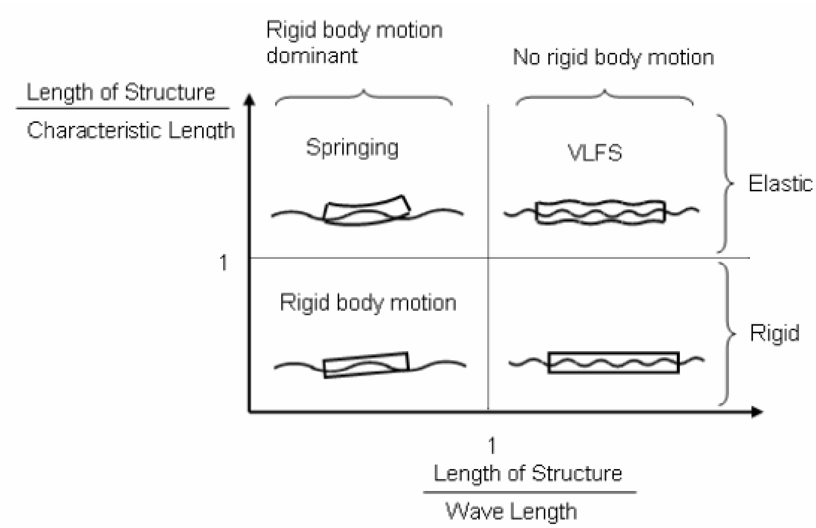


Figure 59: Structure length versus wave length (Parwani, 2013)

A rigid connection is possible and preferred as long as the internal forces stay within the limits of the strength of the connection and platforms. When the internal forces exceed the strength of the connection or platform, failure occurs and it is better to allow more movements to reduce the internal forces. In most cases, the moments in the connection will be the largest in rigid connections. So if possible, it is best to apply semi-hinged connections to reduce the internal moments. This is only applicable when the roll, pitch and yaw movements of the platforms are within comfortable range for the floating city.

There are numerous ways to make fully rigid connections and most of them are a combination of different methods and connection types. The most common rigid connections are:

- Puzzle type connection with bolt/pin
- Male-female connection
- Pre-stressed connection
- In-situ cast concrete connection

Puzzle type connection
These connections are different shaped edges of the platforms which fit on the opposite platform and then pinned together through a bolt/pin. The puzzle type connection is in fact a vertical or horizontal free connection, depending on the shapes on the edge of the platform. Vertical shapes give free movement in vertical direction while horizontal shapes give does not restrict sway movements. But with the adding of bolt/pins, the remaining degree of freedom can be restricted.

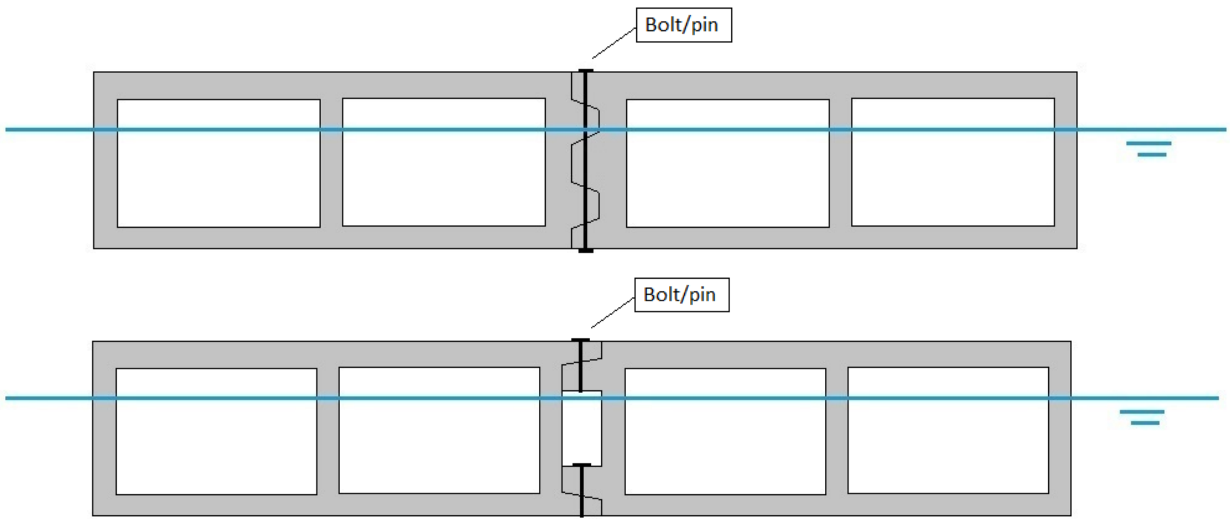


Figure 60: Puzzle type connection with bolt/pin (horizontal shapes)

Main advantage of the puzzle type connection is that is has great self-alignment and is fairly easy to be executed. Disadvantage is that the connection must be fully disconnected for maintenance purposes as the bolts/pins under the water level are quite prone to corrosion.

Pros:
- Very good structural strength
- Easy execution
- Self-alignment possible
- Detachable
- Low costs
- Works in combination with pre-stressing elements

Cons:
- Partly not very durable as pins/bolts are prone to corrosion

Male-female connection

The male-female connection is in fact also a puzzle type connection. The male-female connection is only much simpler because of less material used for the connection. But also because of the less material used, this connection is great to be used when the draught of the platform is small as this connection cannot be executed near the underside of the platform. This connection would be more like a hinged connection when the draught of the platform is large.

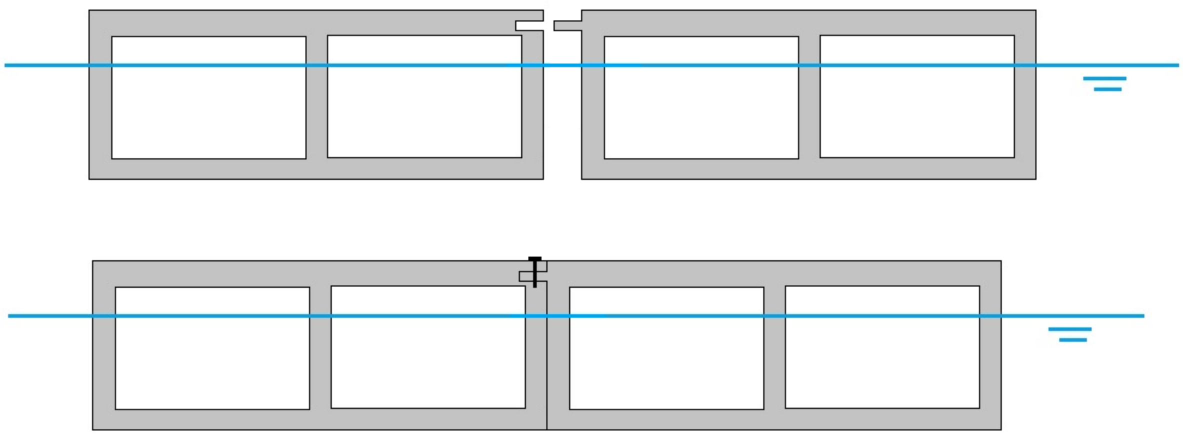


Figure 61: Male-female connection

Pros:

- Easy execution
- Self-alignment possible
- Detachable
- Low costs
- Works in combination with pre-stressing elements

Cons:

- Low structural strength

Pre-stressed connection

Floating platforms can be connected to each other by transiting cables or rods through the floating bodies and then tensioning the cables/rods. This way the cables/rods are pre-stressed and they exert a pre-stressing force on the structure. When the pre-stressing cables/rods are in the lower part of the floating body, the pre-stressing force will cause the platform to bend upwards. An alternative would be to pre-stress a cable/rod between the outer walls of the platforms only.

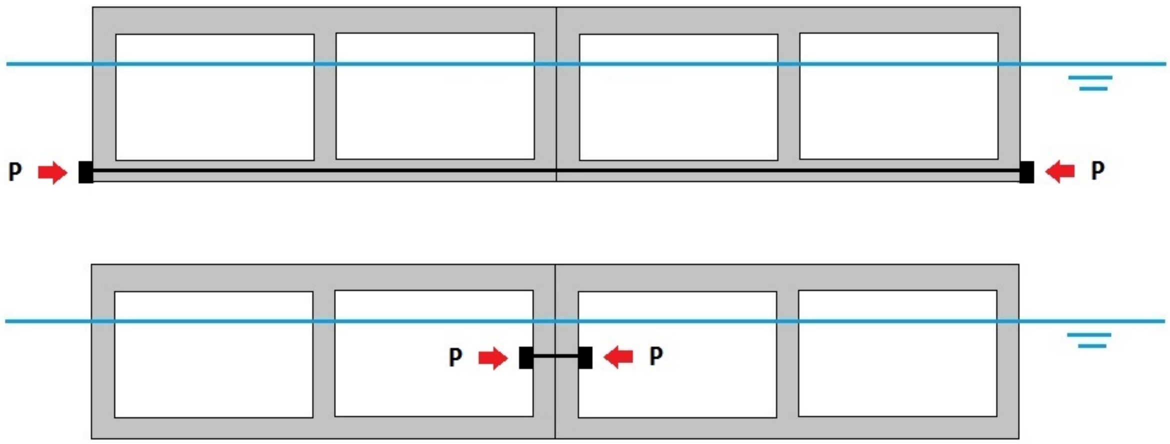


Figure 62: Pre-stressed connection

Main disadvantage of this kind of connection is the difficulty of execution since (salt) water may not enter the ducts where the cables/rods lie during pre-stressing, this will cause corrosion of the rods and affect the strength. Also, this type of connection is not able to be detached easily once applied.

Pros:

- Very good and adjustable structural strength
- Self-alignment possible

Cons:

- Difficult execution
- Not easy detachable

In-situ cast concrete connection
A very simple and straightforward method is to permanently connecting platforms to each other by casting concrete in between the platforms. The strength of the cast connection can be improved by reinforcement bars or even pre-stressing steel. The platforms should be temporarily hold together with other methods while the concrete is cast and be ready. Another problem would be the environment of the location of the floating city. Concrete needs a specific temperature and humidity during the whole process to achieve good quality concrete.

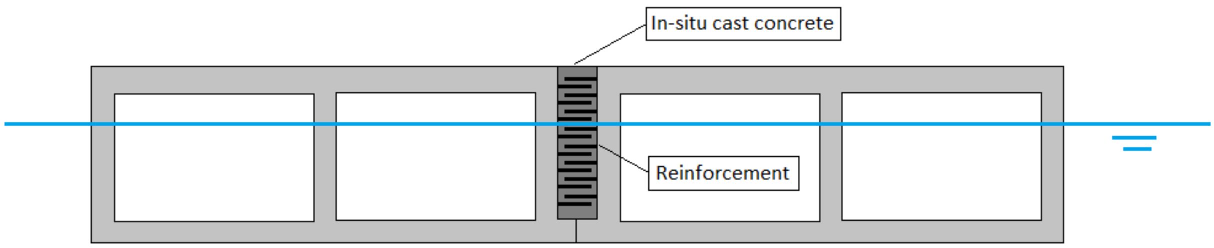


Figure 63: In-situ cast concrete connection

Pros:
- Very good structural strength
- Self-alignment possible
- Works in combination with pre-stressing elements

Cons:
- Difficult execution
- Not easy detachable

Other less common connection types are the pneumatic/hydraulic jacks, hooks, magnets and cables. These are in no way suitable for a big floating community and are not elaborated here, brief information about these connections are to be found in **Appendix 7: Connection types**.

5.4 **Suitable connection type for floating city**

The connections without intermediate distance between the platforms are able to restrict movements in all directions, making these types of connections very rigid compared to connections with intermediate distance between the platforms. A rigid connection is the most favourable for the floating city concept (all movements are undesired for maximum living comfort ability). However, a rigid connection is only possible and preferred as long as the internal forces stay within the limits of the strength of the connection and platforms. When the internal forces exceed the strength of the connection or platform, failure occurs and the options are to design a stronger connection or reducing the internal forces. In general, it is better to allow more movements to reduce the internal forces instead of making a stronger, and thus a more expensive, connection. In most cases, the moments in the connection will be the largest in rigid connections. So if possible, it is best to apply semi-hinged connections to reduce the internal moments. This is only applicable when the roll, pitch and yaw movements of the platforms are within comfortable range for the floating city.

When the requirement is that the connections should be detachable, only the puzzle type connection is the most suitable. When there is no requirement for the platforms to be detachable, then the best option should be by casting in-situ concrete in combination with a pre-stressed cable/rod. The floating city concept in this thesis has the requirement to be detachable, so it is chosen to apply the (horizontal) puzzle type connection with bolts/pins. Depending on the internal forces/moments, it will be quantified whether such a fully rigid connection is possible.

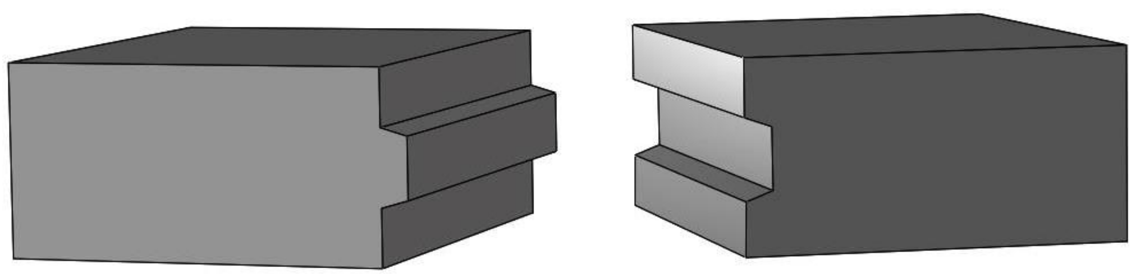


Figure 64: Continues teeth/studs puzzle-type connection

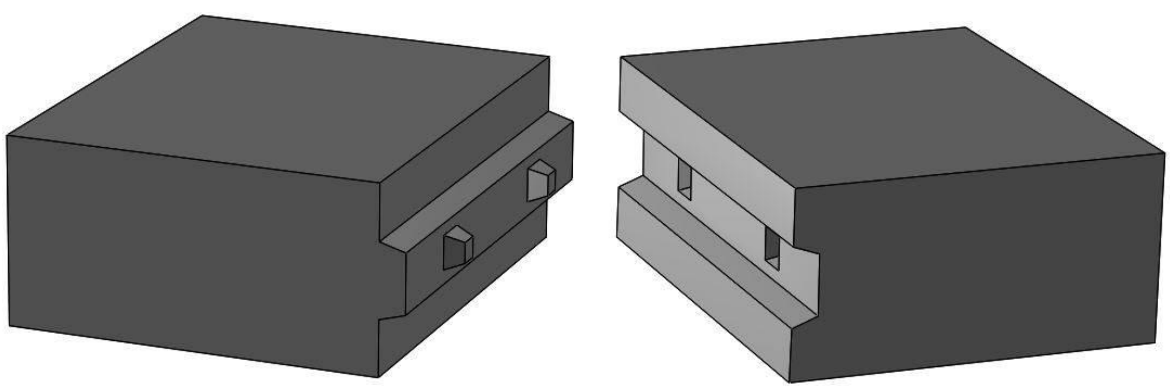


Figure 65: Continues teeth/studs puzzle-type connection with extra ridges and cavities for self-alignment

5.5 Summary and conclusion

An overview of the available connections for the floating city concept is shown below.

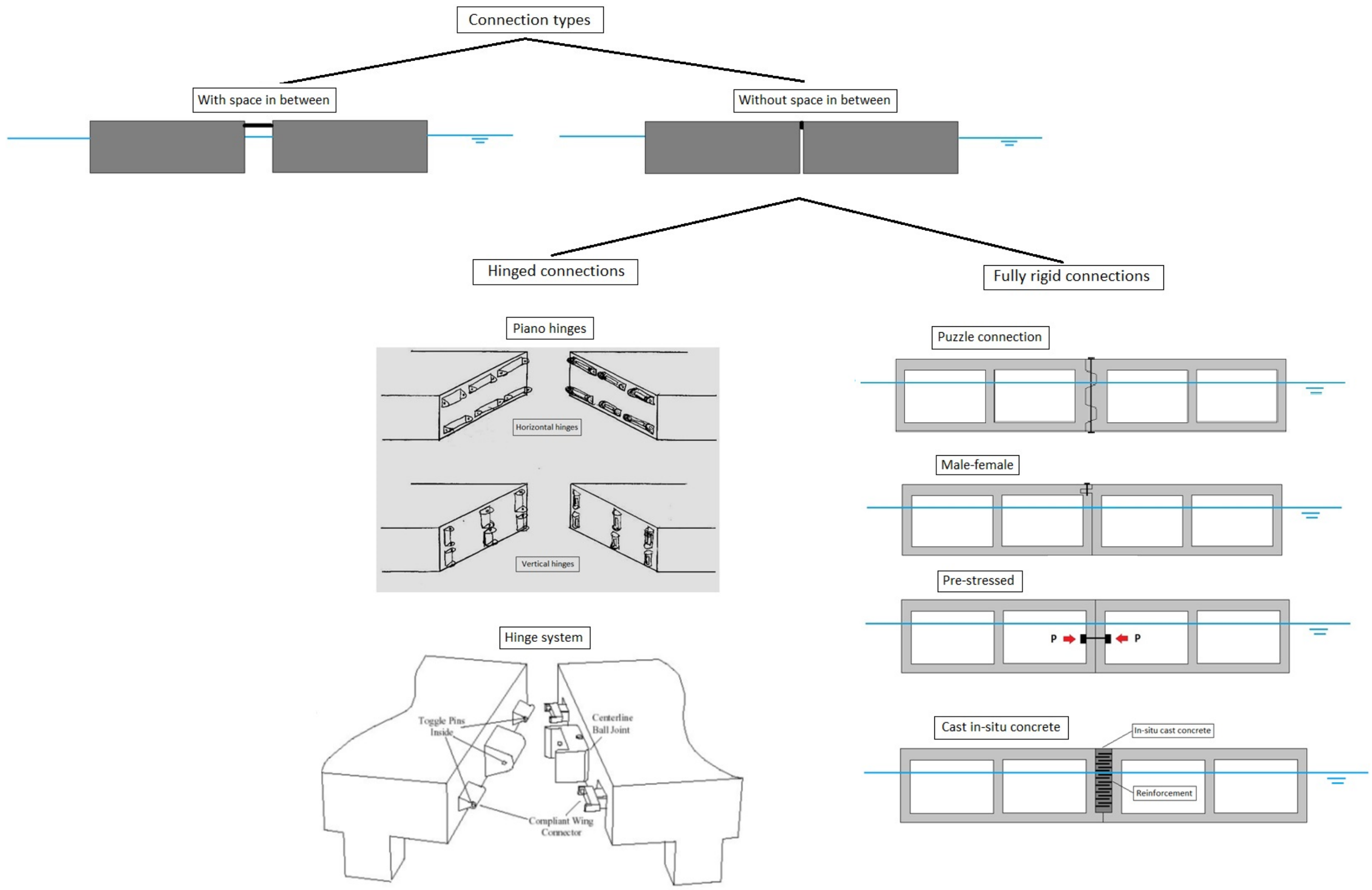


Figure 66: Overview of connections

The connections without intermediate distance between the platforms are able to restrict movements in all directions, making these types of connections very rigid compared to connections with intermediate distance between the platforms. A rigid connection is the most favourable for the floating city concept (all movements are undesired for maximum living comfort ability).

With the information provided in this chapter, a sub question of this thesis *'How are the platforms going to be connected to each other to form a floating city?'* can be answered.

When the requirement is that the connections should be detachable, only the puzzle type connection is the most suitable. These connections are different shaped edges of the platforms which fit on the opposite platform and then pinned together through a bolt/pin. When there is no requirement for the platforms to be detachable, then the best option should be by casting in-situ concrete in combination with a pre-stressed cable/rod. The floating city concept in this thesis has the requirement to be detachable, so it is chosen to apply the (horizontal) puzzle type connection with bolts/pins. Depending on the internal forces/moments, it will be quantified whether such a fully rigid connection is possible.

6 Mooring design

A mooring system is necessary to ensure that the floating structure is kept in position and prevented from drifting away under critical sea conditions and storms. A freely drifting floating structure may lead to damage to the surrounding facilities and infrastructures. It is also inconvenient to live on a constantly moving platform. This chapter will provide information about the different types of mooring systems and the requirements of the most suitable mooring system regarding the floating city will be elaborated. In short, the following paragraphs are being worked out in this chapter:

- *Mooring system types*
- *Mooring anchors*
- *Mooring requirements*
- *Summary and conclusion*

6.1 Mooring system types

Examples of known mooring systems for floating platforms are: the dolphin-frame guide system, the cable and chains system, the tension leg method and the pier/quay wall method (see Figure 9). As the floating city is situated in deep water (in this case 100 m) it is less convenient to use dolphin-frame guide systems or the pier/quay wall method as these types of moorings are big structures and thus require a lot more material for larger water depths. The cable/chain system or tension leg methods only use chains/cables with anchors and are easier to apply. Cable/chain moorings are especially easier and faster to apply when a lot of platforms need to be moored. The difference between the chain/cable and tension leg system is that the tension leg system is focussed on restricting the vertical movement and does not work too well for horizontal movements. The chain/cable system on the other hand can handle horizontal forces and displacements very well, while they perform less good when there is a lot of vertical movement. It is chosen to use the cable/chain system because this system can handle both horizontal and vertical displacements and forces.

The cable/chains system comes in many different types and shapes. The two types of cable/chain systems are the catenary mooring and the taut-leg mooring. The cable/chains of a catenary mooring type arrive horizontally at the seabed, which means that this type of mooring is only loaded by horizontal loads. Most of the restoring forces are generated by the weight of the mooring line. The taut-leg mooring on the other hand arrives at the seabed at an angle, so it is capable of resisting both horizontal and vertical loads. The restoring forces are generated by the elasticity of the mooring line.

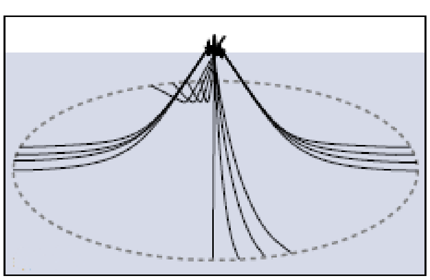


Figure 67: Catenary mooring system (Vryhof anchors, 2010)

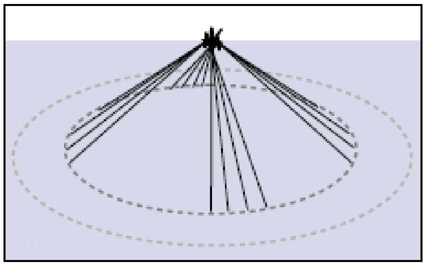


Figure 68: Taut-leg mooring system (Vryhof anchors, 2010)

These two types of cable/chains systems are further divided into three other shape styles, making a total of 6 different cable/chains systems available. The mooring system can be applied as a single point mooring, spread mooring or as a dynamic positioning system.

6.1.1 Single point/buoy mooring

Floating structures and vessels are secured by a single or multiple mooring lines. The mooring lines are all attached to one point of the floating structure or vessel. In most cases, the mooring lines are connected to a floating buoy and the floating structure/vessel is moored to the buoy. The floating structure is allowed to have a ranged movement; that is, the structure may swing around in order to align itself with prevailing wind, wave, and current conditions. This alignment tends to reduce the load on the mooring system. However, the mooring forces enter the structure at one point, which will have to endure a very large force. Because of the movability of the floating structure, a structure with single point mooring system requires a lot of space around the structure. Note that the catenary and taut-leg mooring systems in Figure 67 and Figure 68 are both single point mooring styles because all the mooring lines are gathered at one point of the floating structure.

Figure 69: Single point/buoy mooring [17]

6.1.2 Spread mooring

A spread mooring is the opposite of the single point mooring and its principle is to hold the floating structure/vessel in a relatively fixed position. Multiple mooring lines are spread around the floating structure and are attached on multiple positions instead on one single point. The structure/vessel cannot turn head into the prevailing wind, waves and current. As a result, a spread mooring can experience relatively high loads if wind, currents, or waves act at an angle to the mooring. The floating structure cannot move and rotate freely, but the mooring forces are distributed better over the structure. Smaller forces are easier to introduce into a structure.

[17] http://en.wikipedia.org/wiki/Single_buoy_mooring

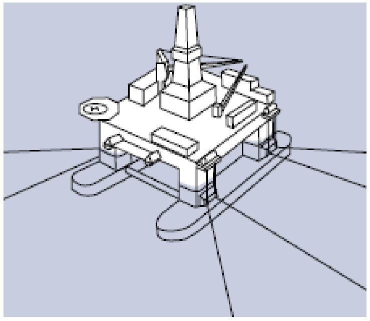


Figure 70: Spread mooring (Vryhof anchors, 2010)

6.1.3 Dynamic positioning system

A Dynamic Positioning System (DPS) has more or less the same principle as the Single Point Mooring. The main purpose is to relieve the structure of some of the loads by turning it head into the wind, waves and currents. Multiple mooring lines are used which come together at a turntable built into the floating structure/vessel. The turntable is controlled by a computer system which also controls the propellers and thrusters in case of moored vessels. The computer system adjusts the turning table and propellers and thrusters such that the mooring lines can take the loads well at the certain situation. Such a dynamic positioning system is thus preferred when the vessel is in boundary conditions which are extreme and frequently changing.

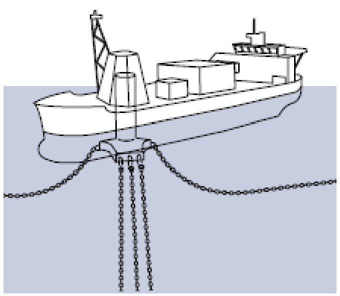


Figure 71: Dynamic positioning system (Vryhof anchors, 2010)

The taut-leg mooring system is chosen because this system handles both horizontal and vertical forces well. And on a significant scale, the taut-leg mooring system uses less mooring line per meter which reduces the costs a bit. And as the floating city is not permitted to displace during use, a spread mooring system is preferred.

6.2 **Mooring anchors**

To better handle the vertical displacements and forces in a cable/chain system, the anchorage on the seafloor is of great importance. There are several types of anchorage to be considered: the dead weight anchor, the drag embedment anchor, the pile and the suction anchor.

6.2.1 Dead weight anchor

The dead weight anchor is the most simple and straight forward anchor. The cable/chains are hold in place by a dead weight resting on the sea floor. The dead weight of the anchor itself will complement the vertical loads and the friction between the anchor and sea floor resists the horizontal loads. As the floating city has a very large dead weight and large loads working on it, the weight of this type of anchorage must be very large too. The anchors are mostly made of steel and concrete elements. The dead weight anchor can be used on either hard or soft soil sea beds.

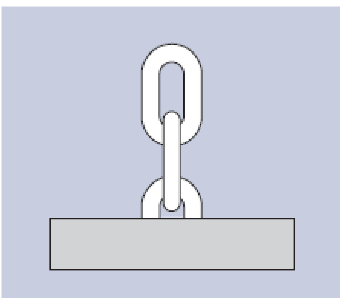


Figure 72: Dead weight anchor (Vryhof anchors, 2010)

6.2.2 Drag embedment anchor

The drag embedment anchor is specifically designed to withstand large horizontal forces and displacements. Its design is such that the anchor penetrates deep into the seabed (either partly or fully) such that the holding capacity is generated by the resistance of the soil in front of the anchor. It cannot handle vertical loads very well; because vertical displacements will pull the anchor out of the seabed (the soil resistance in vertical direction is weaker than in horizontal direction). The drag embedment anchor is usually applied on sea beds with soft soil.

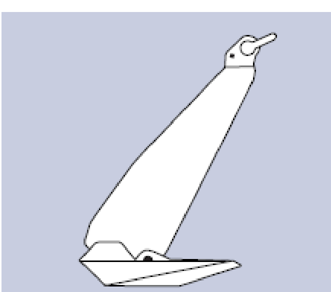


Figure 73: Drag embedment anchor (Vryhof anchors, 2010)

6.2.3 Pile anchorage

The pile anchorage is in fact a hollow steel pipe which is hammered or vibrated deep into the seabed. The holding capacity of the hollow steel pile comes from the friction of the soil along and in the pile shaft. The deeper the pile is installed into the seabed, the more loads it can handle. The pile anchorage is capable of resisting both horizontal and vertical forces. A disadvantage of this type of anchorage is that the anchorage is more or less permanent because the piles cannot be removed fast and easily. The pile properties depend on the condition of the soil of the seabed.

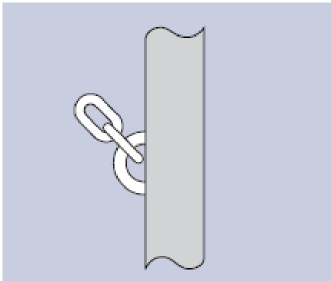


Figure 74: Pile anchorage (Vryhof anchors, 2010)

6.2.4 Suction anchor

Just like the pile anchor, the suction anchor is also a hollow steel pipe. The difference is that the suction anchor is forced into the seabed with a pump which is connected to the top of the pipe. The pump creates a pressure difference which will cause the pipe suck into the seabed when the pressure inside the pipe is lower than the pressure outside the pipe. The pump is removed after the installation of the pipe is done. Because of this ‘suction effect’, the pipe can be installed less deep compared to the normal pile anchor. Another difference is that the diameter of the pipe of the suction anchor is larger than the diameter of the normal pipe anchor. Just like the normal pile anchor, the holding capacity of the suction anchor is generated by the friction of the soil along the suction anchor and lateral soil resistance. The suction anchor is capable of withstanding both horizontal and vertical loads. The suction anchor works best if applied to soft seabed soil.

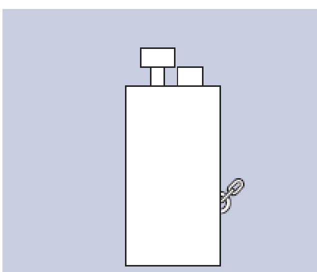


Figure 75: Suction anchor (Vryhof anchors, 2010)

6.2.5 Mooring anchor choice

The mooring lines transfer the load due to the displacements of the platform to the mooring anchors. Assume it is chosen to use dead weight anchors because the dead weight anchors are easy to install and replace. The chosen deadweight anchor must be of sufficient weight to resist the forces and displacement.

Except from vertical motions, the moorings should also bear horizontal motions. Waves exert a horizontal force on the platform, but these forces are more impact forces. Impact forces on a very large mass will not cause the mass to move very fast. Continues drift forces are what causes the platform to drift away and the moorings should prevent this. The largest horizontal force the moorings have to resist is the combination of a typhoon and a current load both exerting on the platform in the same direction. If for example a typhoon with wind speeds of 250 km/h strikes the floating city, the wind load on the high-rise building would then be:

$$Q_{wind} = \frac{1}{2} * 1.225 * \left(\frac{250}{3.6}\right)^2 * 0.7 * 60 = 124060\ N/m^2 \approx 124\ kN/m$$

$$F_{wind} = \frac{1}{2} * 124 * building\ height = \frac{1}{2} * 124 * 50 = 3100\ kN$$

If a current with speeds of 2.50 m/s is present, the current load on the platform would then be:
$Q_{current} = \frac{1}{2} * 1025 * 2.5^2 * 1.0 = 3203\ N/m^2 \approx 3.2\ kN/m^2$
$F_{current} = 3.2 * width * draught = 3.2 * 60 * 10.89 = 2091\ kN$

The explanation of the formulas to calculate these loads are explained in **Appendix 5: Load definition**.

$$F_{mooring,\ horizontal} = F_{current} + F_{wind} = 3100 + 2091 = 5191\ kN$$

The total of the horizontal forces acting on the anchor should be transferred to the subsoil. The friction force of the subsoil should resist the resulting total horizontal force. This friction force is determined by the weight of the anchor, multiplied by a friction coefficient f. In equation form:

$$F_{mooring,\ horizontal} = f * F_{anchor,\ vertical} \rightarrow F_{anchor,\ vertical} = \frac{F_{mooring,\ horizontal}}{f}$$

Assume that the anchor is placed on a soft sand bed (internal friction angle φ of sand is 38°), the friction coefficient f will then be $\tan(\varphi) = \tan(38) = 0.78$.

$$F_{anchor,\ vertical} = \frac{5191}{0.78} = 6644\ kN = 677291\ kg$$

Assume the deadweight anchor is made of steel which has a density of 7850 kg/m^3, the anchor would then have a volume of $\frac{677291}{7850} = 86\ m^3$. This is quite large and not very feasible to realise. In chapter 7 it is quantified that the vertical displacements of the floating platform are very small, this could mean that the drag embedment anchor is the most suitable anchor type for the floating city as it is designed to resist large horizontal loads and less vertical loads.

6.3 Mooring requirements

In short, a taut-leg spread mooring system is used in combination with a dead weight anchorage for the floating city. This is just a rough estimation of which mooring type is to be used. A detailed research is required to determine whether this type of mooring can withstand the loads from the floating city. Now the type of mooring is chosen for the floating city, the requirements regarding the mooring have to be stated.

6.3.1 Mooring line angle

The taut-leg mooring system arrives at the seabed under an angle; this angle determines how well the vertical and horizontal loads are transferred to the anchorage. Most mooring lines of taut-leg mooring systems have an angle between 30 - 45° with the seabed. When the mooring lines are under an angle of 45°, the horizontal and vertical loads are evenly transferred to the anchorage. For angles smaller than 45°, the anchorage will have to withstand larger horizontal forces than vertical forces. Also, less material is used for larger angles of the mooring lines with the seabed which leads to a significant cost reduction, i.e. the mooring lines are shorter when they make a larger angle with the seabed. It is unknown whether the horizontal or the vertical forces on the floating city are prevailing, so it is chosen to apply the mooring lines under an angle of 45° as a first estimation.

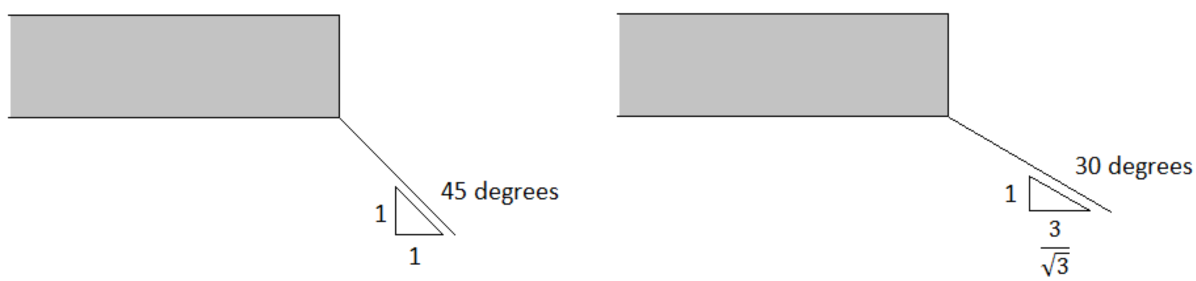


Figure 76: Decomposing into a horizontal and vertical force of the mooring line

6.3.2 Mooring line stiffness

The stiffness of the mooring line depends on the type of material that is used. Chains are usually used for catenary systems because chains have a large weight; the weight of the mooring line generates the restoring force of the catenary mooring system. Especially in large water depths, the weight of the mooring line will increase rapidly. So chains will not be used as mooring line material. Cables can be made of steel wires or synthetic material.

Compared to chains, steel wire ropes have a lower deadweight for the same breaking load and a higher elasticity. The high strength to weight ratio makes the ropes easy to handle and result in lower vertical forces on the floating structure. There are many different compositions of steel wired ropes. The two most common compositions are the multiple strands (generally 6 or 8 strands, a strand consists of steel wires) and the spiral strand. In multiple strand wires, the strands are wound around the core in the same direction. In a spiral strand, the wires are wound around the core in different directions. Spiral strand ropes are more expensive than multiple strand ropes and have a smaller elasticity value. But spiral strand ropes have also a higher strength and fatigue resistance and are less susceptible to corrosion compared to multiple strand ropes. Another benefit of spiral strand ropes is that the wires do not generate torsion forces as loads increase, as this is the case with multiple strand ropes. Because of this aspect, spiral strand ropes are usually preferred for permanent or long term mooring. The cables can be covered with a (plastic) sheath to prevent corrosion of the strands. To further increase the resistance to corrosion, zinc fillers can be wound between the steel strands. Zinc fillers are strands made of zinc which are smaller in diameter than the steel strands.

Figure 77: Multiple strand rope (left) and spiral strand rope (right) [18]

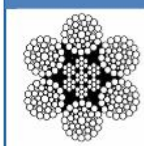
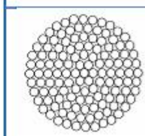
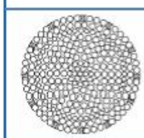
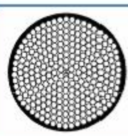
	Wire rope construction	Life expectancy
	Galvanised 6- strand.	6-8 years
	Galvanised unjacketed spiral strand.	10-12 years
	Galvanised unjacketed spiral strand with zinc filler wires.	15-17 years
	Galvanised jacketed spiral strand.	20-25 years
-	Galvanised jacketed spiral strand with zinc filler wires.	30-35 years

Figure 78: Different steel wire rope compositions [19]

As can be seen in Figure 78, spiral strand ropes have a longer life expectancy because of the higher corrosion resistance and the fact that spiral strand ropes do not generate torsion forces which lead to a higher chance of failure of the rope.

[18] http://coolarcticmoorings.weebly.com/types-of-mooring-lines.html
[19] http://www.v-gurp.nl/offshore/line-types.html

Table 14 and Table 15 show the material properties of spiral strand ropes and multiple (six) strand ropes. When comparing the Minimum Breaking Load (MBL) of these two rope types, it can be seen that the spiral strand rope can take a lot more load than the multiple strand rope. But maybe this is also because this table shows the property of a six strand rope, the MBL of an eight strand rope could be in the same range as the spiral strand rope. However, a spiral strand rope does have higher fatigue and corrosion resistances and no torsion forces are generated in the spiral strand rope compared to multiple strand ropes. So between the choice of spiral strand ropes and multiple strands ropes, it is preferred to apply spiral strand ropes as mooring lines for the floating city.

Properties of spiral stand wire rope

Nominal Diameter mm (inch)	MBL kN	Axial Stiffness MN	Nominal Weight in kg/m		Submerged nominal weight kg/m	Nominal Steel Area mm^2	Sheathing Thickness mm
			Unsheathed	Sheathed			
76 (3)	5647	557	28.4	30.4	23.8	3377	8
82 (3.25)	6550	627	33.0	35.1	27.5	3917	8
90 (3.5)	7938	760	39.9	42.9	33.4	4747	10
95.5 (3.75)	8930	855	44.9	48.1	37.5	5341	10
102 (4)	10266	982	51.6	55.3	43.1	6139	11
108 (4.25)	11427	1093	57.5	61.3	48.0	6834	11
114 (4.5)	12775	1222	64.2	68.3	53.6	7640	11
121.5 (4.75)	14362	1353	72.2	76.5	59.7	8589	11
127 (5)	15722	1481	79.1	83.6	66.0	9403	11
133 (5.25)	17171	1599	86.8	91.5	72.4	10314	11
141 (5.5)	19180	1799	97.5	102.4	81.5	11609	11
146.5 (5.75)	20469	1940	105.1	110.2	87.7	12515	11
153 (6)	22070	2110	114.5	119.7	95.5	13616	11

Table 14: Properties of spiral strand rope (Vryhof anchors, 2010)

Properties of six strand wire rope

Diameter mm (inch)	MBL kN	Axial Stiffness MN	Rope weight kg/m	Submerged rope weight kg/m	Torque Factor Nm/kN
64 2.5	3360	189.4	17.3	15.3	4.7
71 2.75	3990	233.0	20.8	18.3	5.2
77 3	4767	278.8	25.7	22.7	5.8
83 3.25	5399	319.7	29.5	26.0	6.3
89 3.50	6414	415.2	35.0	30.9	6.9
96 3.75	6965	483.8	40.5	35.7	7.5
102 4	7799	573.5	44.5	39.3	8.1
108 4.25	8240	642.1	49.8	43.9	8.6
114 4.50	9172	707.0	55.3	48.8	9.1
121 4.75	10055	775.7	60.6	53.5	9.7
127 5	11134	866.6	67.7	59.8	10.2
133 5.25	11728	912.9	73.8	65.5	10.6
140 5.50	12925	1006.1	80.9	71.7	11.2

Note: MBL based on 10 years design life.
Torque factor presented in the last column is an approximate value at 20% applied load.

Table 15: Properties of multiple (six) strands rope (Vryhof anchors, 2010)

Except for steel wires, mooring lines can also be made of synthetic fibres. The properties of synthetic fibres like the weight, strength, elongation, fatigue life, abrasion etc. can all be influenced relatively easily. It depends on the construction of the fibre rope to determine its behaviour. A disadvantage of synthetic fibre ropes is the abrasive behaviour of the material. Due to a relative sensitivity to abrasion, it is important to handle the synthetic fibre ropes with care. Also, the long-term behaviour and application of this material is mostly unknown because the development of these ropes is quite new. But the characteristics of synthetic ropes can be adjusted for different situations and boundary conditions. For example, synthetic fibre ropes are usually prone to creep. Due to tension, the mooring line will elongate during its life time which leads to permanent deformation. However, compositions of synthetic fibres like aramid fibres and gel-spun polyethylene have improved creep properties. Thus each disadvantage of synthetic fibre ropes can be compensated by using different compositions of synthetic material to alter the characteristics of the mooring line. Table 16 shows the properties of a polyester mooring line; this is the most common used synthetic fibre for mooring lines. Note that these ropes are quite large in diameter to attain the same strength as steel wires. Synthetic materials are also far more expensive compared to steel wires.

Polyester mooring line: strength table

Diameter mm	MBL k/N	Total weight kg/m		Submerged weight kg/m		Stiffness kN		
		@2% MBL	@20% MBL	@2% MBL	@20% MBL	EA[1]	EA[2]	EA[3]
113	3723	8.8	8.2	2.1	1.9	7.19e+04	8.43e+04	1.10e+04
137	5754	12.9	12.0	3.1	2.9	1.18e+05	1.38e+05	1.80e+05
154	7446	16.2	15.1	3.9	3.6	1.57e+05	1.84e+05	2.40e+05
169	9138	19.5	18.2	4.7	4.4	1.96e+05	2.30e+05	2.99e+05
183	10830	22.8	21.2	5.5	5.1	2.35e+05	2.76e+05	3.59e+05
195	12522	26.0	24.2	6.2	5.8	2.74e+05	2.22e+05	4.19e+05
207	14215	29.2	27.2	7.0	6.5	3.14e+05	3.68e+05	4.79e+05
227	17261	35.0	32.6	8.4	7.8	3.53e+05	4.14e+05	5.39e+05
245	20307	40.7	37.9	9.7	9.1	3.27e+05	3.83e+05	4.99e+05

Note : Minimum Breaking Load (MBL) in spliced condition.
Weights are presented for a rope loaded to 2% and 20% of MBL
[1] cycling between 10 - 30 % MBL
[2] cycling between 20 - 30 % MBL
[3] cycling between 40 - 50 % MBL

Table 16: Properties of synthetic rope (Vryhof anchors, 2010)

It is chosen to use spiral strand ropes over synthetic fibre ropes because the synthetic fibre ropes are too expensive if they have to be altered for long term usage (synthetic fibre ropes are prone to creep, a solution is to use the more expensive aramid fibre). And comparing Table 14 with Table 16, the spiral strand rope can handle more loads before breaking compared to the polyester rope.

The diameter of the mooring line depends on the amount of load that is to be transferred to the moorings. For a first estimation, a diameter of 153 mm is chosen because this diameter contributes to the highest Minimum Breaking Load (22070 kN). The stiffness of this rope is then 2110 MN.

The mooring line has a weight of 95.5 kg/m. As the water depth is 100 m deep and the mooring line makes an angle of 45° with the sea bed, the length of one mooring line would be $\sqrt{100^2 + 100^2} = 141.42\ m$. This contributes to a weight of $141.42 * 95.5 = 13506\ kg/mooring\ line$, which is 135 kN/mooring line. The deadweight of one floating platform is in the range of 800000 kN, so the weight of the mooring line is negligible.

6.3.3 Mooring line placement

In the offshore engineering, most floating platforms/vessels are moored with 12 mooring lines if the spread mooring system is applied, see Figure 79. But this applies to only one floating platform/vessel. It would require too much mooring lines if each single platform in the floating city has 12 mooring lines. That means if all 60 platforms requires 12 mooring lines, the whole floating city (for 15.000 inhabitants) has $60 * 12 = 720$ mooring lines. The underside of the floating city would be a jungle of mooring lines.

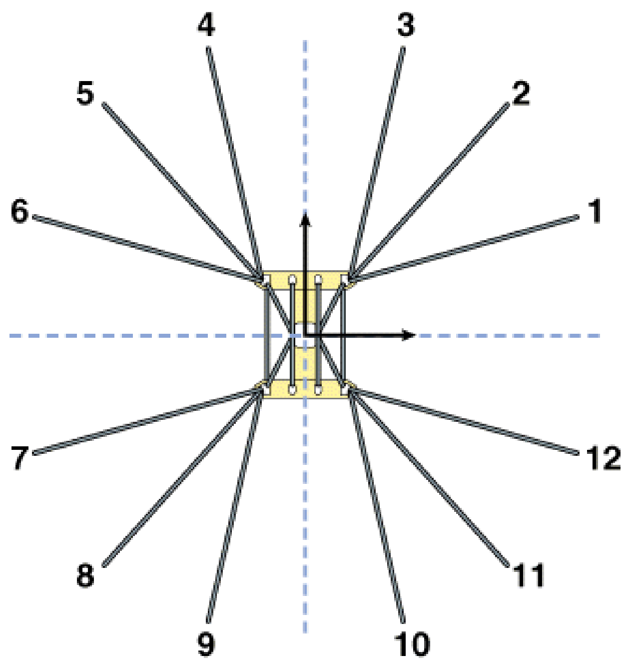


Figure 79: Number of moorings in the taut-leg mooring system [20]

As the mooring lines of one platform also have effect for the adjacent platforms, it can be opted to apply less mooring lines per platform. The 12 mooring lines that are applied to one platform in the offshore engineering can likewise be applied to a set of coupled platforms. The difference is that a set of coupled platforms are larger in dimension compared to a single floating platform/vessel in the offshore engineering, so there are more mooring lines needed to withstand the larger loads and displacements. An example of how the mooring lines can be applied in the case of the model of coupled platforms in this thesis is shown in Figure 80. The orange dotted lines indicate the directions which the mooring lines resist the loads and displacements from. Each set has 3 mooring lines which are spread 45° apart from each other. This way each direction has 6 mooring lines to resist the loads and displacements from that certain direction. This is a first estimation of how the mooring lines can be placed. The number of mooring lines and their placements can change depending on the governing loads acting on the floating city.

[20] http://www.offshore-mag.com/articles/print/volume-58/issue-10/news/production/mooring-with-synthetic-fibers-possible-in-all-water-depths.html

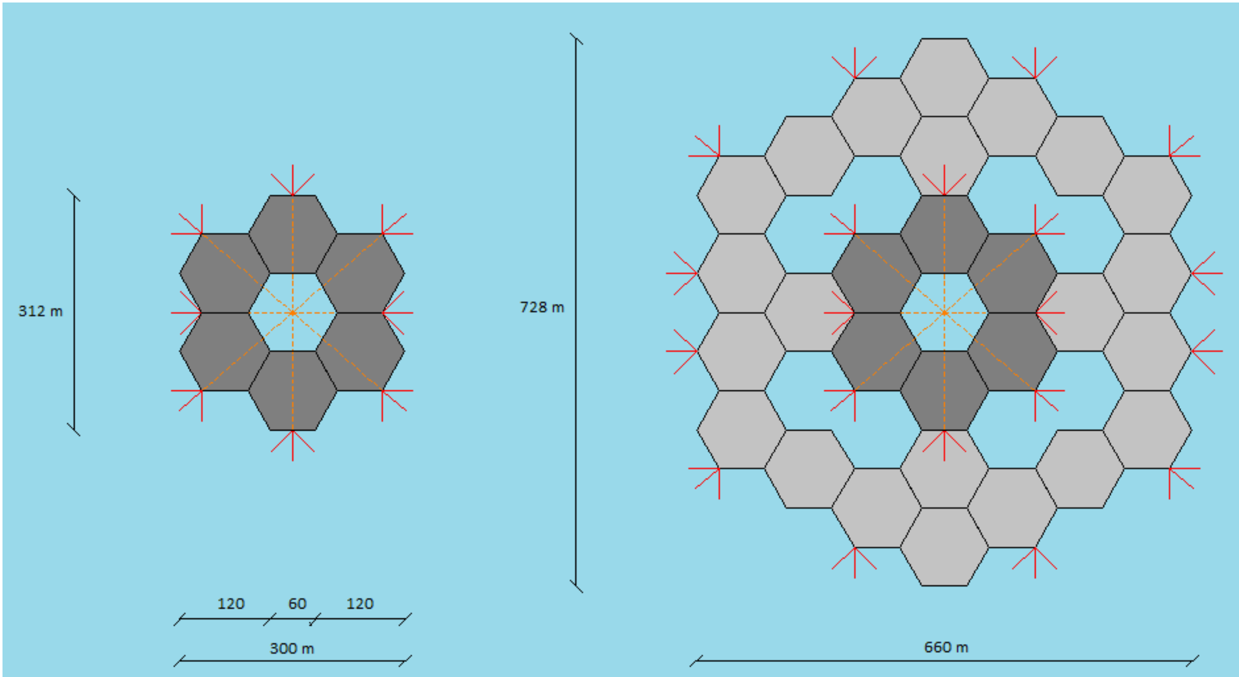


Figure 80: Example of the placing of mooring lines (red lines)

The required amount and positioning of mooring lines will be quantified in chapter 7.

6.4 Summary and conclusion

The mooring lines are to hold the platform in a relatively fixed position. Multiple mooring lines are spread around the floating structure and are attached on multiple positions. The structure/vessel cannot turn head into the prevailing wind, waves and current. This type of positioning of the moorings is called spread mooring. Most mooring lines of taut-leg mooring systems have an angle between 30 - 45° with the seabed. When the mooring lines are under an angle of 45°, the horizontal and vertical loads are evenly transferred to the anchorage. For angles smaller than 45°, the anchorage will have to withstand larger horizontal forces than vertical forces. It is chosen to apply the mooring lines under an angle of 45° as a first estimation. The required amount and positioning of mooring lines will be quantified in chapter 7.

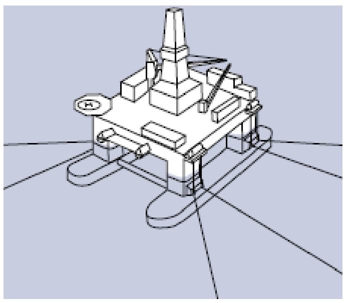


Figure 81: Taut-leg mooring system with spread mooring (Vryhof anchors, 2010)

The mooring lines are made of spiral strand ropes because these steel ropes have a lower deadweight for the same breaking load and a higher elasticity compared to other materials. The high strength to weight ratio makes the ropes easy to handle and result in lower vertical forces on the floating structure. For a first estimation, a diameter of 153 mm is chosen because this diameter contributes to the highest Minimum Breaking Load (22.070 kN). The stiffness of this rope is then 2110 MN.

Regarding the mooring anchor, it is chosen to use drag embedment anchors because it resists the large occurring horizontal loads very well, while it is not good at handling vertical loads. But this is of no concern as the vertical displacements are very small.

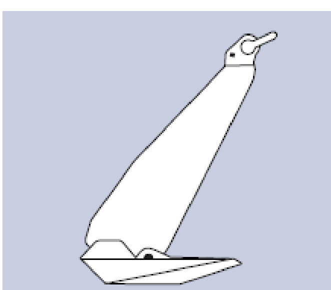


Figure 82: Drag embedment anchor (Vryhof anchors, 2010)

The sub question *'How is the floating city to be moored to stay at one location?'* can be answered with the following characteristics of the chosen mooring system:

- Taut-leg cable/chain system with spread positioning of moorings
- Mooring lines under angle of 45°
- Spiral strand ropes
- Drag embedment anchor

7 Structural dynamics analysis

In chapter 4, the design of the platform is elaborated. Chapter 0 discussed the choice of a suitable connection type and in chapter 6 a mooring system for the floating city is chosen. These three elements (platform, connection and moorings) have to work with each other to realise the basics of a floating city. The platform, connection and moorings have a certain dynamic behaviour when a dynamic force/excitation is exerted on these elements. For example, earthquakes gives the moorings a dynamic excitation which will affect the movements of the platforms. Or wind/wave loads which are exerted on the platforms, making the moorings and connections bear the forces of the moving platforms. In this thesis, the latter dynamic situation with waves will be elaborated. A floating city is always loaded by waves which makes it the most basic dynamic problem. Earthquakes are important too when the floating city is located near an earthquake prone region, however, this is rather situational for each floating city design and will not be elaborated in this thesis. The approach to determine the dynamic behaviour of the platforms due to waves is the same as the approach to determine the dynamic behaviour of the platforms due to earthquake excitations. So the analysis done in this thesis is applicable to future floating city designs which are near earthquake prone regions.

Before the dynamic analysis can be done, several mechanics concerning the dynamic analysis are explained first which are the added water mass, damping and frequency comfort level. The dynamic analysis is divided into three parts for a better understanding of the process. The first approach is to look at a single platform loaded by wave loads, referred to as a 1 mass-spring system. This step is necessary to easily understand the second approach concerning coupled platforms, referred to as a 2 mass-spring system. And eventually, for a complete floating community with multiple platforms a multiple mass-spring system is elaborated. A final research about the influences of the different parameters used in the 2 mass-spring system completes this chapter. In short, the following paragraphs are being worked out in this chapter:

- *Input and output data for the structural dynamic analysis*
- *1 mass-spring system*
- *2 mass-spring system*
- *Multiple mass-spring system*
- *Different scenarios*
- *Summary and conclusion*

7.1 Input and output data for the structural dynamic analysis

In general, a structural dynamics analysis is done to find out the behaviour of a physical structure when loaded by a (dynamic) force. The physical structure is mostly described as an object with only a mass. This mass can have certain displacements, velocities and accelerations (frequencies) which are the behaviour of the mass (physical structure). The behaviour of the mass is not only affected by the type and magnitude of the force acting on it, but also damping and reaction forces play a role. Damping and reaction forces occur because of interaction with other structures or the base where the mass is placed on. In short, a dynamic analysis is about the input of a certain mass, damping and reaction forces with displacements, velocities and accelerations (frequencies) as output. This section will elaborate these in and outputs to give a better understanding of the dynamic analysis.

7.1.1 Considered scenario for the dynamic analysis

The floating platform, interconnection and moorings have to work with each other to realise the basics of a floating city. The platform, interconnection and moorings have a certain dynamic behaviour when a dynamic force/excitation is exerted on these elements. Figure 83 on the next page illustrates the platform and its elements loaded by a dynamic force (waves).

Connection interpretation

In section 5.4 it is explained that a rigid connection in the form of a puzzle-type connection is the best type of connection for the floating community at the moment. This connection is also shown in Figure 83. However, for the dynamic analysis it is opted to apply a hinged connection. This is because a rigid connection in the dynamic analysis will result in no relative motions between the platforms. The relative motions between the platforms are important to calculate the forces in the connection. In reality, the rigid connection will indeed prevent relative motions between the platforms. Also, two platforms rigidly connected to each other in the dynamic analysis will have the same results as one platform with very large dimension.

Load case

Two load cases were presented in section 4.3, a load case with a high-rise building and a load case with low-rise buildings. The floating platform remains statically very stable in both load cases. The draught of the platform with the low-rise building is slightly smaller compared to the draught of the platform with the high-rise building. So it is actually preferred to use low-rise buildings for the floating community. However, the difference in the draught is significant small and high-rise buildings are an interesting option for the floating community to accommodate many inhabitants. So it is opted to use the load case with the high-rise building as the governing load case for the dynamic analysis.

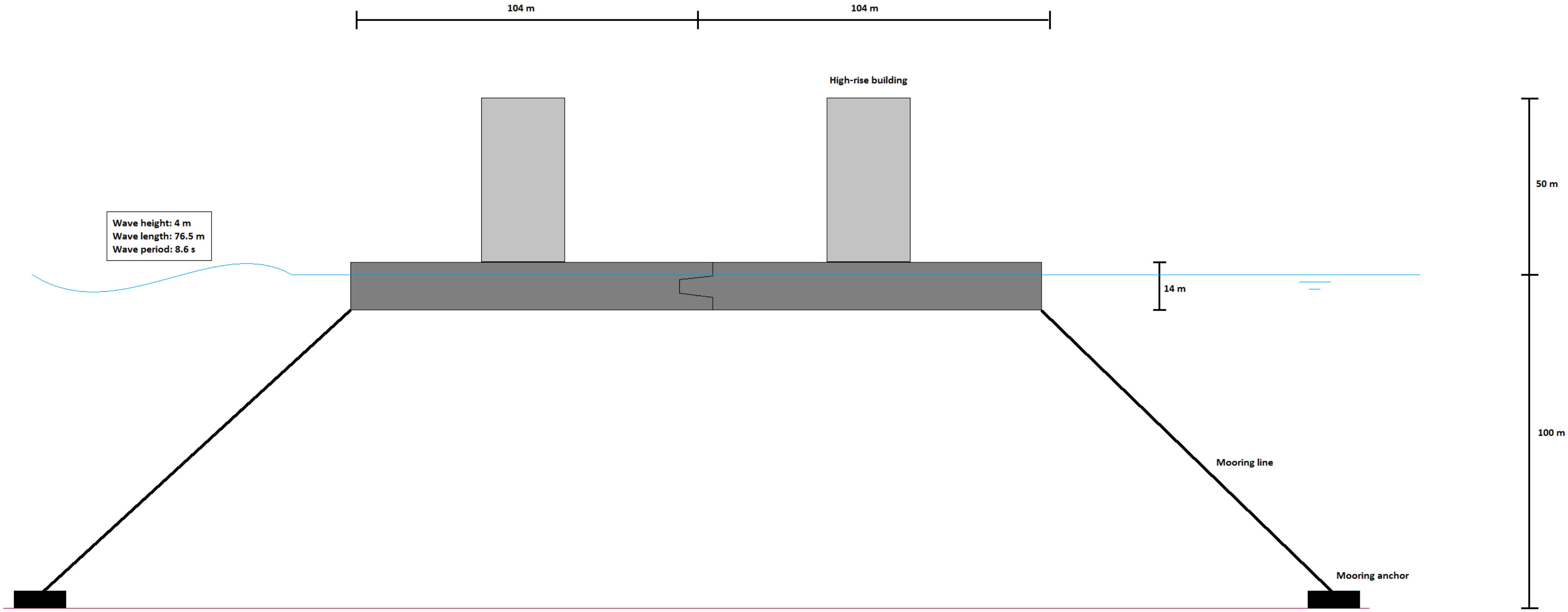


Figure 83: Situation sketch for dynamic analysis

7.1.2 Added water mass

When a structure is moving in water, the surrounding water will be displaced too because of these movements. The displaced volume of water around the structure has a certain inertia which affects the floating structure. This inertia due to the displaced water is referred as added mass or virtual mass. The value of the added mass is dependent on the motion direction, oscillation frequency and the geometry of the structure, making it quite complex to determine the value of the added mass. A rough estimation of the added mass can be treated as if an additional mass of fluid is trapped by the structure, see Figure 84.

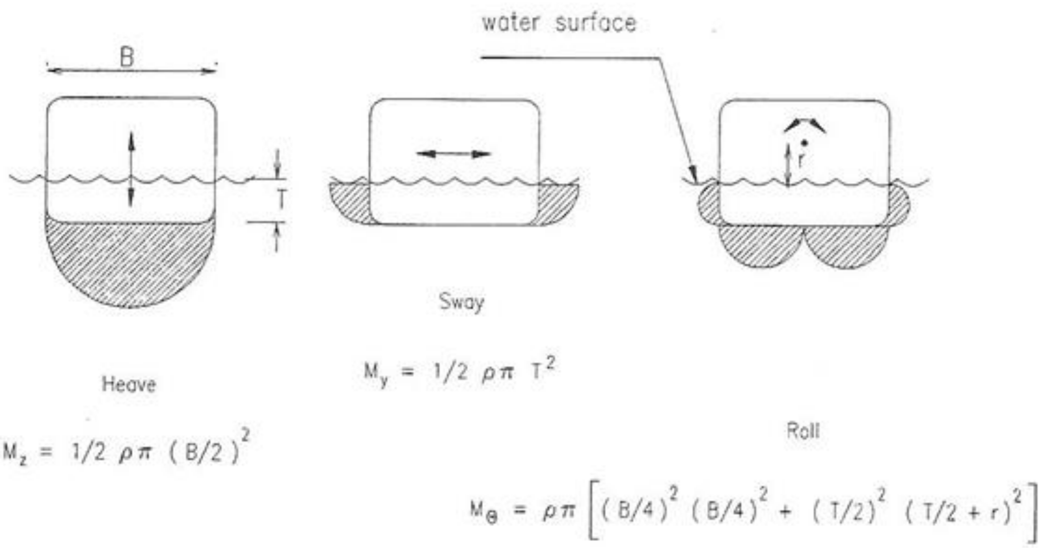


Figure 84: Estimation of added mass (Floating Structures: a guide for design and analysis, 1998)

Using the rough estimation formulas provided in Figure 84, the added mass of the floating platform can be calculated:

$$M_z = \frac{1}{2}\rho\pi\left(\frac{104}{2}\right)^2 = 4.35 * 10^6 kg/m \ \rightarrow \ M_z = 4.35 * 10^6 * 60 = 2.61 * 10^8\ kg$$
$$M_y = \frac{1}{2}\rho\pi * 11^2 = 1.95 * 10^5 kg/m \ \rightarrow \ M_y = 1.95 * 10^5 * 60 = 1.17 * 10^7\ kg$$
$$M_\theta = \rho\pi * \left(\left(\frac{104}{4}\right)^2 * \left(\frac{104}{4}\right)^2 + \left(\frac{11}{2}\right)^2 * \left(\frac{11}{2} + 4\right)^2\right) = 1.48 * 10^9 kgm^2/m \ \rightarrow$$
$$M_\theta = 1.48 * 10^9 * 60 = 8.88 * 10^{10}\ kgm^2\ (60\ is\ the\ length\ of\ a\ side\ of\ the\ platform)$$

For a 3 degree of freedom mass-spring system, the mass matrix of the platform is as following:

$$M = \begin{bmatrix} M_{platform} + M_{building} & 0 & 0 \\ 0 & M_{platform} + M_{building} & 0 \\ 0 & 0 & J \end{bmatrix}$$

And the mass matrix of the added mass is:

$$M_{added} = \begin{bmatrix} M_z & 0 & -M_z y \\ 0 & M_y & M_y z \\ -M_z y & M_y z & M_\theta \end{bmatrix}$$

In a mass matrix, the diagonal values are the mass and mass moment of inertia of the initial structures. The other values are the other masses with respect to the centre of gravity of the initial structure. Z and y indicate the coordinates of the masses with respect to the centre of gravity of the structure. However, these are neglected because they are very small compared to the values of the added mass, see Figure 85. The y coordinate concerning M_z is equal to 0 because the centre of mass of M_z is in the same vertical axis as the centre of gravity of $M_{platform}$. The z coordinate concerning M_y is very small because of the large draught and the large construction height of the platform.

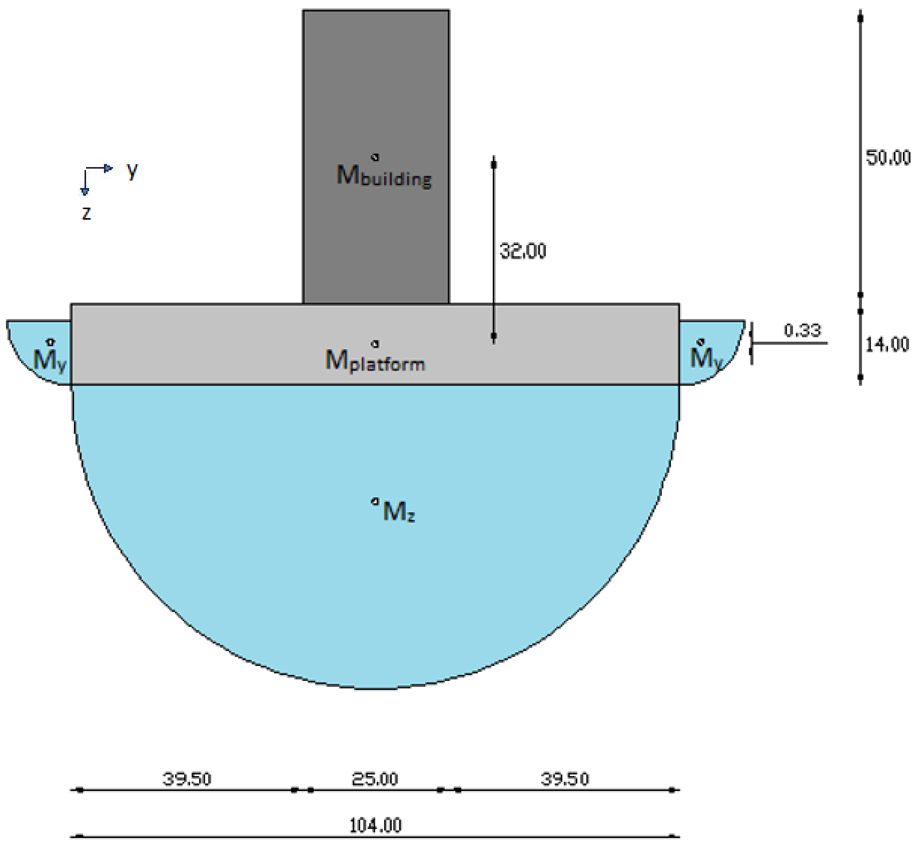


Figure 85: Visualization of added mass (dimensions in m)

The mass matrix of the added mass and the original mass matrix of the platform can be added together to form a final mass matrix:

$$M = \begin{bmatrix} M_{platform} + M_{building} + M_z & 0 & 0 \\ 0 & M_{platform} + M_{building} + M_y & M_{building}z \\ 0 & M_{building}z & J + M_\theta \end{bmatrix}$$

In the mass matrix, M stands for the different masses and J is the mass moment of inertia. All the other parameters in the matrix are known except for the mass moment of inertia J. The mass moment of inertia for a rectangular block can be calculated as follows:

$$J = \frac{m}{hl}\int_{-\frac{1}{2}h}^{\frac{1}{2}h}\int_{-\frac{1}{2}l}^{\frac{1}{2}l}(x_1^2 + x_2^2)dx_1dx_2$$

$$J = m\left(\frac{1}{12}l^2 + \frac{1}{12}h^2\right)$$

Filling in the other values of the mass matrix:

$M_{platform} = 7.51 * 10^7\ kg$
$M_{building} = \frac{2*91500*1000}{9.81} = 1.86 * 10^7\ kg$
$J = 6.89 * 10^{10}\ kgm^2$
$z = 32\ m$

$$M = \begin{bmatrix} 3.55 * 10^8 & 0 & 0 \\ 0 & 1.05 * 10^8 & 5.95 * 10^8 \\ 0 & 5.95 * 10^8 & 1.58 * 10^{11} \end{bmatrix}$$

7.1.3 Damping

The hydrostatic forces on the floating platform are represented as springs with certain 'stiffness', these are the reaction forces on the structure. However, these are not the only forces to take into account. Damping forces also play a role on the motions of the platform and can significantly reduce the amplitude of the movements of the system, see Figure 86.

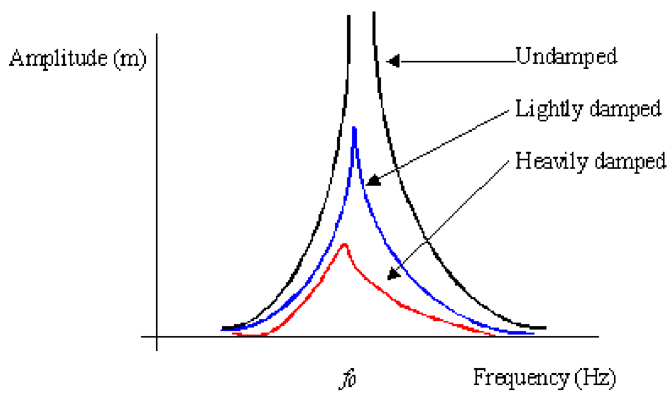


Figure 86: Amplitude frequency response with and without damping

Taking damping forces into account, the amplitude during resonance is not infinite anymore and it should be able to calculate this value of amplitude. However, damping plays a minor role when the frequency band is sufficient far away from the resonance region.

Later in section 7.2.2, the amplitudes of the displacements are calculated. The displacements are dependent on the periods of the waves. When the periods of the waves are close to the natural frequency of the structure, resonance occur and the amplitude will go to infinite, thus leading to large displacements.

The amplitudes go to infinite at the following frequencies:
0.0148 rad/s for the vertical motion.
0.0130 rad/s and 0.0260 rad/s for the horizontal motion.
0.0130 rad/s and 0.0260 rad/s for the rotational motion.

The assumed wave height of 4 m with a wave period of 8.6 s contributes to a wave frequency of $\frac{2\pi}{8.6} = 0.73\ rad/s$ which is far away from the resonance frequency of the platform. Waves with a period of $\frac{2\pi}{0.0321} = 195\ s$ or larger would induce large heave motions. Such large wave periods are found in tsunami waves. So damping can be neglected for this system in the thesis.

7.1.4 Frequency comfort levels

The dynamic analysis provides information about the movements of the platforms when loaded by a wave load. These movements (heave, sway, roll etcetera) can cause discomfort of living on the platform. There are several ways to determine the comfort level for the inhabitants. However, all these methods are not 100% accurate as many factors play a role in determining the vibration nuisance, like:

- Intensity
- Frequency
- Duration of action
- Frequency of occurrence
- Location
- Direction
- Position of the body
- Health of inhabitants
- Activity
- Secondary effects (slamming, jingling etc.)

In the Netherlands, the limit values for vibration nuisance are derived from:

- TNO
- DIN 4150 part 2 1975 (pre-norm)
- ISO 2631

TNO

The limits for the permissibility of vibrations for humans according to TNO are given in Figure 87. The figure is derived from a TNO report BI-67-107 drawn up by H. van Koten on the basis of ISO 2631. In this graph, there are several levels of 'noticeability' of the vibration nuisance. Depending on the accelerations of the structure and the occurring frequency, the level of 'noticeability' can be determined.

DIN 4150 (pre-norm 1975)

The DIN 4150 limits for vibration nuisance were stated in Germany. Similarly as the TNO graph, the DIN graph also states a few different levels of vibration nuisances. The difference is that the DIN graph is also dependent on the following:

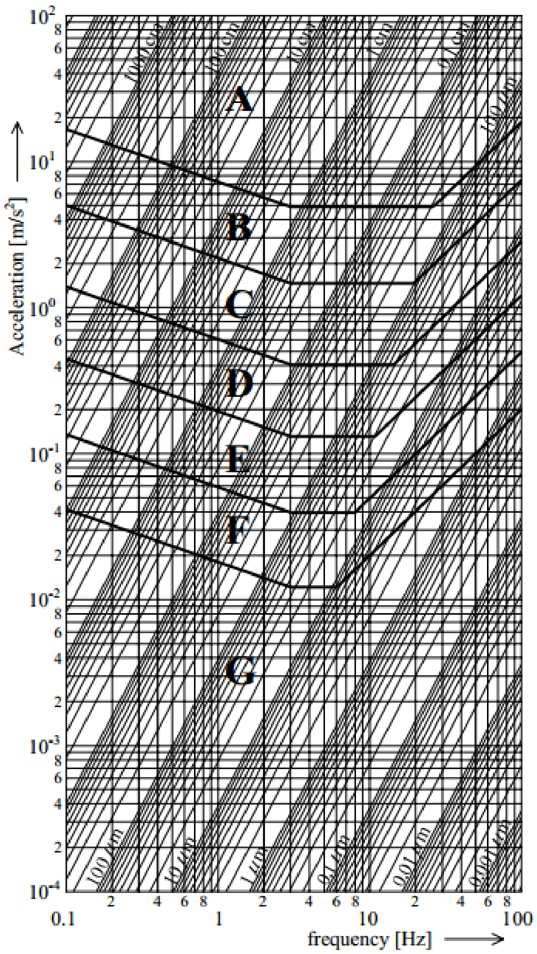
- Location of the vibration (type of area)
- Time of day
- Frequency of occurrence

ISO 2631

ISO 2631 uses simple graphs and formulas compared to TNO and DIN 4150. Only three different levels are being distinguished:

- Limit I (reduced comfort boundary): An acceptable limit value of the vibration level for everyday activities.
- Limit II (fatigue-decreased boundary): Repeatedly vibration nuisance at which persons shows signs of fatigue.
- Limit III (exposure limit): Maximum tolerable vibration nuisance for humans

Between the methods of TNO, DIN 4150 and ISO 2631, in practice it is preferred to use the graphs of TNO and DIN 2631 as ISO 2631 has a shallower distinction between nuisance levels. DIN 4150 is preferred when the assessment of vibration nuisance is for well-described situations. In this thesis, the graph of TNO will be used to determine the comfort level of vibration nuisances. For reference, the other graphs are found in **Appendix 8.2 Frequency comfort levels**.



description of noticeability		admissibility for people in buildings	global judgement of influence on structures	examples
A	unbearable	inadmissible	possible collapse	emergen-cies
B	unpleasant quickly tiresome	inadmissible	local damage	sudden pulling up of a car
C	strongly noticeable	hardly admissible	cracking of masonry	elevators trams
D	clearly noticeable	rough manual labour	Introduction of light cracking	start of seasick-ness
E	noticeable	short periods in houses	no influence on normal buildings	
F	hardly noticeable	long periods in houses	no influence	
G	not noticeable		no influence	

Figure 87: Limits to accelerations according to TNO (CIE4140 Dynamics of structures lecture notes)

7.2 1 Mass-spring system

The 1 mass-spring system concerns a system which exists of only one platform.

7.2.1 1 Mass-spring system without moorings

The floating platform can be schematized as a rigid, infinite stiff block founded on vertical and horizontal springs. These kinds of schematizations are called mass-spring systems. In reality, the platform is not infinitely stiff and hogging/sagging moments occur, but these are neglected for now and are to be calculated in the structural design of the platform. The springs represent the 'stiffness' of the water which are used to indicate the hydrostatic forces on the floating platform. Furthermore, the platform is excited by a sinusoidal motion which represents the vertical wave motion.

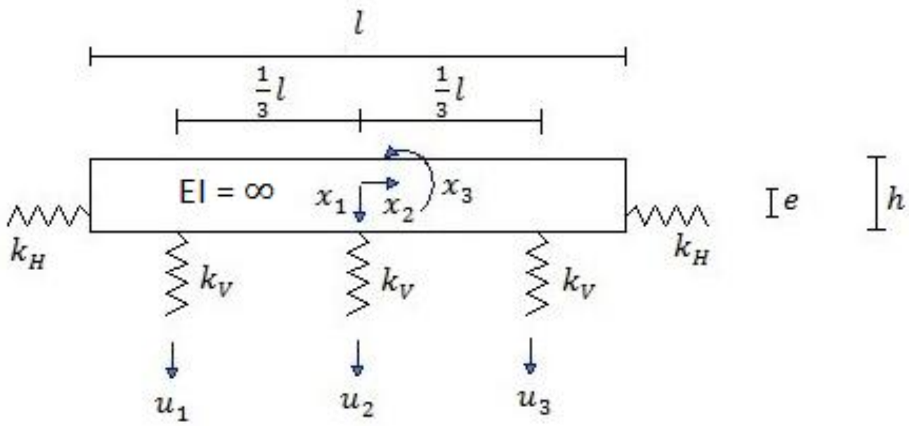


Figure 88: Floating structure schematised as a mass-spring system

In Figure 88: $k_V = spring\ stiffness\ of\ water\ in\ vertical\ direction$
$k_H = spring\ stiffness\ of\ water\ in\ horizontal\ direction$

$l = length\ of\ floating\ structure$
$h = height\ of\ floating\ structure$
$e = eccentricity\ of\ water\ mass\ on\ the\ sides\ (half\ of\ the\ draught)$

$Vertical\ wave\ motions$:
$u_1(t) = H_s \sin(\omega(t - \Delta t))$
$u_2(t) = H_s \sin(\omega t)$
$u_3(t) = H_s \sin(\omega(t + \Delta t))$

The hydrostatic forces act on the whole underside of the platform, so it would be logical to assume that the springs should be represented as a continues spring system. However, for the convenience and understanding of the calculations it is chosen to represent the hydrostatic forces with 3 individual springs.

The vertical spring stiffness of the water can be calculated with the principle of Archimedes:

$$F_{buoyancy} = \rho_w g V = \rho g * A * D$$
$$\frac{F_{buoyancy}}{D} = k = \rho_w g * A$$

Where:
- $F_{buoyancy}$ = Buoyant force/Archimedes force
- ρ_w = Density of fluid
- g = Acceleration due to gravity
- V = Volume of displaced fluid
- A = Bottom area of structure
- D = Draught

This value of the vertical spring stiffness is divided by 3 to obtain the spring stiffness of each individual spring. The horizontal spring stiffness of the water is calculated in a same approach.

To determine the displacements and forces on the floating structure, the displacement method is used to set up the equations of motion. The derivation of the equation of motion can be found in **Appendix 8: Structural analysis**.

The equation of motion concerning only the hydrostatic forces is presented as follows:

$$M\ddot{x_1} + 3k_V x_1 = k_V(u_1 + u_2 + u_3)$$
$$M\ddot{x_2} + 2k_H x_2 + 2ek_H x_3 = 0$$
$$J\ddot{x_3} + 2ek_H x_2 + \left(2e^2 k_H + \frac{2}{9} l^2 k_V\right) x_3 = \frac{1}{3} lk_V(u_1 - u_3)$$

The set of equation of motions can be written in matrix form see below.

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & J \end{bmatrix} * \begin{bmatrix} \ddot{x_1} \\ \ddot{x_2} \\ \ddot{x_3} \end{bmatrix} + \begin{bmatrix} 3k_V & 0 & 0 \\ 0 & 2k_H & 2ek_H \\ 0 & 2ek_H & 2e^2 k_H + \frac{2}{9} l^2 k_V \end{bmatrix} * \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} k_v(u_1 + u_2 + u_3) \\ 0 \\ \frac{1}{3} lk_V(u_1 - u_3) \end{bmatrix}$$

Note that the displacement method is now about a 2 dimensional platform. This means that the analysis will work out 3 degrees of freedom for the platform (which are the heave, surge and pitch motions). It is possible to work out the problem for a 3 dimensional problem, which will introduce all 6 degrees of freedom. The mass and stiffness matrix will then turn into a 6 by 6 matrix which is quite huge to work out. Although this is still possible for the 1 mass-spring system. But later on for the 2 mass-spring system each platform will have 6 degrees of freedom resulting in a 12 by 12 matrix. So to keep the same approach throughout this thesis, it is chosen to only look at 3 degrees of freedom at a time.

7.2.2 1 Mass-spring system with moorings

The floating structure is being moored with anchors to the bottom of the sea. The forces acting on the floating structure due to the water buoyancy is elaborated in the previous section. These forces remain the same in the situation where extra moorings are added to the floating structure, so only the spring-stiffness's of the moorings are taken into account in the displacement method.

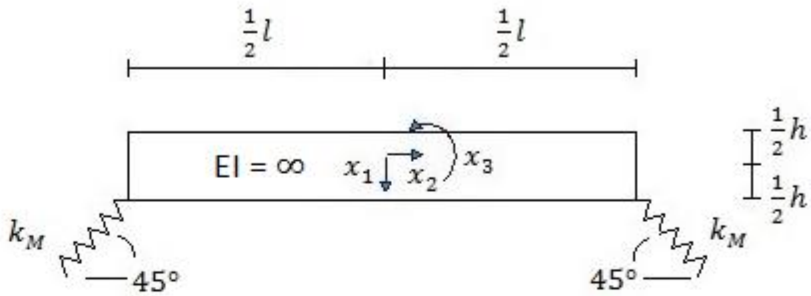


Figure 89: 1 mass-spring system with moorings only

In Figure 89: $k_M = spring\ stiffness\ of\ mooring\ line$

$l = length\ of\ floating\ structure$
$h = height\ of\ the\ floating\ structure$

For the spring stiffness of the chains, the Law of Hooke is being used: $k_M = \frac{EA}{l_M}$, where EA is the stiffness of the mooring line (2110 MN) and l_M is the length of the mooring line.

The displacement method is again applicable to this situation and the equation of motion is as follows:

$$M\ddot{x_1} + k_M x_1 = 0$$
$$M\ddot{x_2} + k_M x_2 - \frac{l-h}{2} k_M x_3 = 0$$
$$J\ddot{x_3} - \frac{(l-h)}{2} k_M x_2 - \frac{(l-h)(h-l)}{4} k_M x_3 = 0$$

The set of equation of motions can be written in matrix form see below.

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & J \end{bmatrix} * \begin{bmatrix} \ddot{x_1} \\ \ddot{x_2} \\ \ddot{x_3} \end{bmatrix} + \begin{bmatrix} k_M & 0 & 0 \\ 0 & k_M & -\frac{l-h}{2} k_M \\ 0 & -\frac{(l-h)}{2} k_M & -\frac{(l-h)(h-l)}{4} k_M \end{bmatrix} * \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

In combination with the equation of motion due to the water buoyancy, the stiffness matrix K of the system including water buoyancy and moorings can be constructed:

$$K = \begin{bmatrix} 3k_V + k_M & 0 & 0 \\ 0 & 2k_H + k_M & 2ek_H - \dfrac{l-h}{2}k_M \\ 0 & 2ek_H - \dfrac{(l-h)}{2}k_M & 2e^2k_H + \dfrac{2}{9}l^2k_V - \dfrac{(l-h)(h-l)}{4}k_M \end{bmatrix}$$

With the addition of the added mass, the equations of motion are as following in matrix form:

$$\begin{bmatrix} M_{platform} + M_{building} + M_z & 0 & 0 \\ 0 & M_{platform} + M_{building} + M_y & M_{building}z \\ 0 & M_{building}z & J + M_\theta \end{bmatrix} +$$

$$\begin{bmatrix} 3k_V + k_M & 0 & 0 \\ 0 & 2k_H + k_M & 2ek_H - \frac{l-h}{2}k_M \\ 0 & 2ek_H - \frac{(l-h)}{2}k_M & 2e^2k_H + \frac{2}{9}l^2k_V - \frac{(l-h)(h-l)}{4}k_M \end{bmatrix} = \begin{bmatrix} k_v(u_1 + u_2 + u_3) \\ 0 \\ \frac{1}{3}lk_V(u_1 - u_3) \end{bmatrix}$$

By solving these matrices in Maple, the following amplitude frequency responses are obtained:

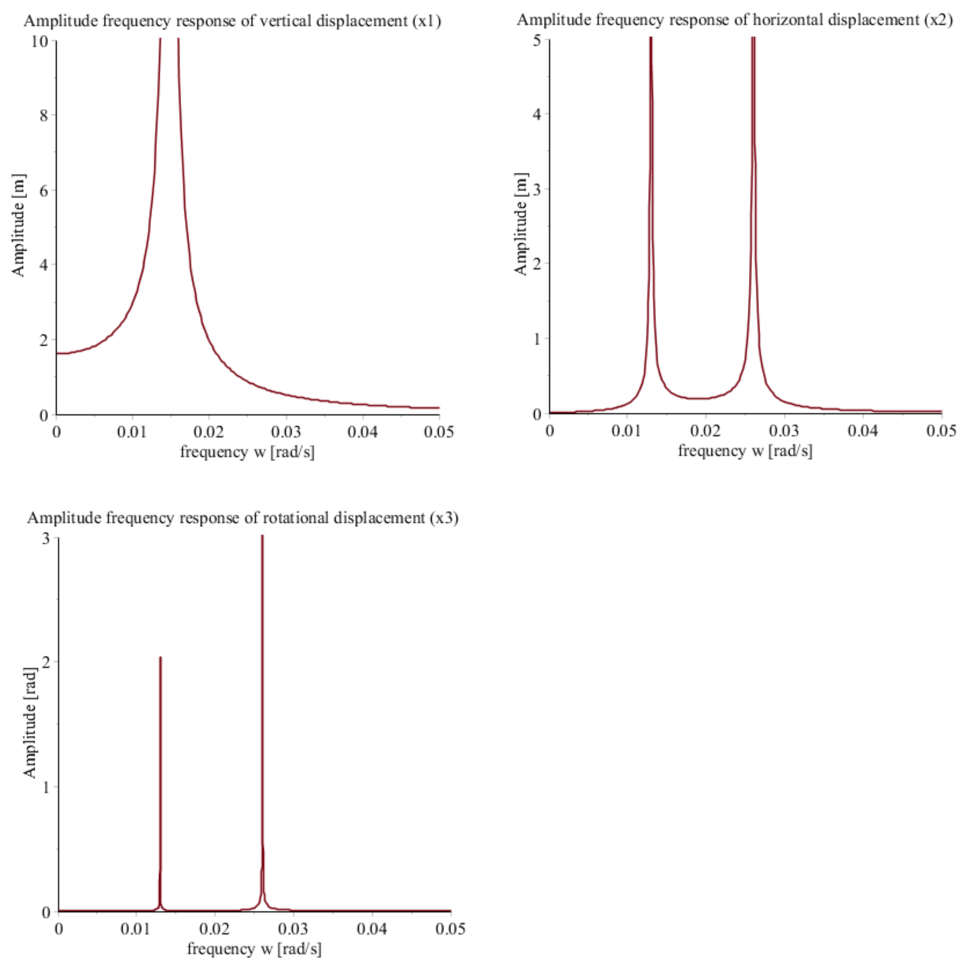


Figure 90: Amplitude frequency responses of 1 mass-spring system

In the amplitude frequency responses of Figure 90, the amplitudes have peaks (go to infinity) at the following values for the frequency:
0.0148 rad/s for the vertical motion.
0.0130 rad/s and 0.0260 rad/s for the horizontal motion.
0.0130 rad/s and 0.0260 rad/s for the rotational motion.
This means that if the platform is loaded by a wave with these frequencies, the platform will induce very large motions which are not favourable.

The occurring wave of 4 m has a frequency of $\frac{2\pi}{8.6} = 0.73\ rad/s$, which is very far away from the frequency region where the amplitude will go to infinite. So it can be expected that the displacements of the platform due to these waves will be very small. The following values for the displacements are computed from the calculations:
x_1 = 0.00066 m = 0.66 mm (vertical motion)
x_2 = 0.00057 m = 0.57 mm (horizontal motion)
x_3 = 0.00010 rad → 0.00010*length = 0.00010*104 = 0.0104 m (vertical displacement due to rotation)

These motions are executed at the following accelerations:
a_1 = 0.00035 m/s^2 (vertical motion)
a_2 = 0.00031 m/s^2 (horizontal motion)
a_3 = 0.00005 rad/s^2 → 0.00005*length = 0.00005*104 = 0.0056 m/s^2 (vertical acceleration due to rotation)

According to Figure 87, the TNO graph, the accelerations and occurring wave frequency belongs to a comfort level in the area G (motions are not noticeable). The results of the accelerations were acceptable when they were in area F (hardly noticeable), this means that inhabitants can comfortably live on the (single) floating platform under almost all circumstances.

7.3 2 Mass-spring system

The 2 mass-spring system concerns a system of two platforms which are connected to each other. In chapter 5 is elaborated that the floating city concept should use fully rigid connections if these are possible. The possibility lies in whether the internal forces in the connections exceeds the strength limits.

7.3.1 Solving the system for the displacements

The floating platform can again be schematized as a rigid, infinite stiff block founded on vertical and horizontal springs (hydrostatic forces) and diagonal springs (moorings). And again, the platform is excited by a sinusoidal motion which represents the vertical wave motion. The connection is now schematized as a structural hinge although it should be a fully rigid connection. When the connection is schematized as a rigid connection in the model, then the two platforms will act as one rigid beam so there will be no difference with the 1 mass-spring system. Due to the hinge, there will be a difference in the displacement method compared to the 1 mass-spring system.

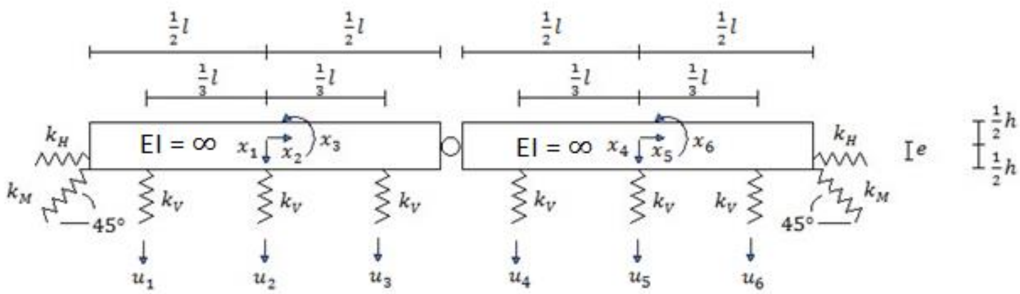


Figure 91: 2 mass-spring system model

To determine the displacements and forces on the floating structure, the displacement method is again used to set up the equations of motion. The derivation of the equation of motion can be found in **Appendix 8: Structural analysis**. The mass and stiffness matrices can be constructed as follows:

$$M := \begin{bmatrix} M\_p1 + M\_b1 + M\_z1 & 0 & 0 & 0 & 0 & 0 \\ 0 & M\_p1 + M\_b1 + M\_y1 & M\_b1\, z & 0 & 0 & 0 \\ 0 & M\_b1\, z & J\_p1 + M\_\theta 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & M\_p2 + M\_b2 + M\_z2 & 0 & 0 \\ 0 & 0 & 0 & 0 & M\_p2 + M\_b2 + M\_y2 & M\_b2\, z \\ 0 & 0 & 0 & 0 & M\_b2\, z & J\_p2 + M\_\theta 2 \end{bmatrix}$$

$$K := \begin{bmatrix} 3\,kv + \frac{1}{2}\,km & -\frac{1}{2}\,km & \frac{1}{4}\,(l-h)\,km & -\frac{1}{2}\,km & -\frac{1}{2}\,km & -\frac{1}{4}\,(l-h)\,km \\ -\frac{1}{2}\,km & kh + \frac{1}{2}\,km & e\,kh - \frac{1}{4}\,(l-h)\,km & \frac{1}{2}\,km & kh + \frac{1}{2}\,km & -e\,kh + \frac{1}{4}\,(l-h)\,km \\ \frac{1}{4}\,(l-h)\,km & e\,kh - \frac{1}{4}\,(l-h)\,km & \frac{2}{9}\,l^2\,kv + e^2\,kh + \frac{1}{8}\,(l-h)^2\,km & -\frac{4}{9}\,l\,kv - \frac{1}{4}\,(l-h)\,km & e\,kh - \frac{1}{4}\,(l-h)\,km & -e^2\,kh - \frac{2}{9}\,l^2\,kv + \frac{1}{8}\,(l-h)^2\,km \\ -\frac{1}{2}\,km & \frac{1}{2}\,km & \frac{1}{4}\,(l-h)\,km & 3\,kv + \frac{1}{2}\,km & \frac{1}{2}\,km & -\frac{1}{4}\,(l-h)\,km \\ -\frac{1}{2}\,km & kh + \frac{1}{2}\,km & -e\,kh + \frac{1}{4}\,(l-h)\,km & \frac{1}{2}\,km & kh + \frac{1}{2}\,km & e\,kh - \frac{1}{4}\,(l-h)\,km \\ \frac{4}{9}\,l\,kv + \frac{1}{4}\,(l-h)\,km & e\,kh - \frac{1}{4}\,(l-h)\,km & -\frac{2}{9}\,l^2\,kv - e^2\,kh - \frac{1}{8}\,(l-h)^2\,km & -\frac{1}{4}\,(l-h)\,km & e\,kh - \frac{1}{4}\,(l-h)\,km & \frac{2}{9}\,l^2\,kv + e^2\,kh + \frac{1}{8}\,(l-h)^2\,km \end{bmatrix}$$

The displacements of the platform are obtained by assuming the steady-state response of the structure; this can be done with the help of the program Maple just like with the 1 mass-spring system. The following amplitude-frequency responses are obtained.

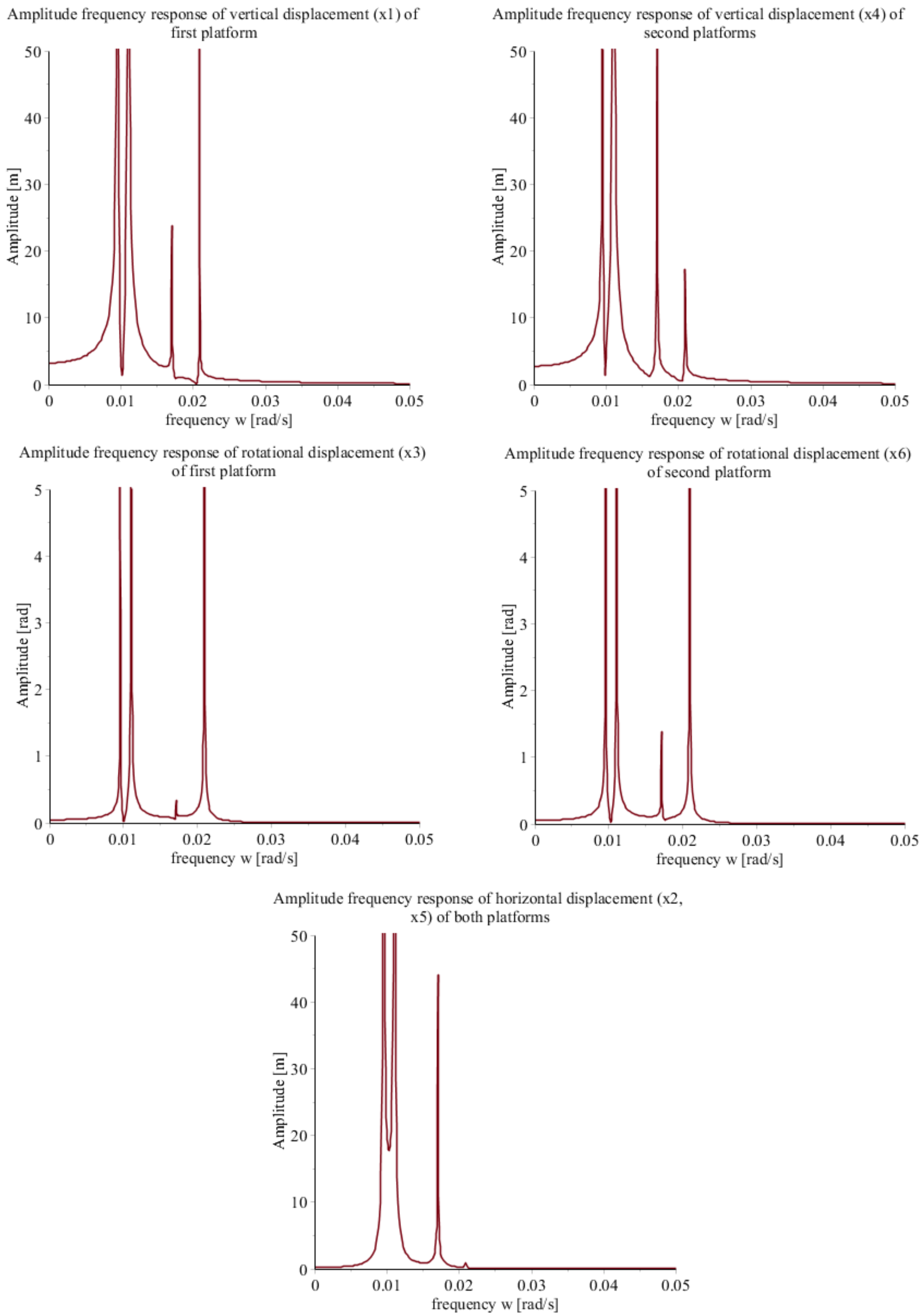


Figure 92: Amplitude frequency responses of 2 mass-spring system

As can be seen in Figure 92, the motions of the first and the second platform are almost identical. At least in the sense that both platforms reach a large amplitude at almost the same frequencies. The amplitudes of the above graphs go to infinite at the following frequencies:
$\omega_1 = 0.008\ rad/s$
$\omega_2 = 0.012\ rad/s$
$\omega_3 = 0.017\ rad/s$
$\omega_4 = 0.022\ rad/s$

The assumed wave height of 4 m with a wave period of 8.6 s contributes to a wave frequency of $\frac{2\pi}{8.6} = 0.73\ rad/s$ which is far away from the resonance frequency of the platforms.

The maximum value for the vertical motion with a wave frequency of 0.73 rad/s is:
$x_1 = 0.00066\ m = 0.66\ mm$
$x_4 = 0.0060\ m = 6\ mm$

The maximum value for the horizontal motion with a wave frequency of 0.73 rad/s is:
$x_2 = x_5 = 0.00034\ m = 0.34\ mm$

The maximum value for a vertical displacement due to rotation with a wave frequency of 0.73 rad/s is:
$x_3 = x_6 = 0.00006\ rad \rightarrow 0.00006 * length = 0.00006 * 104 = 0.00624\ m = 6.24\ mm$

These motions are executed at the following accelerations:
a_1 = 0.00035 m/s^2 (vertical motion of first platform)
a_2 = 0.00018 m/s^2 (horizontal motion of both platforms)
a_3 = a_6 = 0.00003 rad/s^2 → 0.00003*length = 0.00003*104 = 0.0031 m/s^2 (vertical acceleration due to rotation of both platforms)
a_4 = 0.0032 m/s^2 (vertical motion of second platform)

Result is that the first platform has the same displacements and accelerations as in the 1 mass-spring system. The second platform attached to the first platform is having larger displacements than the first platform, in the order of 10 times bigger. But the displacement of the second platform is still very small and not noticeable.

7.3.2 Connection force

Regarding the requirement that the rotation and tilting position of the platform must maintain an obliquity of 0.01% (with a platform length of 120 m this means a vertical displacement of 0.012 m is allowed) to prevent damage to structures between the platforms, this requirement is in fact exceeded due to the rotations. But this is not a problem since a hinged connection is used in the model, thus allowing rotations between platforms. In reality a rigid connection is preferred to resist these rotations, so this displacement due to rotation does not occur. As in chapter 5, it is indeed chosen to apply a rigid connection in the form of a puzzle type connection, see Figure 60. With the known displacements and rotations, the stresses in the connection can be calculated. The largest stresses in the connection are due to the rotation of each platform. A simple estimation of the force active on the connection can be calculated with a rule of thumb, see Figure 93.

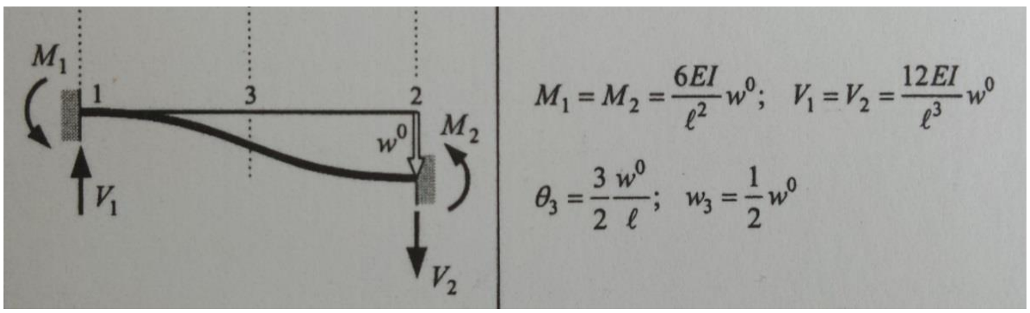


Figure 93: Rule of thumb for beam with displaced fixed ends (Hartsuijker)

In Figure 93, the platform is not infinitely stiff anymore. The bending stiffness of the platform can be estimated by taking the elastic modulus E multiplied with the area moment of inertia I.

$$I = \frac{1}{12} * wh^3 - 2 * \frac{1}{12}\left(\frac{w}{2} - t_{inner} - t_{outer}\right)\left(h - t_{top} - t_{bottom}\right)^3$$
$$I = \frac{1}{12} * 104 * 14^3 - 2 * \frac{1}{12} * 51.25 * 12^3 = 9021\ m^4$$
$$E \approx 30 * 10^6\ kN/m^2$$
$$EI = 2.7 * 10^{11}\ kNm^2$$

The largest occurring displacement would be due to a rotating platform which leads to w^0 = 0.00624 m. Filling all the known parameters in the rule of thumb leads to the forces in the connection.

$$M_1 = M_2 = \frac{6*2.7*10^{11}}{104^2} * 0.00624 = 9.35 * 10^5\ kNm$$
$$V_1 = V_2 = \frac{12*2.7*10^{11}}{104^3} * 0.00624 = 1.80 * 10^4\ kN$$

The bending moment is the largest and will induce the largest (bending) stress on the concrete. The maximum stress is calculated as follows:

$$\sigma_{connection,max} = \frac{M*\frac{1}{2}*draught}{I} = \frac{9.35*10^5*\frac{1}{2}*14}{9021} = 725\ kN/m^2$$

The connection (concrete) will experience a tensile and a compressive stress. Usually the upper part of the connection will experience tensile stress while the lower half experiences compression, but this is not always the case. In Figure 94 a stress diagram is shown of the cross section with a puzzle-type connection, the positive sign indicates a tensile stress while the negative sign indicates a compressive stress. The actual stress on the connection can be smaller than calculated above depending on the size of the connection. In the formula/calculation above, the bending moment is multiplied with half the draught of the platform.

But as can be seen in Figure 94, the connection itself is not as large as half the draught, resulting in a significant smaller stress in the connection.

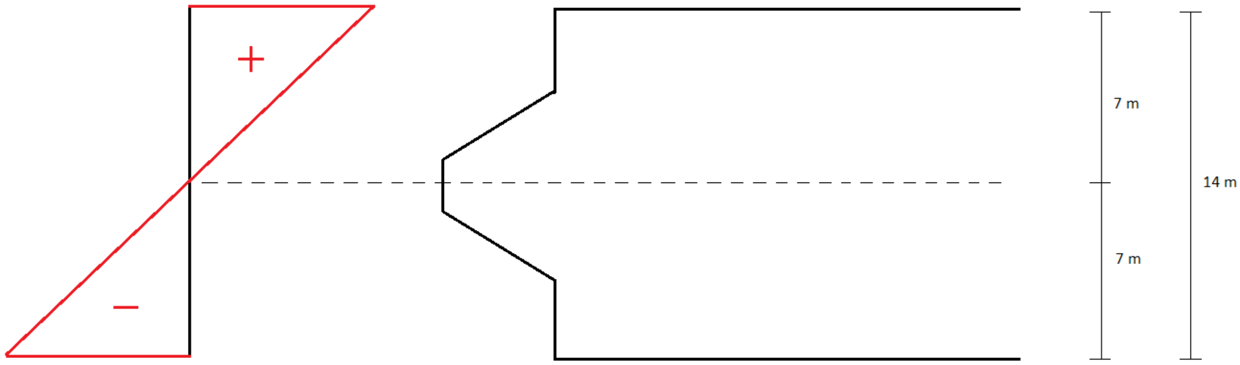


Figure 94: Stress diagram of connection

Of course this rough calculation is not very accurate, a complete structural analysis should be done on the connection to retrieve the connection forces which is not in the scope of this thesis. Because the displacement is very small, the force on the connection is very small too. The chosen puzzle type connection is made from concrete. Concrete has a high compression strength but low tensile strength. To compensate for the low tensile strength of concrete, reinforcement bars or pre-stressing steel are to be used. Concrete has a compressive strength of 20 – 40 MPa (20000 – 40000 kN/m^2) and a tensile strength of 2 – 5 MPa (2000 – 5000 kN/m^2). The stresses are in a safe margin for this rough estimation, but a detailed structural analysis is still needed.

The maximum tensile stress concrete can take is 5000 kN/m^2. By reversing the calculation with this maximum value, the maximum displacement/rotation a platform may have is found out.

$$\sigma_{connection,max} = 5000\ kN/m^2 = \frac{M_{max} * \frac{1}{2} * draught}{I} = \frac{M_{max} * \frac{1}{2} * 14}{9021} \rightarrow M_{max} = 6.44 * 10^6\ kNm$$
$$M_{max} = \frac{6 * 2.7 * 10^{11}}{104^2} * x = 6.44 * 10^6\ kNm \rightarrow x = 0.043\ m = 43\ mm$$

This maximum value is quite low, because of the low value for the tensile stress. Usually, reinforced concrete is used which has a much higher tensile strength. Reinforcement bars have a tensile yield strength of 500 MPa (500000 kN/m^2) which is 100 times stronger than the tensile strength of concrete. Using reinforced concrete, the displacement can even reach 4.3 m before failure.

$$\sigma_{connection,max} = 500000\ kN/m^2 = \frac{M_{max} * \frac{1}{2} * draught}{I} = \frac{M_{max} * \frac{1}{2} * 14}{9021} \rightarrow M_{max} = 6.44 * 10^8\ kNm$$
$$M_{max} = \frac{6 * 2.7 * 10^{11}}{104^2} * x = 6.44 * 10^8\ kNm \rightarrow x = 4.3\ m$$

The tensile strength of reinforced concrete can further be improved by using pre-stressing steel reinforcement.

7.3.3 Mooring force

In the structural model, only one mooring line on each side of the platform is applied. Each mooring line had a Minimum Breaking Load of 22070 kN which corresponds to a rope stiffness of 2110 MN. The force in the mooring can be calculated by multiplying the assumed spring stiffness of the mooring by the occurring displacement.

$$F_{mooring,\ heave} = \pm\frac{k_M}{\sqrt{2}}x_4 = \frac{14920}{\sqrt{2}} * 0.006 = 63.30\ kN$$

$$F_{mooring,\ pitch} = \pm\frac{(l-h)}{2\sqrt{2}}k_M x_3 = \frac{(104-14)}{2\sqrt{2}} * 14920 * 0.00006 = 28.48\ kN$$

Except from vertical motions, the moorings should also bear horizontal motions. Continues drift forces are what causes the platform to drift away and the moorings should prevent this. The largest horizontal force the moorings have to resist is the combination of a typhoon and a current load both exerting on the platform in the same direction. In section 6.2.5 it is calculated that the total horizontal force is in the range of $F_{mooring,\ horizontal} = F_{current} + F_{wind} = 3100 + 2091 = 5191\ kN$ which is well below the Minimum Breaking Load.

In all cases, the mooring forces are not exceeded so a single mooring line on each side of the platform is sufficient. The thickness of the mooring line can even be reduced as the forces in the mooring lines are not very large. Looking at Table 14, a spiral strand rope with a nominal diameter of 76 mm and a Minimum Breaking Load of 5647 kN already suffices the strength requirements.

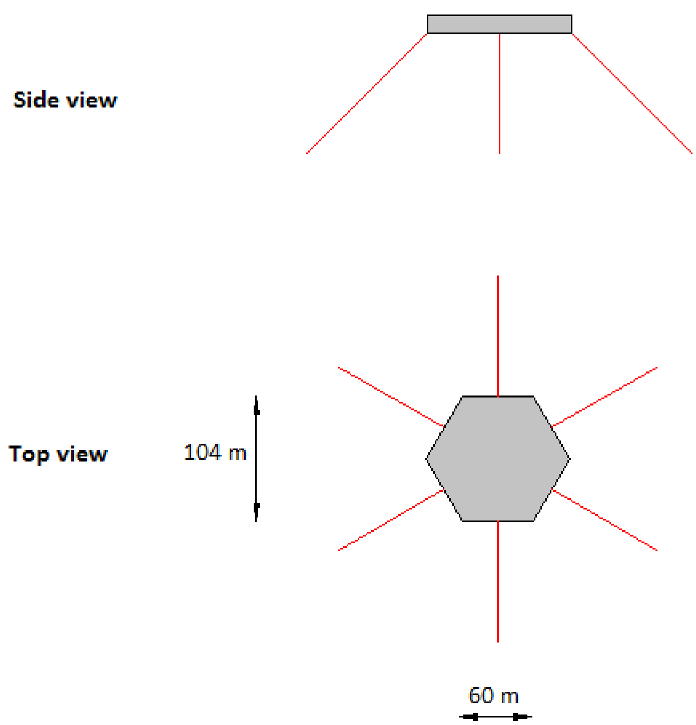


Figure 95: Mooring lines placement

7.4 Multiple mass-spring system

Comparing the results of the one and the two mass-spring systems, the outcomes of the occurring displacements and accelerations were the same for the first initial platform and the attached platform experiences displacements 10 times larger than the displacements of the first platform. From this statement, it can be concluded that a second platform/mass attached to the first platform/mass is not beneficial. However, because of the large dimensions of the platforms the displacements of the first platform are very small. Which means that the second platform experiences a displacement 10 times larger than this small displacement, which is still significant very small.

It is proven that the displacements of a 2 mass-spring system are within acceptable range. But the floating community will consist of more than 2 platforms connected to each other. So instead of a 2 mass-spring system, a multiple mass-spring system should be looked at. An attached platform experiences displacements 10 times larger than the displacements of the initial platform. If this behaviour would be the same for a third, fourth and fifth etcetera platform attached in a chain formation, then the displacements of the last platform will experience a very large displacement. A third platform will experience a displacement 10 times larger than the second platform (which means 100 times the displacements of the first platform) and a fourth platform will experience a displacement 1000 times larger than the first platform etcetera. This behaviour is actually the same as the characteristics of a whip. A whip experiences a very large displacement towards the end of the whip even when a small displacement is given at the beginning.

7.4.1 2 mass-spring system in reality

The reason for the above mentioned 'whip-like-behaviour' is because a hinged connection is used in the dynamic analysis. A hinge was purely used in the structural schematisation of the coupled platforms to calculate the forces occurring in the connection between the platforms. But in reality a rigid connection is used which means that two coupled platforms actually act as one large single platform. The theoretically assumed displacements, see Figure 96, are exaggerated and are actually not occurring. By restricting these displacements, the (rigid) connection must be able to resists the occurring bending moments and forces.

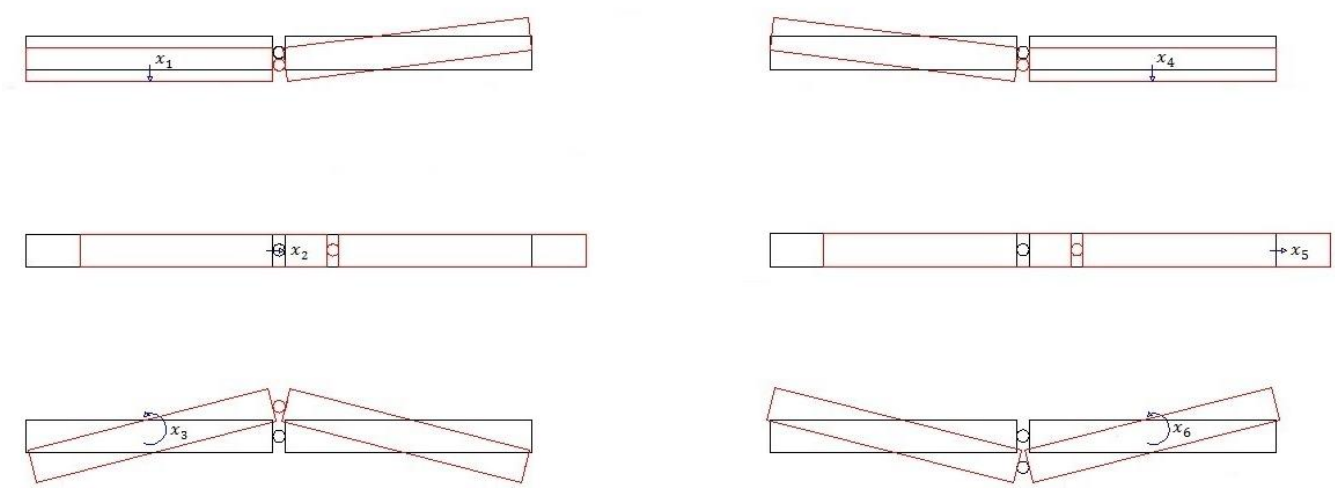


Figure 96: Exaggerated displacements of 2 mass-spring system

Assume the two platforms are rigidly connected in the model, thus making it effectively one large single platform. The dimensions are doubled in this case. Due to the larger dimensions, a lot more weight is present in the form of dead load and added water mass. The results of this large platform are shown in the table below.

	Basic situation	**Larger platform**
Variables:		
Platform length	104 m	208 m
Platform width	60 m	120 m
Wave height	4 m	4 m
Wave period	8.6 s	8.6 s
Wave length	76.5 m	76.5 m
Results:		
x_1	$6.63*10^{-4}$ m	$1.25*10^{-4}$ m
x_2	$3.45*10^{-4}$ m	$0.04*10^{-4}$ m
x_3	$0.60*10^{-4}$ rad	$0.23*10^{-4}$ rad
x_4	$59.90*10^{-4}$ m	
x_6	$0.60*10^{-4}$ rad	
a_1	$3.54*10^{-4}$ m/s^2	$0.67*10^{-4}$ m/s^2
a_2	$1.84*10^{-4}$ m/s^2	$0.02*10^{-4}$ m/s^2
a_3	$0.30*10^{-4}$ rad/s^2	$0.13*10^{-4}$ rad/s^2
a_4	$32.00*10^{-4}$ m/s^2	
a_6	$0.30*10^{-4}$ rad/s^2	

Table 17: Results of two platform rigidly connected (effectively one large platform)

The main reason why such low displacements and accelerations are achieved is because of all the extra mass of the 'platform'. As can be seen, by increasing the dimensions of the 'platform' the motions and accelerations decrease drastically. This also quantifies the statement that if the length of the structure is greater than the wavelength, the heave response becomes significant smaller.

Result is, the displacements and rotations are a lot smaller when rigid connections are used as it is in reality compared to hinged connections. Thus making a multiple mass-spring system viable. However, to make sure rigid connections in a multiple mass-spring system are indeed experiencing lower connection forces due to smaller displacements, it is best to find this out with a small scale experiment/modelling program.

Assume the displacements of the model with hinged connections are the displacements in reality even if rigid connections are applied. So the second platform experiencing a displacement 10 times larger than the first platform and the third platform has a displacement of 10 times the second platform etcetera. Using the general reinforced concrete with a concrete tensile strength of 500000 kN/m^2, the platforms may still have displacements up to 4.3 m (see calculation in section 7.3.2) before exceeding the tensile strength limit. So for this chosen design of the hexagonal platform with sides of 60 m and a construction height of 14 m, it is possible to connect up to 4 platforms together in a linear formation:

$$x_{first\ platform} = 0.00066\ m = 0.66\ mm$$
$$x_{second\ platform} = 0.0060\ m = 6\ mm$$

$x_{third\ platform} = 0.060\ m = 60\ mm$
$x_{fourth\ platform} = 0.60\ m = 600\ mm$
$x_{fifth\ platfom} = 6.0\ m = 6000\ mm \rightarrow exceeds\ limit$

Note that the displacement of the second platform is in fact 'only' 9 times larger than the displacement of the first platform. So this means actually that the maximum of platforms connected to each other is 5 platforms ($x_{first\ platform} = 0.66\ mm \rightarrow x_{second\ platform} = 6\ mm \rightarrow x_{third\ platform} = 54\ mm \rightarrow x_{fourth\ platform} = 486\ mm \rightarrow x_{fifth\ platfom} = 4374\ mm \rightarrow exactly\ the\ limit$). But for a safety marge, it is just assumed that the displacements of following platforms are 10 times larger.

With this outcome, it can be said that till now a reliable floating community of 16 platforms (in a configuration of 4 by 4 platforms) can be realised which is possible to house approximately 4000 inhabitants.

7.4.2 Simplification of multiple mass-spring system

Multiple rigidly connected platforms act as a single rigid platform with larger dimensions. Take for example the most right configuration of platforms in Figure 97. Assumed that all the platforms are very strong rigidly connected, the floating community is one big platform with several mooring lines at each side, see Figure 98.

Regarding the mooring lines, the bigger the floating community is going to be, the more mooring lines are needed would be a logical theory. The conclusion given is that one mooring line at each side of the platform is sufficient to bear the occurring mooring forces and platform displacements. So in multiple connected platforms, each free side of the platform which is not connected to another platform hosts a mooring line, see Figure 97. All the mooring lines are perpendicular on the side of the platform, making the platform withstand waves and currents coming from 6 directions. However, this way some mooring lines 'cross' each other at adjacent platforms.

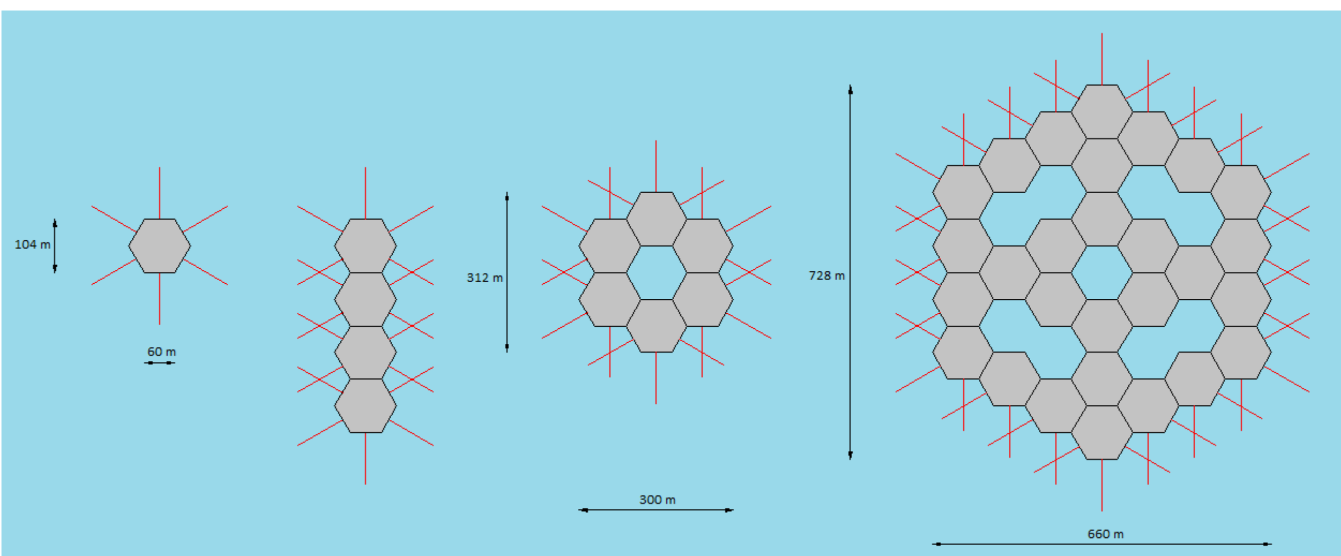


Figure 97: Mooring line placement for coupled platforms

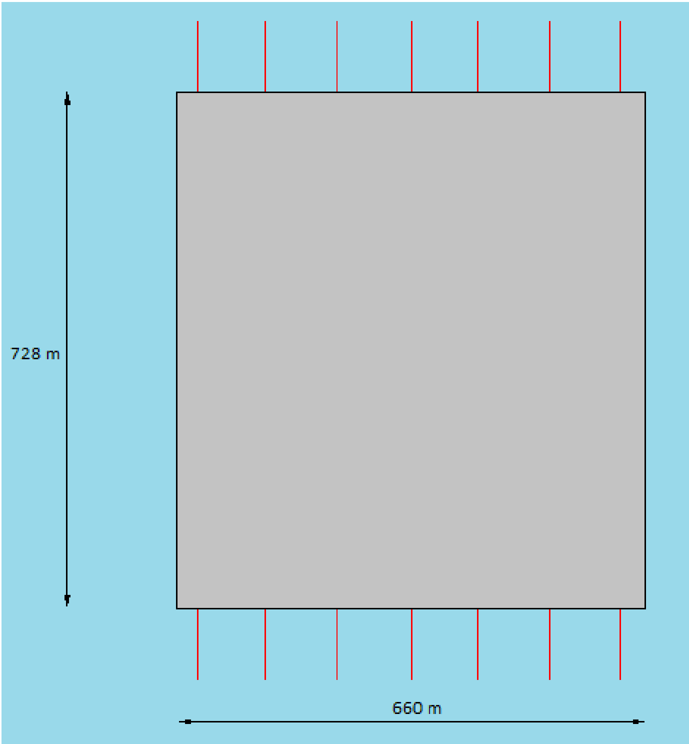


Figure 98: Interpretation of multiple connected platforms

The total surface area of the 'platform' in Figure 98 is $728 * 660 = 480480\ m^2$. One hexagonal platform had a surface area of 9353 m^2, so the 'platform' in Figure 98 is estimated to be $\frac{480.480}{9.353} \approx 50\ platforms$. For a quick calculation of the displacements on this big 'platform', the mass of it is taken as 50 times a single hexagonal platform and 7 mooring lines are attached at each side of the platform. By using the Maple sheet used for the 1 mass-spring system, the following results are obtained.

The amplitudes go to infinite at the following frequencies:
$\omega_1 = 0.0058\ rad/s$
$\omega_2 = 0.0076\ rad/s$
$\omega_3 = 0.0093\ rad/s$

The maximum value for the heave motion with a wave frequency of 0.73 rad/s is:
$x_1 = 0.00012\ m = 0.12\ mm$

The maximum value for the horizontal motion with a wave frequency of 0.73 rad/s is:
$x_2 = 0.000004\ m = 0.004\ mm$

The maximum value for a vertical displacement due to rotation with a wave frequency of 0.73 rad/s is:
$x_3 = 0.000023\ rad \rightarrow 0.000023 * length = 0.000023 * 728 = 0.017\ m = 17\ mm$

These motions are executed at the following accelerations:
a_1 = 0.000067 m/s^2 (vertical motion)
a_2 = 0.0000021 m/s^2 (horizontal motion)
a_3 = 0.000012 rad/s^2 → 0.000012*length = 0.000012*728 = 0.0087 m/s^2 (vertical acceleration due to rotation)

The vertical displacement due to heave is significant smaller as expected, but the vertical displacement due to pitch is larger however. The large displacement due to pitch is not so accurate here because the small rotation of 0.000023 rad is multiplied with the full length of the platform which is 728 m. In reality, the platforms will not have such a full inclination over the full length.

7.5 Different load scenarios

The displacements and accelerations of the 2 mass-spring system is solved for the specific condition of equal symmetric loading and the wave conditions with 4 m wave height, 8.6 s wave period and 76.5 m wave length. Other situations are imaginable for instance higher wave heights, larger wave periods (tsunami), eccentric loading, different amount of moorings etcetera. The results for each scenario is acquired by using the same Maple calculation file as the 2 mass-spring system, but only certain variables are changed. In all the scenarios, the various results should not exceeds the following values.

Output	**Limit**
Acceleration a	< 0.04 m/s^2
$\sigma_{connection}$	< 500000 kN/m^2
$F_{mooring}$	< 22070 kN

Table 18: Output limits

A note at the limitation of the displacements. It is several times stated in this thesis that the relative displacements between platforms should not be too large as this will cause damage to any structures which are at the intersection of two platforms (e.g. roads, lines, pipes etcetera). The (rigid) connection should bear all the forces which are caused by the displacements. So the criteria for the relative displacement between platforms is translated into the strength of the connection $\sigma_{connection}$.

The following load scenarios are looked in to:

- Larger single platforms
- Tsunami wave
- (More) severe wave conditions
- Shallow water depth
- Eccentric loading
- Change in mooring lines
- Combination of all unfavourable loading

Note that all these load scenarios are still about the wave load and its boundaries. Other loads like wind/hurricane and earthquakes etcetera are not in the scope of this thesis. For those loads, another dynamic analysis should be done.

The displacements, accelerations and connection and mooring forces are all acceptable in all the above load scenarios. Except for in the case of a tsunami. For the results of all the load scenarios, see **Appendix 8.4: Results of different load scenarios**.

From the case of changing the stiffness of the mooring lines. It can be concluded that the role of the moorings can be neglected in the mass-spring system as the moorings do not contribute to a decrease of the displacements. All the values for the displacements and accelerations are not changed even when no moorings are applied in the model. The moorings are there to make sure the floating community does not drift away from its location due to repeated displacements.

Tsunami load case

A tsunami wave in deep waters is not characterised by its wave height, but by its large wave length and period. When a tsunami wave approaches very shallow water (ea. the shore) the tsunami can increase to several meters height as 30 m. Even breakwaters specially constructed to withstand a destructive crashing wave of 30 m height has a high probability of failure. There is no way that the floating community can survive such a tsunami wave whenever the floating community is going to be situated in really shallow waters, so this situation will not be elaborated. When the floating community is going to be situated in waters with a water depth of several kilometres, the wave height of a tsunami is several centimetres and the tsunami wave will cause no problems. The input of the tsunami characteristics in the model fits a tsunami wave in intermediate shallow water as the water depth in this model is just 100 m deep. This is the most interesting situation with a tsunami wave to observe the behaviour of the floating community.

Variables:			
Wave height	4 m	2 m	0.20 m
Wave period	1200 s	1200 s	1200 s
Wave length	200000 m	200000 m	200000 m
Results:			
x_1	4.38 m	2.19 m	0.22 m
x_2	0.46 m	0.23 m	0.023 m
x_3	0.066 rad	0.033 rad	0.0033 rad
x_4	3.61 m	1.81 m	0.18 m
x_6	0.081 rad	0.041 rad	0.0041 rad
a_1	$1.20*10^{-4}$ m/s^2	$6.00*10^{-5}$ m/s^2	$6.00*10^{-6}$ m/s^2
a_2	$1.27*10^{-5}$ m/s^2	$6.33*10^{-6}$ m/s^2	$1.27*10^{-7}$ m/s^2
a_3	$1.82*10^{-6}$ rad/s^2	$9.09*10^{-7}$ rad/s^2	$1.82*10^{-7}$ rad/s^2
a_4	$9.90*10^{-5}$ m/s^2	$4.95*10^{-5}$ m/s^2	$9.90*10^{-6}$ m/s^2
a_6	$2.22*10^{-6}$ rad/s^2	$1.11*10^{-6}$ rad/s^2	$2.22*10^{-7}$ rad/s^2
$\sigma_{connection}$	$3.30*10^5$ kN/m^2	$1.65*10^5$ kN/m^2	16513 kN/m^2
$F_{mooring, heave}$	38154 kN	19077 kN	1907 kN
$F_{mooring, pitch}$	38534 kN	19267 kN	1924 kN

Table 19: Results for the 2 mass-spring system when a tsunami occurs

The large displacements causes large connection and mooring forces. But another problem is, how fast can the platforms rise with the rising water level? If the water elevates 4.38 m and the platforms do not respond fast enough, a 4.38 m column of water will be on the platform which causes the platforms to sink because of the extra mass. This problem is illustrated in Figure 99. On the other hand, if the platform rises too fast, citizens will notice the displacement and become uncomfortable.

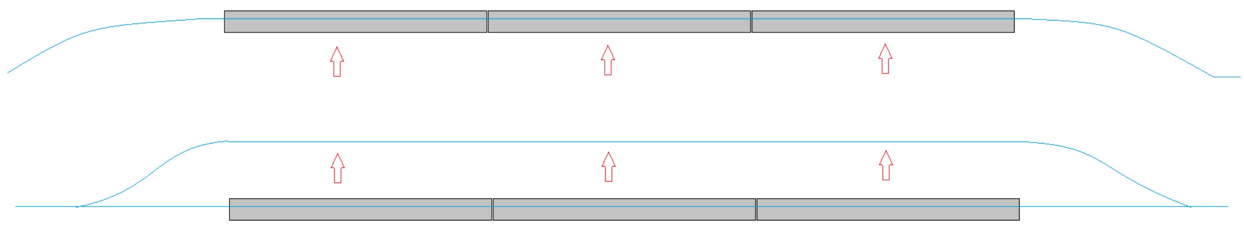


Figure 99: Rising water level due to tsunami wave

From the results it is seen that the accelerations of the displacements are very low. This means that citizens will not notice the 4.38 m elevation of the floating community. The floating community will rise with a speed of $\frac{2\pi}{1200} * 4.38 = 0.023\ m/s$. The water elevation due to the tsunami wave will rise with a speed of roughly $\frac{4}{1200} = 0.0033\ m/s$. This means that the platforms are able to response fast enough to a large water elevation.

Due to the long wave length and the long wave period of the tsunami, the platforms will have displacements almost equal to the wave height as expected. Resonance of the system actually takes place. The problem with large heave motions is that the moorings will endure a very large force, which can even exceed the current Minimum Breaking Load of 22070 kN for moorings with a rope stiffness of 2110 MN. Less stiff moorings can cope better with large displacements but cannot bear large forces. A mooring line with a rope stiffness of 557 MN and a Minimum Breaking Load of 5647 kN also fails during the occurrence of a tsunami wave. And even if the mooring lines do not break, the platforms with mooring lines will maintain at the original water level while other platforms will rise with the water level, see the following figure.

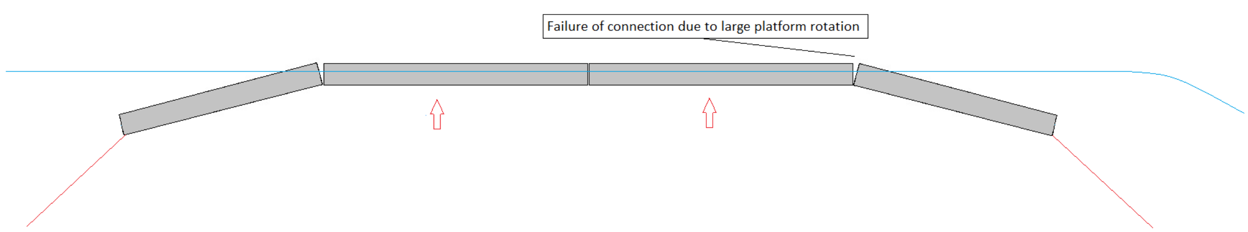


Figure 100: Elevation of platforms when mooring lines do not break

A solution to prevent the mooring lines from breaking and to prevent the problem illustrated in Figure 100 is to have an adjustable mooring line system. Such a system should extend the mooring line only whenever a very large heave motion is detected. The mooring lines are then extended and locked into their new length which is suitable for the new water depth.

Overall, the main conclusion about the occurrence of a tsunami wave is that failure totally depends on the wave height of the tsunami wave. With smaller wave heights (tsunami wave in very deep waters) the heave motion is considerable smaller which leads to smaller connection and mooring forces.

7.6 Summary and conclusion

In chapter 4, the design of the platform is elaborated. Chapter 0 discussed the choice of a suitable connection type and in chapter 6 a mooring system for the floating city is chosen. These three elements (platform, connection and moorings) have to work with each other to realise the basics of a floating city. The platform, connection and moorings have a certain dynamic behaviour when a dynamic force/excitation is exerted on these elements.

An analysis about the dynamics of connected platforms is done by modelling the platforms as a mass-spring system. The floating platform is schematized as a rigid, infinite stiff block founded on vertical and horizontal springs (hydrostatic forces) and diagonal springs (moorings). And the platform is excited by a sinusoidal motion which represents the vertical wave motion. By assuming different displacements of the platforms, all the forces in the springs can be expressed as a function of a certain displacement. By collecting all the forces in a logical manner, a so called equation of motion is obtained to solve the unknown displacements of the system.

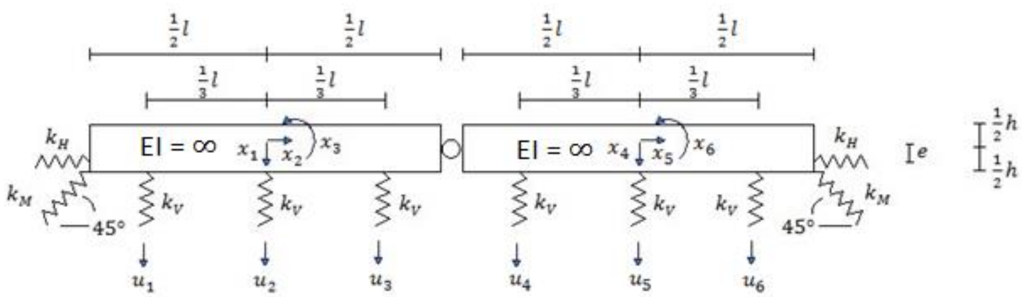


Figure 101: 2 mass-spring system model

Comparing the results of the one and the two mass-spring systems, the outcomes of the occurring displacements and accelerations were the same for the first initial platform and the attached platform experiences displacements 10 times larger than the displacements of the first platform. From this statement, it can be concluded that a second platform/mass attached to the first platform/mass is not beneficial. However, because of the large dimensions of the platforms the displacements of the first platform are very small. Which means that the second platform experiences a displacement 10 times larger than this small displacement, which is still significant very small. This behaviour is actually the same as the characteristics of a whip. A whip experiences a very large displacement towards the end of the whip even when a small displacement is given at the beginning. The reason for this 'whip-like-behaviour' is because a hinged connection is used in the dynamic analysis. A hinge was purely used in the structural schematisation of the coupled platforms to calculate the forces occurring in the connection between the platforms. But in reality a rigid connection is used which means that two coupled platforms actually act as one large single platform. So expected is that the attached platforms will not really experience displacements 10 times larger.

8 Conclusion and recommendations

8.1 Conclusions

The main question in this thesis to be answered is defined as '*Is it possible and realistic to create floating cities from a structural perspective*'.

The answer is that it is theoretically possible to realise floating cities with modular floating platforms rigidly connected to each other. The platforms are inhabitable under severe wave circumstances and they experience very small displacements as long as the connections between the platforms are very rigid constructed. However, to make sure rigid connections in a multiple mass-spring system are indeed experiencing lower connection forces due to smaller displacements, it is best to find this out with a small scale experiment/modelling program.

From the results and calculations in this thesis, it is reliable to connect up to 4 platforms in a linear formation for the chosen design of the hexagonal platform with sides of 60 m and a construction height of 14 m. This means that a floating community of 16 platforms (in a configuration of 4 by 4 platforms) can be realised and house approximately 4000 inhabitants.

The research in this thesis has also come with the following conclusions about 'Realising floating cities'.

Land reclamation versus floating city

- Compared to land reclamation, it is estimated that floating platforms would be more cost effective with water depths larger than 120 m in the Netherlands and 60 m in Singapore.

Platform shape and dimensions

- Hexagonal shaped platforms are the most reliable platform shape for constructing different floating city configurations.
- A hexagon with sides of 60 m results in the optimal size for the platform. Smaller hexagons results in larger draughts with small freeboards. Larger hexagons results in larger freeboards with small draughts.
- Because of the large surface area of the platform, the platform is statically very stable. The moment due to buoyancy is far greater than the other moments. The platform will quickly restore itself to its initial position when it is forced in tilting. Even in extreme cases; like hurricanes and when a high rise building is placed near the edge of the platform (eccentric load), the platform still remains statically stable.

Platform interconnections

- Although a hinged connection in a mass-spring system results in very small displacements, a fully rigid connection type is always preferred for realising a floating community.
- A puzzle-type connection (or concrete toothed) connection is the most easy, cost effective and straightforward connection type to be used.

Mooring systems

- Mooring systems do not contribute to the displacements of the platforms. In other words, they do not reduce the displacements no matter how stiff the mooring line is. The moorings are there to prevent the platforms from drifting away due to repetitive displacements of the platforms.

Dynamic stability

- Comparing the results of the one and the two mass-spring systems, the outcomes of the occurring displacements and accelerations were the same for the first initial platform and the attached platform experiences displacements 10 times larger than the displacements of the first platform. From this statement, it can be concluded that a second platform/mass attached to the first platform/mass is not beneficial. However, because of the large dimensions of the platforms the displacements of the first platform are very small. Which means that the second platform experiences a displacement 10 times larger than this small displacement, which is still significant very small. This behaviour is actually the same as the characteristics of a whip. A whip experiences a very large displacement towards the end of the whip even when a small displacement is given at the beginning. The reason for this 'whip-like-behaviour' is because a hinged connection is used in the dynamic analysis. A hinge was purely used in the structural schematisation of the coupled platforms to calculate the forces occurring in the connection between the platforms. But in reality a rigid connection is used which means that two coupled platforms actually act as one large single platform. So expected is that the attached platforms will not really experience displacements 10 times larger.
- Because of the above conclusion and the fact that rigid connections are used in reality, a multiple mass-spring system can be solved as a 1 mass-spring system where the multiple platforms are schematised as a 'platform' with very large dimensions.
- The main reason why such low displacements and accelerations in the mass-spring system are achieved is because of the dimensions and the masses of the platforms. If the length of the structure is greater than the wavelength, the heave response becomes significant smaller. Also, the natural frequency of the platforms are very small. This means that resonance only occurs at very large wave periods like in a tsunami.
- The coupled platforms are inhabitable under most extreme conditions except for the situation where a tsunami wave approaches shallow water. For a situation where the floating community is in deep waters (>1000 m depth), a tsunami wave is then just a mere water elevation which gives no problems to the floating community.

8.2 Recommendations

There are still a lot to find out and research about the subject of floating cities as not everything could be included in this thesis. The following aspects would be interesting for further research.

Land reclamation versus floating city

- A complete accurate cost analysis for a specific location should be done to determine whether land reclamation or floating cities would be a more cost effective solution. The costs of reclamation sand can make a big difference in the required water depth to make a floating city economic more feasible.

Platform shape and dimensions

- A structural calculation for the platform is needed to maximise the strength of the platform. Structural calculation to determine how much reinforcement steel is needed and whether pre-stressing elements are needed etcetera.
- Maybe the use of other materials instead of concrete might get better structural strength for the platform. However, any reduction in weight of the platform is not preferred for the dynamic stability.
- Load transfer from buildings and other live loads on top of the platform to the inner walls of the platforms should be investigated. Especially when the inside of the platform is used for other purposes (parking garage for example) which leads to a reduction and/or openings in inner walls.

Platform interconnections

- A more accurate structural calculation regarding the forces, moments and stresses in the platform connection is needed to really assure the reliability of the connections.
- Maintenance and the repair of the connections should be detailed looked into as the connections are very crucial to the floating community.

Mooring systems

- A thorough and detailed mooring design is essential. The mooring design depends on the location of the floating city. Different sea beds require different anchoring methods.

Dynamic stability

- A same dynamic analysis approach as in this thesis should be done to check the effect of earthquakes and typhoons on the floating platforms.
- The platforms are considered to be infinite stiff in the mass-spring systems. To cope with the stiffness of the platforms for more accurate results, a finite element method/analysis could be used.
- A multiple mass-spring system should be looked at with 6 degrees of freedom per platform (3D view) when a definite layout of the configuration of the floating city is available. This also could be done best with a finite element method/analysis.

Execution and construction

- Now it is clear that the floating city concept is structurally and dynamically feasible, the last question remains whether it is possible to effectively build it. A research on the construction method and the time management of the hexagonal platforms is essential to start realising the floating city concept.

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