ELEVATING DECISION-MAKING FOR MAINTAINING INNER-CITY QUAY WALLS

A conceptual decision-making model for implementing intervention measures for inner-city quay walls

M.N. (Malcolm) Badu-Sampene

Gemeente Amsterdam

TU Delft Delft University of Technology

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Malcolm Nigel Badu-Sampene

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AUTHOR

Name:	M.N. Badu-Sampene
Student no.	4425804
E-mail:	M.N.Badu-Sampene@student.tudelft.nl

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GRADUATION COMMITTEE MEMBERS

Chair:	Prof. dr.ir. M.J.C.M. Hertogh
1st Supervisor:	Ir. Y. Liu
2nd Supervisor:	Assist. Prof. dr. ir. J.G. de Gijt
External Supervisor:	Ir. H.E.M.Temmink

PREFACE

This thesis titled: 'Elevating decision-making for maintaining inner-city quay walls' is compiled as the final fulfilment of the master Construction Management & Engineering at the TU Delft.

My thesis journey started in November 2018. To be honest it was quite challenging for me to find a suitable thesis topic. The master Construction Management & Engineering is focussed on educating students on various aspects, such as project management, legal and finance. However, during the master the management side was highlighted more in contrast to the 'hard-core' technical issues in the construction industry. My goal was therefore to find an actual topic from a construction management point with a hydraulic, soil or structural 'flavour' to increase my knowledge in this field. Additionally, I preferred an organisation which enabled me to work and conduct my research simultaneously. After conversations with different professors and potential internship companies I decided to choose the topic quay walls and conduct my research at the municipality of Amsterdam.
During the preliminary phase of my research it became clear that there is still a lot of research regarding this topic that needs to be carried out. My interest was drawn to the immense challenge the municipality is facing, almost 200 km of quay walls need to be renewed because they have reached the end of their lifespan. This is a costly, time-consuming and complex issue. However, there is also another side to this, which are the challenges on the short-term. There are critical quay walls which need to be addressed now because of safety issues. Therefore, I decided to focus on improving decision-making surrounding the implementation of intervention measures on the short-term. This enabled me to analyse in-depth technical solutions while at the same time focusing on the managerial side through decision-making.

First, I would like to thank the municipality of Amsterdam for giving me this opportunity and enabling me to gain work experience. Furthermore, for creating synergy between working and conducting my research. Next, I would like to thank my supervisor Harro Temmink for his guidance and support, especially for keeping me on track during moments when I deviate from the scope. Also, for motivating me and for putting my mind at rest when I got stuck during our weekly meetings.
My direct colleagues for reducing the workload when I was working on my thesis. Finally, all the colleagues who took the time to discuss this topic with me.

I would also want to thank my supervisors from the TU Delft. Marcel Hertogh for his though-provoking comments and keeping me on my toes, especially taking other relevant aspects into consideration. Jarit de Gijt for introducing me to the topic quay walls and his out-of the box but straight forward way of thinking. Last but not least is Yan Liu for his support, advice and comments, even when he was abroad for a few months.

Finally, my family and friends. Thank you all for your support during the final stages of my master. It was a long and tough journey but I can proudly say that hard work pays off! Special thanks to my sisters Vanessa and Stephanie, my parents and my girlfriend for always having my back.

Malcolm Badu-Sampene
Amsterdam, 23 august 2019

EXECUTIVE SUMMARY

It is no secret that (asset)managers are currently dealing with a difficult task to maintain and improve the quality of their assets. The main reason for this urgency is the change of use and the (nearing) end of lifespan of these assets. This is especially the case regarding the inner-city quay walls. These quay walls are usually owned and managed by local governments. The city of Amsterdam in particular has a tough task ahead of them. Approximately 200 km of quay wall need to be maintained or renewed of which the technical state is unknown. A vast majority of these inner-city quay walls are retaining walls on wooden piles. The absence of this information makes it extremely difficult for the asset owner, to determine the current technical state of their quay walls. The combination of limited information and time have shown in practise that a quay wall can fail at any moment. To prevent this from happening a variety of intervention measures (= in Dutch beheersmaatregelen) can be deployed to 'extend' the lifespan of the quay walls (short-term). Thereafter a systematic approach can be applied to rebuild or renovate these quay walls (long-term). However, the implementation of intervention measures is an overall complex task due to the densely built area and the stakeholders with divergent interests. Each intervention measure has a certain impact on the core principles within an organisation and external stakeholders, in this case referred to as decision-making criteria.
Therefore, the goal of this research is to provide an objective conceptual decision-making model to determine which intervention method is best suited for a particular location while considering the impact on certain predetermined criteria. The following research question was formulated:

How can a decision-making model be applied to determine which intervention measure is best suited for maintaining inner-city quay walls while considering decision-making criteria?

This research revealed six important topics which need to be incorporated in to the decision-making model, which are the critical cases (1), failure mechanisms (2), intervention measures (3), characteristics of the physical surrounding and the intervention measures (4), decision-making criteria (5) and lastly mitigation measures (6). Additionally, three decision-making moments are identified.

These six topics are used as input to establish a conceptual decision-making model for quay walls. This model is then applied to a case to validate the model. Additionally, interviews with other municipalities in the Netherlands are conducted to discuss parts of the decision-making model. The results of the case and interviews are used to update the decision-making model. This resulted in the decision-making model presented in Figure 1. The steps and decision-making moments are described subsequently.

The model is based on the bounded rationality theory and the political theory. In case of the rational theory decision-makers follow a series of logically successive phases with the idea that this will result in a rational decision. The linear character of this theory should simplify the path to a suitable decision. However, *inadequate information and control* regarding the quay walls show signs of bounded rationality. Therefore, this theory is considered suitable in the quay wall decision-making model. The political theory is based on the arena model. Decisions made at this stage will affect a variety of actors which have divergent objectives. In order to minimize the impact, it is important to take their objectives in to account, especially actors

with large decision-making power. Dealing with a variety of interdependent actors in such an environment can be seen as an arena.

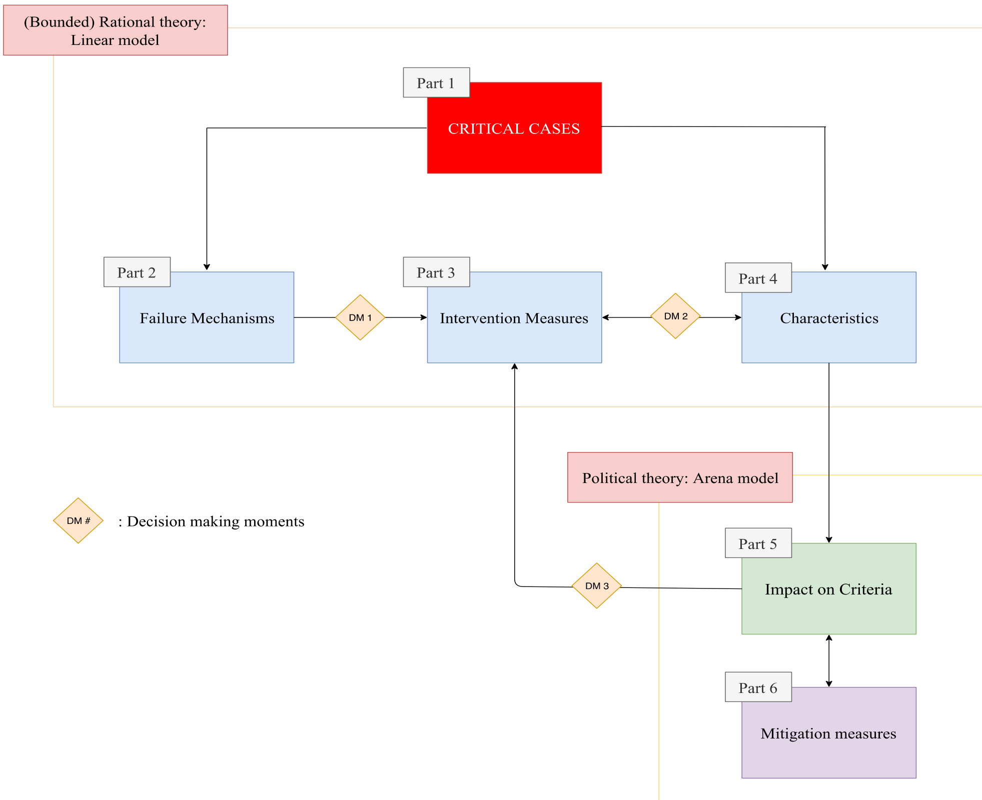

Figure 1 Conceptual decision-making model (own illustration)

Part 1:
Every decision-making process starts with the identification of the problem. In this case the quay wall section which is considered critical is used as staring point. It starts with identifying of the case, the scope, problem and objectives. A radius of ca. 300 m (i.r.t. to the critical quay wall) is chosen to take projects and other physical aspects into consideration.

Part 2:
After the problem is identified the next logical step is to translate the problem in to failure mechanisms based on the observed signals. Two limit states are identified namely the Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The first limit state describes the actual failure of the structure (collapse). The latter explains that the quay wall does not need to collapse entirely for it to lose its function. Regarding the ULS there are five main areas identified in order for the quay wall to collapse which is failure of the soil (1), failure of the construction (2), loss of equilibrium of the elements (3), loss of equilibrium due to water pressure (4) and piping and cracking (5). For each type of quay wall a variety of failure mechanisms are identified which are related to the five areas. The interviews revealed that the most common failure mechanisms regarding the inner-city quay walls (retaining walls on wooden piles are: broken head beams, damaged or absences of an erosion screen and a damaged quay wall floor. The last two failure mechanisms can cause sinkholes, which is difficult to detect but can have large consequences if they appear.

Part 3:
In this part the different failure mechanisms are coupled with the intervention measures. The failure mechanisms determine which intervention measure is best suited. This research revealed 23 theoretical intervention measures, 5 measures were focussed on reducing the driving forces and 18 on increasing the resisting forces. Additionally, two out-of-the box measures were proposed, namely the application of geo encapsulated sand elements and lowering the retaining height of the quay wall. The results revealed that the measure: lowering the quay wall was considered valuable from a safety perspective. Interviews with other municipalities did not result in additional intervention measures.

Part 4:
In part 4 the characteristics of the intervention measures and the cases are described. For the characteristics of the intervention measures a detailed description is given of the activities needed to implement the measure. In order words: what do we need to do in order to implement the selected intervention measure. Another input in this part is to look at the specific characteristics of the surroundings. The objective is to couple the characteristics of the intervention measure and the surroundings in order to determine what the impact will be on the criteria which will be used in part 5.

Part 5:
Part 5 looks at the characteristics which are determined in part 4 to measure the impact on the criteria. The case study and interview result showed that each municipality has his own set of decision-making criteria. Safety is considered the most important criteria. It cannot be considered a trade-off because assets are required to meet certain safety levels, which are stipulated in the legislation. Other criteria such as cost, economy, liveability and accessibility are of secondary importance. It depends on the political climate which criteria is more important. This research also revealed that in order to deviate from the mandatory safety levels, a policy change is necessary. For instance, if accessibility has a higher importance level than safety, a (temporary) new legalisation should be made. Sufficient widely-based support needs to be created for this new legislation.

Part 6:
In this last part mitigation measures are proposed in order the minimize the impact on the criteria. If the impact is considered too high mitigation measures need to be implemented. Such as compensating business owners along the quay wall if the road becomes unavailable.

Decision-making moment 1:
In the first decision-making moment a choice of intervention measures is made based on the perceived failure mechanism(s). There are two possibilities, namely intervening in time and failing to failing to intervene in time (see Figure 2). The latter will result in (economic) damages and injuries or fatalities. This research proposed a methodology to determine these economic damages, due to lack of theoretical approaches. The methodology is based on 7 impact areas, containing 6 physical aspects and 1 impact area related to the loss of life. The case study revealed significant damages in case a quay wall section fails. This ranged from 2 to 50 million depending on the location, number fatalities, and failure length. The number of facilities is the largest contributor to the total damages.
In case timely intervention takes place three outcomes were identified, namely reducing the driving forces, increasing the resisting forces and waiting for additional information. The latter outcome was identified after applying the model on a case.
This decision-making moment is time sensitive. The quay wall can fail if waiting for additional information takes too long. On the other hand, making decisions based on available

information and observed failure mechanisms can result in wrong decisions. Monitoring (XYZ -direction) is a useful tool to determine possible failure. Furthermore, a trade-off can be made to accept the risks and consequences if the quay wall fails or to implement intervention measures.

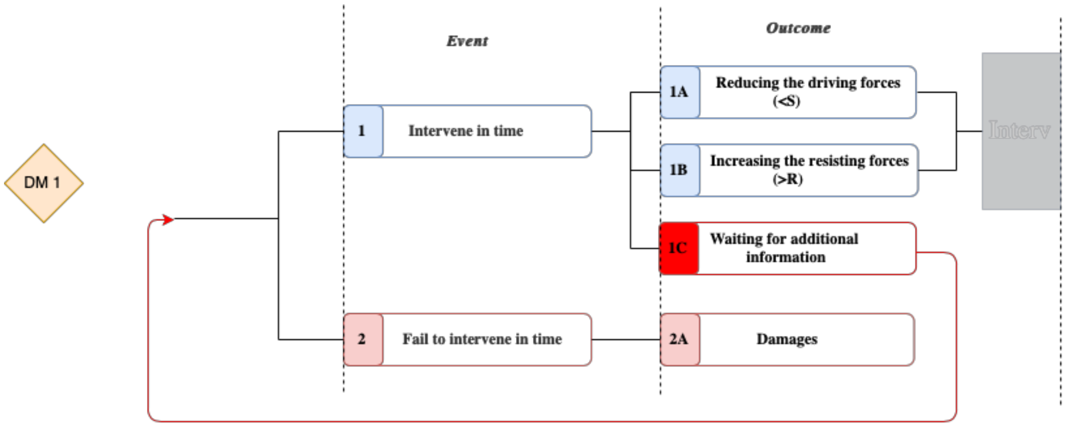

Figure 2 Possibilities after identifying the failure mechanisms (own illustration)

Decision-making moment 2:

The second decision-making moment takes the physical surrounding of the quay wall into consideration and the failure mechanism(s) determined in the first decision making moment. The characteristics of the specific intervention measures are reflected against the characteristics of the surroundings. The goal is to make decisions based on the intervention measures and the location specific aspects. These aspects are presented in Table 1.

Table 1 Physical aspects which can influence the choice of intervention measure

Analysis of the surroundings (non-exhaustive)		
	Indicator	Description
1	Buildings	Assessed depending on the distance between the quay wall and buildings
2	Houseboats	The number, size and type of houseboats present are analysed
3	Pipelines/Cables	Available sources need to be consulted to determine the location of the pipelines and cables. In the Netherlands the Kadaster can provide this information.
4	Trees and plants	Municipal departments provide information about the number of trees and their condition. Sometimes this information is made public by local governments.
5	Service	This part describes the available services such as shops, bars and other public or private services people make use of.
6	Roads and waterways	All available information regarding the waterway and road is described, such as the depth, width and the type of users.
7	Other physical exceptions/projects	Other additional physical aspects are described in this part. Such as public toilets and poster columns. Furthermore, planned and project in execution are described here. This can have significant impact on the quay wall.

Decision-making moment 3:

In the last decision-making moment, the characteristics of the surroundings and suitable intervention/prevent measure are explained through the predetermined criteria. This will reveal what the impact of the prevention or intervention measure will be. If the impact of a certain intervention is considered too high, the decision can be made to revisit other intervention measures. Or mitigation measures can be introduced to reduce the impact level on the stakeholder(s). Decision-making should involve actors such as the local (and national) government, organizations and residents. Each of the stakeholder has its own set of interests and power and can willingly or unwillingly hamper the process.

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1 INTRODUCTION

Headliners such as: 'Amsterdam to tackle neglected bridges and quays' and 'Technical state of the quay wall: worse than assumed' are statements issued by the New York Times and the Volkskrant, which cannot be ignored any longer. The issues surrounding quay walls and bridges are urgent and need to be tackled sooner rather than later. In the present-day government bodies in large cities are faced with a difficult task to maintain and improve the quality of their assets. The main reason for this urgency is the change of use and the (nearing) end of lifespan of these assets. In the Netherlands local government bodies are in particular dealing with these kind of issues regarding their inner-city quay walls. These distinctive iconic walls are located along the canals of the city and can be more than 100 years old (Gemeente Amsterdam, 2018). These inner-city quay walls have different functions. The most important functions are retaining, mooring, protecting and bearing (CURNET, 2005; Wel, 2018). The inner-city quay walls were initially constructed to withstand a smaller amount of load than in the present day. This is mainly due to the increase of (heavy) traffic in these area's (Gemeente Amsterdam, 2018). Furthermore, natural decay (because of aging) of these walls increases the sense of urgency (Vervoort, 2013). This is especially the case regarding retaining walls on wooden piles.

Throughout the years a lot of information regarding existing quay walls have become difficult to find. This has unknown reasons. The absence of this information makes it extremely difficult for the asset owner, to determine the current technical state of their quay walls. Relatively expensive inspections need to be carried out along hundreds of kilometres of quay walls. This poses a dilemma. Doing nothing is risky because it only increases the probability of failure. Renewing all the quay walls on the other hand is nearly an difficult task, it is a time consuming and costly procedure. Furthermore, renewing a different quay wall sections simultaneously means that (a significant part of) the city centre will not be accessible for a long period of time.

1.1 Problem definition

The motive of this research is the current situation in Amsterdam. The municipality of Amsterdam is dealing with one major problem, lack of knowledge regarding the technical state of the quay walls. A majority of the quay walls are old and have reached the end of their lifespan. This means that quay walls in Amsterdam can fail at any moment, which in turn, can have large (financial and societal) consequences. Failure occurs if the load or solicitation (S) is larger than the resistance (R) of the structure (Kapur & Pecht, 2014; Wel, 2018; Wolters, 2012). To prevent this a variety of intervention measures can be deployed to 'extend' the lifespan of the quay walls (short-term). Thereafter a systematic approach can be applied to rebuild or renovate these quay walls (long-term).
Also, a majority of the quay walls are situated in the densely populated inner-city. When deploying intervention measures there are a lot of constraints which need to be taken in to account, such as dwellings, water and (underground)pipelines. Another important issue are the stakeholders living and working in the surrounding area. Successfully implementing intervention measures highly depends on satisfying key stakeholders. Stakeholders are described by Bryson (1988) & Moore (1995) as an actor (can be both internal and external) which is willing or unwilling involved in a project and can influence the progress of the project via interaction. Stakeholders can have significant decision-making power and therefore play

an important role. A negative attitude towards implementing intervention measures can result in delays, additional costs and lack of trust in the municipality. Another aspect which is considered important is safety. As discussed earlier the combination between time constraint and lack of information can result in accidents. These accidents can cause tangible or intangible damages. In any case safety should be safeguarded and accidents need to be prevented. If an accident occurs with injuries and/or fatalities it may result in social and political unrest.
The implementation of intervention measures is an overall complex task due to the densely built area and the stakeholders with divergent interests.

1.2 Main objective

To secure the safety of the quay walls there are generally two options, namely decreasing the load or increasing the resistance of the structure (de Gijt & Douairi, 2017; Movares, 2018). As mentioned earlier there are different intervention measures that can be implemented to achieve this result. Initial conversations with managers at the municipality of Amsterdam revealed that intervention measures are chosen solely on the identified failure mechanisms. However, each intervention measure has an impact on for instance the surroundings, stakeholders and other criteria. In addition, not every intervention measure is applicable in a certain area due to location specific constraints. Therefore, the goal is to improve decision-making surrounding the implementation of the different intervention measures. This is achieved by taking the failure mechanisms, intervention measures and factors which can influence these decisions in to account. By combing these aspects a more suitable and objective intervention measure can be chosen early on.

The objective of this research is to provide a decision-making model to determine which intervention method is best suited for a particular location while considering the impact on certain predetermined criteria.

1.3 Scope and boundaries

The problem related to the quay walls are large and complex, therefore boundaries are set to ensure the feasibility of this research.

- Intervention measures

In this research intervention measures are described as temporary measures which can be implemented to 'extend' the lifespan of the quay wall (by means of modification) or to relieve the quay wall from large forces (such as removing parking spaces). The explanation is that intervention measures need to take place in order to prevent further decay of the quay wall.

- Inner-city quay wall

There are a variety of different types of quay walls. In this research the main focus is on inner-city quay walls. Inner-city in this research is referred to as the densely built area in the city centre of the city. It however depends on the size of the city how large this area is. Quay walls situated near industrial areas outside the city centre and ports are not part of the scope. Preliminary research has shown that retaining walls on wooden piles are the most common and oldest type of quay walls in city centres. These are also referred to as type 2 quay walls.

- Criteria

Criteria are needed to determine which aspects are considered important when making decisions. For example, safety, accessibility and costs are usually decisive criteria in infrastructure projects. And are assumed to be interrelated with each other. These criteria are determined based on literature research and are further elaborated on in this research.

1.4 Research question

In this section the main research question is presented. Also, sub-questions are compiled to answer the main research question. The main research question is as followed:

How can a decision-making model be applied to determine which intervention measure is best suited for maintaining inner-city quay walls while considering decision-making criteria?

Sub-questions:

- What are currently the failure mechanisms related to quay walls?
- What are the possible consequences or intervention measures for inner-city quay walls after a failure mechanism has been determined?
- What is the state-of -art regarding the decision-making theories and models?
- Which decision-making criteria related to maintaining inner-city quay walls can be identified?
- What kind of theoretical conceptual decision-making model can be established for quay walls and applied in practise?
- How can the conceptual decision-making model be updated?

1.5 Research method and approach

In this section the research method and approach are discussed in order to ensure reproducibility. This means that the steps taken in this research are clearly defined and documented in such a way that somebody else can conduct the same research. In section 1.5.1 the research approach is explained (see Figure 3). In section 1.5.2 the research method is further elaborated on.

1.5.1 Research approach

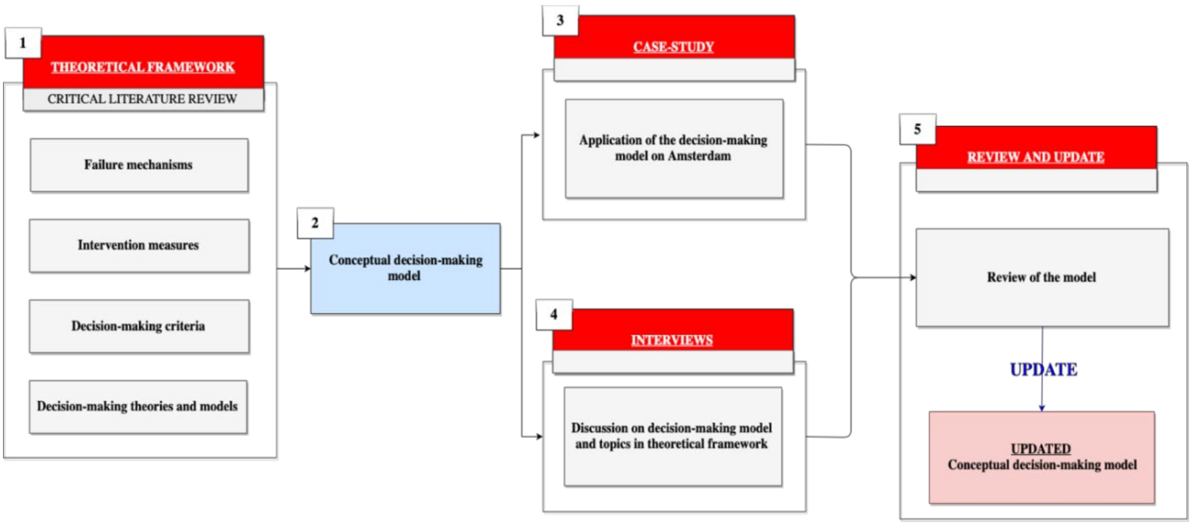

Figure 3 Overview research approach and methods (own illustration)

1. Theoretical framework

First, the different failure mechanisms related to inner-city quay wall are discussed. This will give more understanding regarding the pre-stages of failure and how quay walls actually fail. The next step focuses on the different intervention measures, which is a crucial part of this research. This information will mainly be derived from the literature. Also, consultation with professionals will take place to find out if there are other suitable and innovative solutions. Next, the decision-making criteria are described. These criteria will be determined based on literature review and consultation with professionals. This step will reveal which criteria are considered valuable. In the last part decision-making models and theories are looked at in more detail. In order to make well-balanced decision it is important to look at different decision-making models described in the literature. By analysing different models and their (dis)advantages it will become clear which model is best suited for this research.

2. Conceptual decision-making model

Based on information retrieved from the theoretical part a conceptual decision-making model is established. The elements discussed in the theoretical framework are crucial topics to create the conceptual decision-making model. This model should be used to choose a suitable intervention measure based on the quay wall which is being assessed.

3. Case-studies

In this phase the conceptual model is used in practice in order to test its applicability to a specific case. The main objective is to validate the model. According to Verhoeven (2011) validation explains to what extend the research is free of systematic errors or bias. In this case the case study is used as tool to check if the model contains any errors. The goal is to increase the reliability of the model. After validation it will become clearer if certain parts of the model need to be adjusted.

4. Interviews

Another part of validation of the model is through interviews. At this stage of the research interviews with other municipalities are conducted. The goal is to find out if there are other additional failure mechanisms, intervention measures, decision-making criteria that can be considered valuable for this research. Also, the conceptual decision-making model will be discussed to check if adjustments are necessary. Assetmanagers and project leaders from large cities (such as Utrecht, Den Haag, Rotterdam) are approached. Approximately 5 interview with different municipalities including one organisation responsible for the waterways in the region of Amsterdam is used as basis.
In addition, the organisation responsible for the waterways is also interviewed. Quay walls are hydraulic structures which are situated alongside the waterways. These organisations are important stakeholders with significant decision-making power when it comes to activities near and on the waterways.

5. Review of the model

The results from the case study and interview will be used to update the conceptual decision-making model. These findings are incorporated in to decision-making model to establish an 'updated' decision-making model for quay walls. This step is performed to increase the reliability of the model. The end result will be a decision-making model with input from practitioners (interviews with municipalities) and the case study.

1.5.2 Research method

In this section an explanation if given of the applied research method. This will reflect the type of method used as described in the literature. According to Baarda (2014) there are generally three methods to collect data, namely through questions, observation and utilizing existing material (through testing and investigation). In this research two of the three methods are applied. First, interviews, which is part of asking questions. And secondly desk and literature research, which is part of utilizing existing material. Baarda (2014) explains observation as analysing the behaviour of people and using this information to draw conclusions. In context of this research observation is not considered a relevant method.

For the interviews a semi-structured list of closed and open questions will be applied (interview protocol). This is necessary in order to compare the different answers in an efficient way but still leave room for other relevant topics that can contribute to this research. The objective is to approach stakeholders such as the municipality to gather additional information for the decision-making model.
Regarding desk and literature research different sources will be used to increase the reliability and validity of the information. Based on this information a more comprehensive explanation can be given.

1.6 Scientific, practical and social relevance

The relevance of this research can be viewed from a scientific, practical and societal point of view. First the scientific relevance explains what kind of gap this research tries to close. This gap is determined based on literature review. The practical and social relevance are intertwined with each other. The goal of this research is to establish a decision-making model in order to improve decision-making surrounding the implementation of intervention measures. These decisions will eventually impact the people working and living in Amsterdam. In this section these perspectives are explained in more detail.

Scientific relevance
There is a lack of scientific literature regarding the interdependencies of decision-making criteria. Most literature addresses the decision-making criteria separately. In city centres which are densely populated it is impossible to ignore this. This research tries to explain how certain decision-making criteria are related to each other by utilizing other scientific models. Another scientific aim of this research is to determine a method to calculate the damages after a quay wall has failed. Literature research has revealed that damage calculations are mainly focused on flood risk assessments. These flood risk assessments use economic exposure values and so-called damage functions. The damage functions are based on flood heights. Applying these methodologies on quay wall failure in the city of Amsterdam is not accurate. Therefore, this research aims to analyse different methodologies and propose a more suitable approach.

Practical relevance
The practical relevance for the municipalities is to find out what kind of impact intervention measures will have on certain decision-making criteria. Until now there is no similar research done. However a relevant research is conducted by Breederveld (2017). In this study a 'construction stakeholder matrix'(C&S-matrix) is used to determine which construction method results in the least resistance from stakeholders. Results from this study can be used as input for determining the impact on stakeholders in this study.

The end result of this research can help the municipalities to strategically improve their quay walls while minimizing the impact on their decision-making criteria. This part is more focussed on improving the internal processes within the municipality.

Social relevance
One of the most important responsibilities of the municipality is 'duty of care'. This means that the main objective of the municipality is to take care of its citizens. While doing so they take of certain public values (such as transparency, sustainability, equality etc.) when fulfilling their tasks. In this particular case the intervention measures will have a significant impact on the people working and living in Amsterdam. The duty of care is taken in to account when the impact of intervention measures on its surroundings is addressed and if possible minimized. This research aims to provide more detailed information regarding these impacts.
Furthermore, different media channels such as the Volkskrant, Parool, AT5 and New York Times have recently addressed the problems associated with the quay walls. This is in response of the press release issued by the municipality of Amsterdam on 7th of February 2019. This shows that the topic of quay walls is an important and actual subject which needs to be tackled sooner rather than later.

1.7 Layout of the report

In this section the layout of the report is presented. For clarity reasons the chapters are coupled with the sub-questions (section 1.4) and presented in Table 2.

Table 2 Overview of the layout of the report

Chapter	Title	Research question
2	Background information quay walls	
3	Failure mechanism of inner-city quay walls	What are currently the failure mechanisms related to inner-city quay walls?
4	Intervention measures	What are the possible consequences or intervention measures for inner-city quay walls after a failure mechanism has been determined?
5	Decision-making theories & models	What is the state-of -art regarding the decision-making theories and models?
6	Decision-making criteria	Which decision-making criteria related to maintaining inner-city quay walls can be identified?
7	Conceptual decision-making model	What kind of theoretical conceptual decision-making model can be established for quay walls and applied in practise?
8	Case study: Quay walls in Amsterdam	
9	Critical analysis of the conceptual decision-making model	How can the conceptual decision-making model be updated?

This report consists of four parts. The first part of the thesis describes the theoretical framework. Five topics are discussed in this section. First background information of the quay walls aregiven. This section gives relevant background information about the history and application of quay walls. Next the different failure mechanisms related to the quay walls are addressed. These failure mechanisms need to be identified in order to find out how quay walls fail. In section 4 an overview is given of the possible outcome and intervention measures after a failure mechanism has been identified. In section 5 different decision-making theories and models are discussed. This is necessary to know how and why decisions are made. Section 6 explains the different decision-making criteria. The possible intervention measures have a certain impact on people, organisations and the environment. Literature study has revealed that these impact areas are generally used as decision-making criteria.

The second part of the thesis is dedicated to the conceptual decision-making model. The information retrieved from the theoretical framework is used as input to establish this model.

In the third part of the thesis Amsterdam is used as case study for the application of the conceptual decision-making model. The same steps are followed as in the theoretical framework. However, in the last section the conceptual decision-making model for Amsterdam is applied to a specific case.

Chapter 9 contains the fourth part. In this chapter the conceptual decision-making model is reviewed. Input from interviews and the analysis of the case can yield certain changes in the decision-making model. Finally, in the last chapters of this thesis (section 11 and 10) the conclusion and discussion are presented.

2 BACKGROUND INFORMATION QUAY WALLS

In this chapter background information is given about quay walls. First a brief introduction is given regarding the history of quay walls. In section 2.2 and 2.3 the functions and typologies of quay walls are discussed respectively. Then in the last section the management strategies and the current state of art related to quay walls are further elaborated on.

2.1 History of quay walls

Quay walls are earth-retaining structures with the main purpose to hold back earth and maintain a difference regarding the elevation of the ground surface (CURNET, 2005; Zhou, 2006). The type of quay walls coincides with the development of sea trade and vessels. The sea trade started around 6000 BC around the Mediterranean Sea (Egypt) and Africa. This search was necessary to provide various goods for increasing populations. In order to facilitate the sea trade large vessels and ports were needed to load and unload various goods. As time progressed technological developments enabled ports to improve the design of the vessels, cranes and thus the type of quay wall construction (De Gijt, 2010). This is reflected when analysing the different materials used for constructing quay walls. Literature study revealed that the first quay walls were built of wood and stone (De Gijt, 2010; Gemeente Amsterdam, 2018). Steel and concrete were used more frequently as construction material after the invention of iron in 1900. The shape of the quay wall did not change over time, however the retaining height did. This is mainly because of application of steel, which has more strength than other materials (Breederveld, 2017; De Gijt, 2010; Tilborg, 2016).

Quay walls were not only built in ports for large vessels, but also in (centre) cities. These inner city quay walls were initially built for smaller vessels to moor in order to load and unload goods and store them in the nearby warehouses (Daalder & Speet, 2005; Gemeente Amsterdam, 2016). Nowadays these inner-city quay walls have become iconic structures in cities (CURNET, 2005; Gemeente Amsterdam, 2018; SBRCURnet, 2013). The quay walls are used for different purposes depending on the situation at hand. These functions are described in section 2.2.

2.2 Functions of quay walls

Quay walls have variety of functions. Regarding inner city quay walls there are five important functions, namely (CURNET, 2005; SBRCURnet, 2013; Wel, 2018):

- Bearing function

The quay wall must be able to safely transfer the vertical loads from street level such as traffic to the subsoil. This includes forces caused by loading and unloading goods from vessels and operating heavy vehicle such as cranes.

- Retaining function

The quay wall is used to establish a clear distinction between land and water. A difference in elevation is needed to keep the water from reaching the land. The soil on the land-side is retained by the quay wall structure.

- Mooring function

In city centres vessels can moor at the quay walls. This is done with the help of fenders or bollards. In some cities there are also small vessels and houseboats situated in the canals. Municipalities usually select certain locations where it is allowed to moor. These rules are stipulated in their policy guidelines.

- Traffic function

In the densely built cities the spaces directly behind the quay wall has a parking function. Next to the parking spaces there is a usually a lane, which goes in one direction. Between the parking spaces there are generally bike racks and/or trees.

- Public function

Events are regularly held in the canals and along the quay walls. Recreation like fishing and sailing can also take place along the quay walls. The quay walls situated in city centres can have significant monumental value.

As discussed earlier the development of construction materials to build the quay walls has developed over time. The change of materials resulted in different construction techniques and thus the type of quay walls. Section 2.3 describes the different quay wall typologies.

2.3 Quay wall typologies

De Gijt (2005) distinguishes four basic types of quay walls. These types are presented in Figure 4. Example's for each type are also illustrated in the aforementioned figure. These differences highly depend on the construction method used in a specific country and the location of the quay wall.

1. Gravity walls

The retaining capacity is obtained by the self-weight of the structure. The structure of these gravity walls ensures sufficient shear resistance in the soil to prevent the quay wall from failure mechanisms, such as sliding and overturning.

2. Sheet pile walls

In cases where sheet piles are applied the retaining capacity is obtained through soil pressures. Sheet piles can be made from different materials such as concrete, wood or steel. The sheet piles are usually applied in cases of large retaining heights.

3. Structures with relieving platforms

These relieving platforms are in principle sheet piles with a relieving platform. This platform reduces the tensile forces in the foundation and the forces on the underlying retaining wall significantly.

4. Open berth quays

This structure has the visual appearance and characteristics of a jetty and is usually constructed over a slope. It can be described as a deck on (concrete) piles. A possibility is to apply a vertical sheet pile on the upper part of the slope.

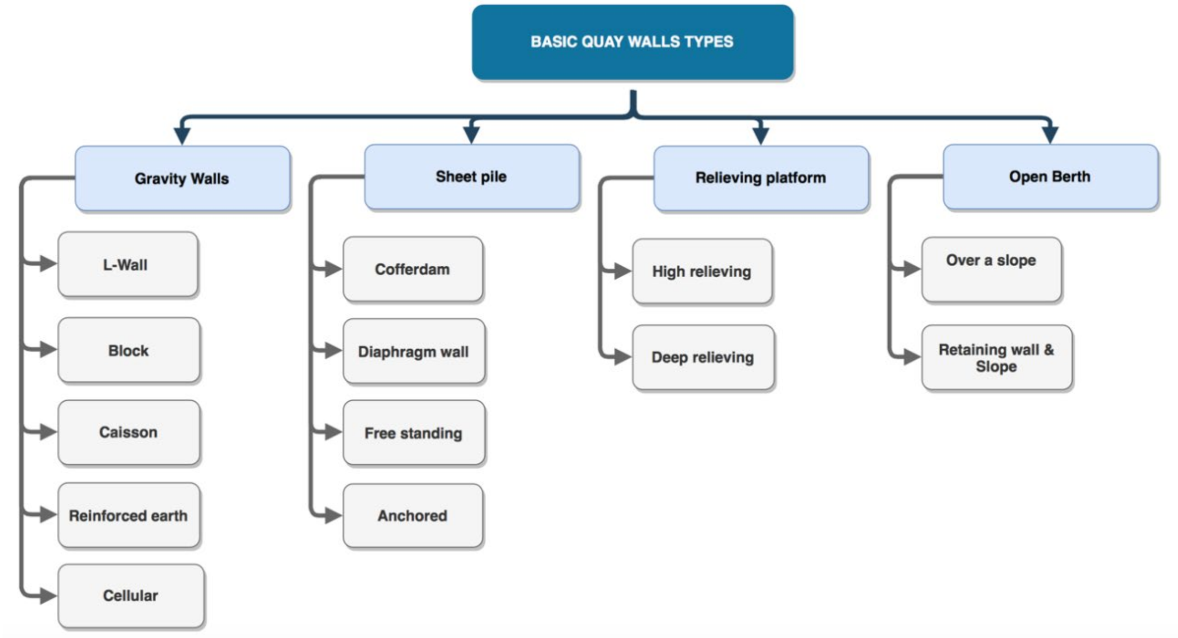

Figure 4 Quay wall typologies (own illustration)

Regarding inner city quay walls the SBRCURnet (2013) distinguishes four types of quay walls. These types are described subsequently below and illustrated in Figure 5.

- Type 1: Retaining wall (constructed directly on the load-bearing layer)

A retaining wall constructed directly on the load-bearing layer can for example, be a solid construction of piled masonry, basalt columns, a caisson construction, or a concrete construction. The construction is directly founded on the substrate, or often on a (reinforced) concrete floor. Furthermore, L-walls which are directly constructed on the load bearing layer also falls under this category of quay walls.

- Type 2: Retaining wall on piles

A retaining wall based on piles consists of a solid weight wall of piled masonry or basalt columns on floor with underneath piles. The piles can be wooden, concrete or steel tubular piles, whereby at least one row of strut is usually placed in order to be able to transfer the horizontal.

- Type 3: L-wall on piles

This type of quay wall is constructed in a L-shape. It consists of a relieving platform to reduce the horizontal loads on the piles. The L-wall is a relatively new construction type and are usually found in urban areas. The piles are usually screwed in to the soils where after the L-wall is cast in-situ.

- Type 4: Sheet piles

Sheet pile constructions are earth retaining structures driven into the ground. Steel or concrete sheet piles can be used for this, but also wood and plastic for lighter structures such as paving. The sheet piles can be placed with an anchored strengthen the structure.

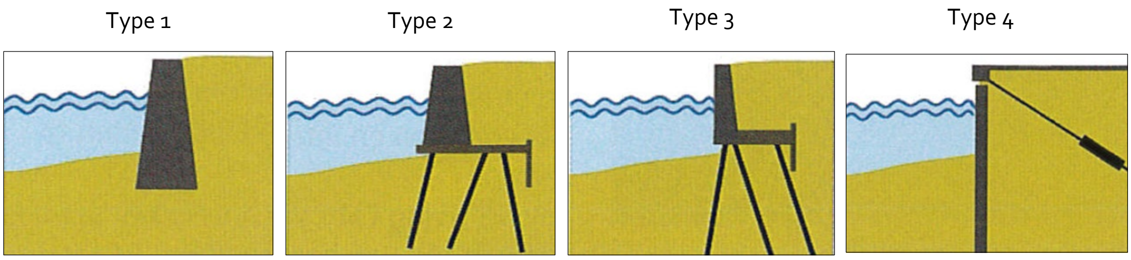

Figure 5 Most common type of quay walls in cities (SBRCURnet, 2013)

Different materials can be used for the (sheet) piles such as concrete and wood. Type 1 and type 2 are the most common types in city centres. These two types are also the oldest. Type 3 and 4 quay walls are relative new methods. Throughout the years different construction methods are used for the construction of quay walls. The application of new construction methods coincides with the change of functional requirements (Tilborg, 2016). The time line illustrated in Figure 6 shows these changes.

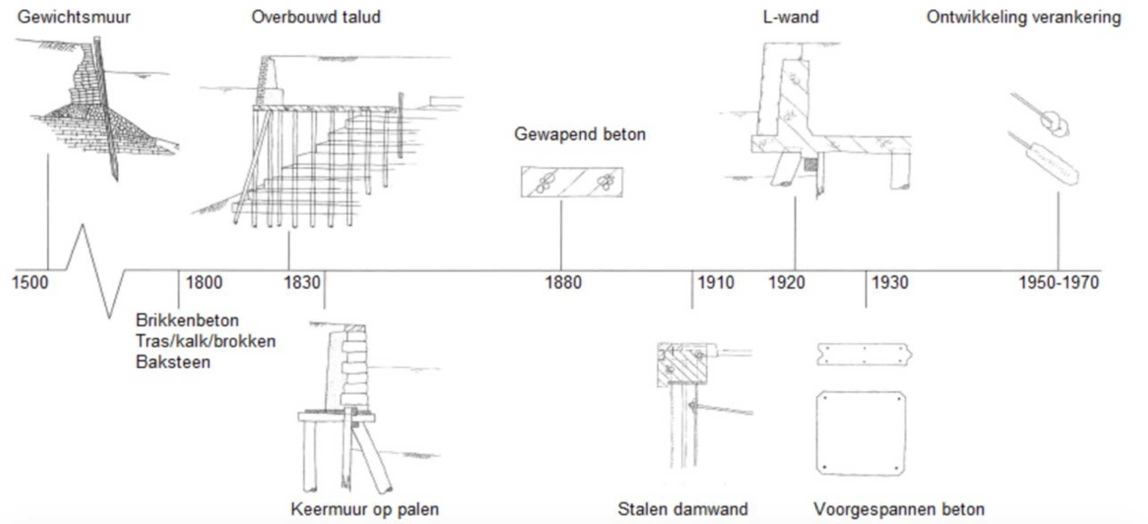

Figure 6 The application of different types of quay walls in time (SBRCURnet, 2013)

2.4 Managing quay walls and state of art

As discussed in the previous sections quay walls fulfill different functions and are therefore important assets. Quay wall are generally part of public infrastructure and thus owned and managed by (local) governments. As like most public assets, management strategies are deployed to maintain and renew quay walls when they reach the end of their life span. The literature distinguishes two main types of infrastructure asset management, which is operational and strategic asset management (Hastings, 2015; Steyn & Nicholas, 2016; Too, Betts, & Arun, 2006; Wilmott Dixon, 2010). Operational infrastructure asset management focusses on ensuring that the asset works accordingly. This means that is should fulfil its function during its intended life time. Strategic asset management however deals with the integration of the environment, businesses and user needs. This type of assetmanagement looks at the asset from a broader perspective by taking other assets and actors in to account. The end goal is to optimize the value of the asset (Hastings, 2015).

Currently asset managers of quay walls focus mainly on operational asset management. In this case the goal is to keep the quay wall operational. This statement is underlined by De Gijt (2005). He describes that present management strategies of quay walls are based on an operationally-focused concept. This concept only uses available information to maintain the quay wall. This type of management can be categorized as reactive management. In these cases, intervention takes place after damages, complaints or when defects have been identified. He further explains that this type of management is outdated and there is a need for change towards a more pro-active management style. Within this type of management style, the quay wall is analysed and modelled based on a set of predetermined objectives. The analysis will reveal certain threats and areas of attention. This in turn will result in a variety of preventive maintenance activities. These measures are then included in a management plan to maintain the quay wall for a certain amount of years. Literature study has revealed that proactive maintenance strategies is expected to improve the performance of an asset. A reactive maintenance strategy on the contrary is expected to be associated with lower performance (CURNET, 2005; Hastings, 2015; Swanson, 2001).

Each type of quay wall has his own characteristics and failure mechanisms. In light of a more pro-active management style, it is necessary to find out how these quay wall types fail in order to take appropriate measures against them. These failure mechanisms are addresses in the next chapter.

3 FAILURE MECHANISMS OF INNER-CITY QUAY WALLS

This chapter describes the failure mechanisms related to the four types of inner-city quay walls discussed in chapter 2.3. The failure mechanisms will indicate how these quay walls can fail. By identifying these failure mechanisms suitable measures can be taken against them. In this chapter the following research question is answered:

What are currently the failure mechanisms related to inner-city quay walls?

First an overview is given of the ultimate limit state of quay walls based on the international guidelines. Next, the failure mechanisms related to the four quay wall types are explained subsequently. Finally, a conclusion is given by answering the aforementioned sub-question.

3.1 Limit states of quay walls

A failure mechanism describes in what kind of way a structure fails and therefore loses his function. This can have two main causes is made, namely due to a permanent or temporary situation (CURNET, 2005; Meijer, 2006). In case the structure fails then a permanent situation is in effect. When the structure has not failed yet than it is called a limit state. A limit state is described as a condition of the structure in which it can no longer comply with the design requirements. The literature distinguishes two general limit states (Kapur & Pecht, 2014; Roubos, et. al, 2018; Wel, 2018; Wolters, 2012):

- Ultimate limit state (ULS)

This limit state occurs during an extreme situation and the describes the state of the structure just before failure. When the ULS is exceeded the structure will fail. Depending on the type of quay wall structure there are a variety of failure mechanisms which can be identified. Extreme deformations over a certain period of time can also cause the structure to fail.

- Serviceability Limit State (SLS)

SLS deals with the limit state related to the functionality of the quay wall. The deformations are significantly high which causes the structure to lose his function during its service lifetime. This is usually reflected in the appearance of the structure (such as cracks and displacements).

From a mathematical point of view a limit state can be expressed as a limit state function. In principle two contrary factors are considered. First the strength of the structure itself (resistance) and secondly the loads working on the structure (Solicitation). To prevent failure the resistance must be larger than the solicitation. This is usually expressed in terms of a reliability function. This is denoted by the following equation:

$$Z = R - S \tag{1}$$

where: Z = ultimate state value; R = resistance of the structure; S = solicitation or load working on the structure. The ultimate limit state is reached when Z is equal to zero.

For assessing and designing quay walls there are a variety of guidelines that can be consulted. In this research the guidelines for European purposes will be used as starting point. These Eurocodes contain European guideline for designing and assessing the safety of every construction and generally have precedence over the national guidelines. However due to the level of detail of the national guidelines these are also considered valuable for this research. The following guidelines are used:

European Perspective

- Eurocode 7 Part 1: General Rules (CEN, 2016)

National perspective (The Netherlands)

- Handbook Quay walls (CURNET, 2005)
- Inner-city Quay walls (SBRCURnet, 2013)

3.2 Failure mechanisms

The European committee for standardization (CEN, 2016) have identified five important areas related to the ULS, namely:

GEO – Failure of the soil:
Failure or very large deformation of the (sub)soil, where the strength of the soil provides a significant contribution to the resistance.

STR – Failure of the construction:
Internal failure or very large deformation of the structure (or parts of the structure). For example, the walls or piles, where the material should provide a significant contribution to the resistance.

EQU – Loss of equilibrium due resistance of elements
Loss of equilibrium of the structure or the subsoil, where the structure is conceived as a stiff whole. In this case the strength of the materials and the (sub)soils do not significantly contribute to the resistance.

UPL – Loss of equilibrium due to water pressure
Loss of equilibrium of the structure or subsoil due to uplift of the structure. In such cases the there is a change of pore-water pressure under a low permeability ground layer. and/or vertical loads.

HYD – Piping & cracking of the subsoil
Hydraulic heave, internal corrosion and piping occurs due to different hydraulic gradients. The upwards seepage forces act against the weight of the soil causing the effective stress to reach zero. These soil particles are then lifted away vertically by the water flow.

These five areas can specifically be translated to the failure mechanisms of the four types of quay walls. A full overview of these failure mechanisms can be found in appendix A.

As discussed in section 3.1 the SLS should also be considered when analysing failure mechanisms. A loss of function can also be considered a failure. SBRCURnet (2013) explains that failure can occur when deformation exceeds certain boundary conditions. This is the case when:

- There is loss of functionality;
- Ethical boundaries are exceeded;
- Deformation of the structure have a direct impact on the surroundings. In order words the direct impact caused by SLS has surpassed acceptable boundaries.

3.3 Concluding remarks

Literature review has revealed that it is important to analyse the ultimate limit state of quay wall before assessing the failure mechanisms. Two limit states are identified namely the Ultimate limit state (ULS) and Serviceability Limit State (SLS). The first limit state describes the actual failure of the structure (collapse). The latter explains that the quay wall does not need to collapse entirely for it to lose its function. Regarding the ULS there are five main area's identified in order for the quay wall to collapse which is failure of the soil (1), failure of the construction (2), loss of equilibrium of the elements (3), loss of equilibrium due to water pressure (4) and piping and cracking (5). For each type of quay wall a variety of failure mechanisms are identified which are all related to the five areas. Overview of these failure mechanism are presented in appendix A. Furthermore, the SLS, which expresses the loss of function of the quay wall, should also be considered when assessing the failure mechanisms.

4 INTERVENTION MEASURES

This chapter focusses on the consequences after the failure mechanisms discussed in chapter 3.2 have been identified. These consequences need to be outlined in order to find out which measure is best suited. Therefore, the following research question is answered in this chapter:

What are the possible consequences or intervention measures for inner-city quay walls after a failure mechanism has been determined?

First an overview is given of the possible outcomes after a failure mechanism has been identified by means of an event tree. Then, these possibilities are described in more detail in the subsequent paragraph. Concluding with the conclusion of this chapter.

4.1 Consequences after identifying a failure mechanism

In principle the failure mechanisms described in section 3.2 can be coupled with a variety of intervention measures. However, in this research a distinction is made between intervening in time and failing to intervene in time. When a timely intervention takes place there are two options which are *decreasing* the load on the structure and *increasing* the resistance of the structure. This can take place after/during the SLS has been exceeded and just before the ULS is exceeded. In practice it also possible that even though the failure mechanisms are detected in time, the quay wall collapses. This means that ULS and thus SLS has been exceeded. In this case failure can have large financial consequences. Due to the possibility of occurrence this consequence is also analysed in this research by means of financial damages. These aforementioned possibilities are translated in to an event tree (see Figure 7).

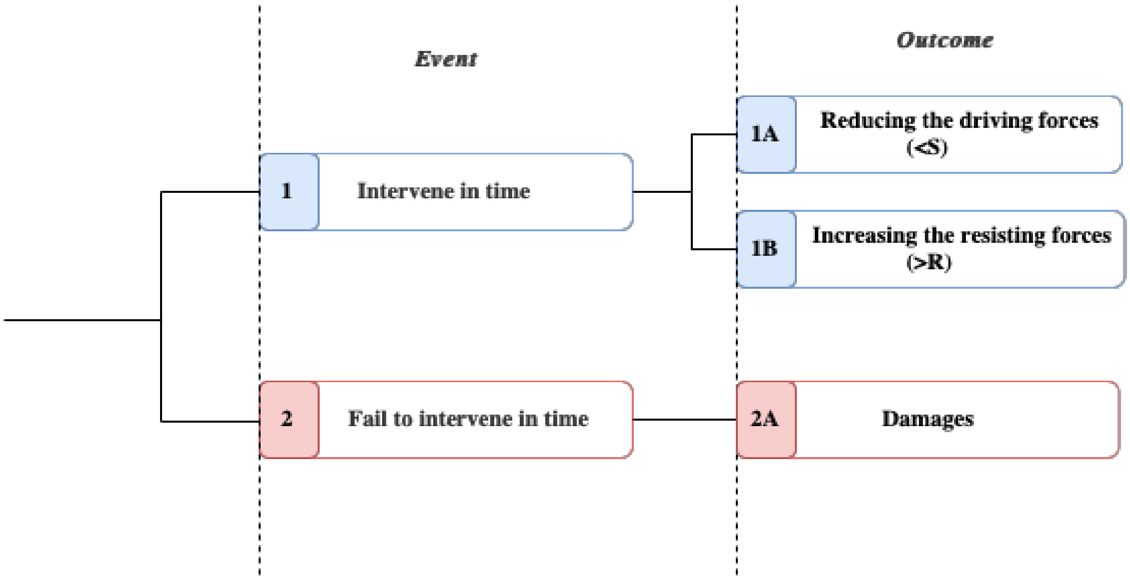

Figure 7 Possibilities after identifying the failure mechanisms (own illustration)

4.2 Intervene in time

A timely intervention means that failure of the quay wall has not taken place (yet). In other words, the quay wall has not collapsed. However, there are certain signals that a failure mechanism may occur. If this is the case then there are two possible measures which can be deployed. Which is reducing the driving forces and increasing the resisting forces of the structure. These measures can be carried out at different locations on the quay wall. A schematic representation is given of the different locations in Figure 8. A representation of a type 2 (retaining wall on wooden piles) quay wall is used to indicate these locations, they are lettered from A to D. These possibilities are described subsequently in the following sections.

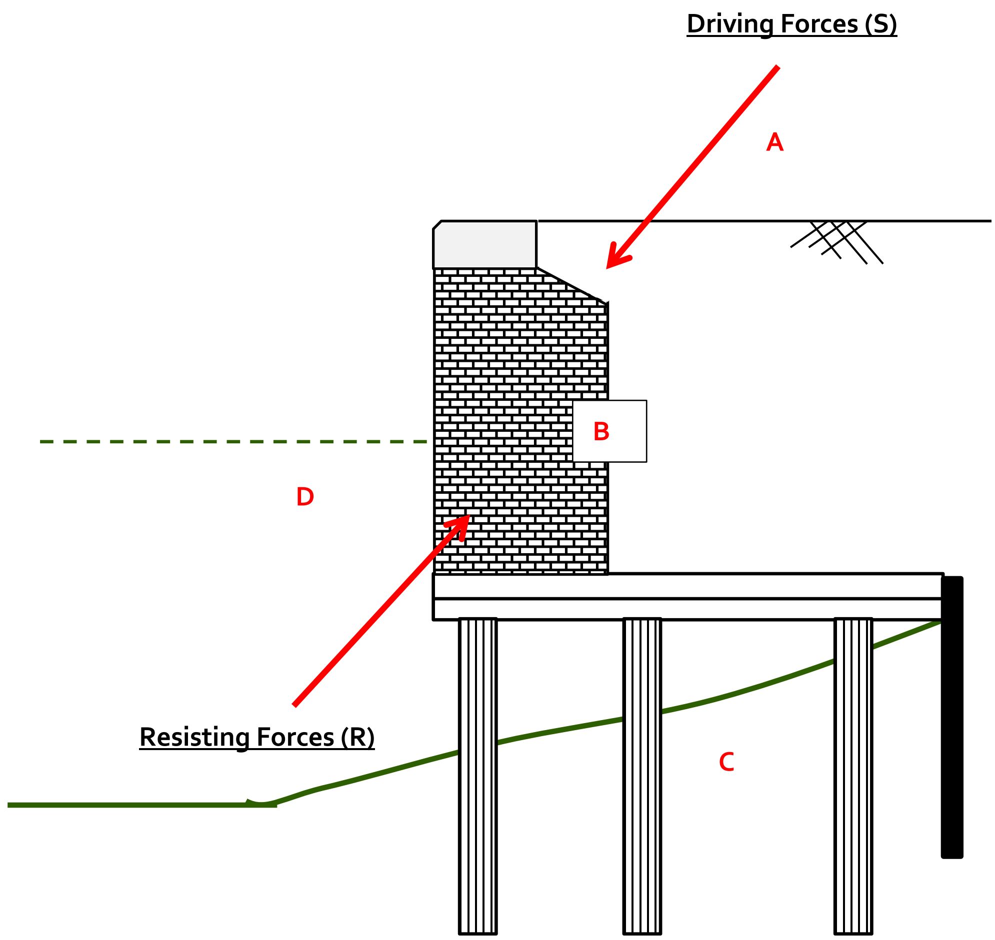

Figure 8 Overview of intervention measures at the locations A – D (own illustration)

4.2.1.1 Reducing the driving forces

The measures related to decreasing the driving forces are relatively less drastic measures, because of the activities needed to implemented them. These measures can be carried out at two different locations, namely on top (location A) and behind (location B) the retaining wall. An overview of the intervention measures are presented in Table 3. A schematic representation of these measures are found Figure 9. Intervention measures 2 and 4 are excluded in this overview because it highly depends on the location and the situation at hand.

Table 3 Intervention measures reducing the driving forces (<S)

	Description	Location	Source
1	Removing the parking spaces	A	(Movares, 2018)
2	Reducing the amount of heavy traffic	A	(Movares, 2018)
3	Removing trees (with large roots)	A	(Movares, 2018)
4	Removing other permanent loads (e.g. containers, poster columns)	A	(Movares, 2018)
5	Apply light fill material	B	(De Gijt & Douairi, 2017; Movares, 2018)

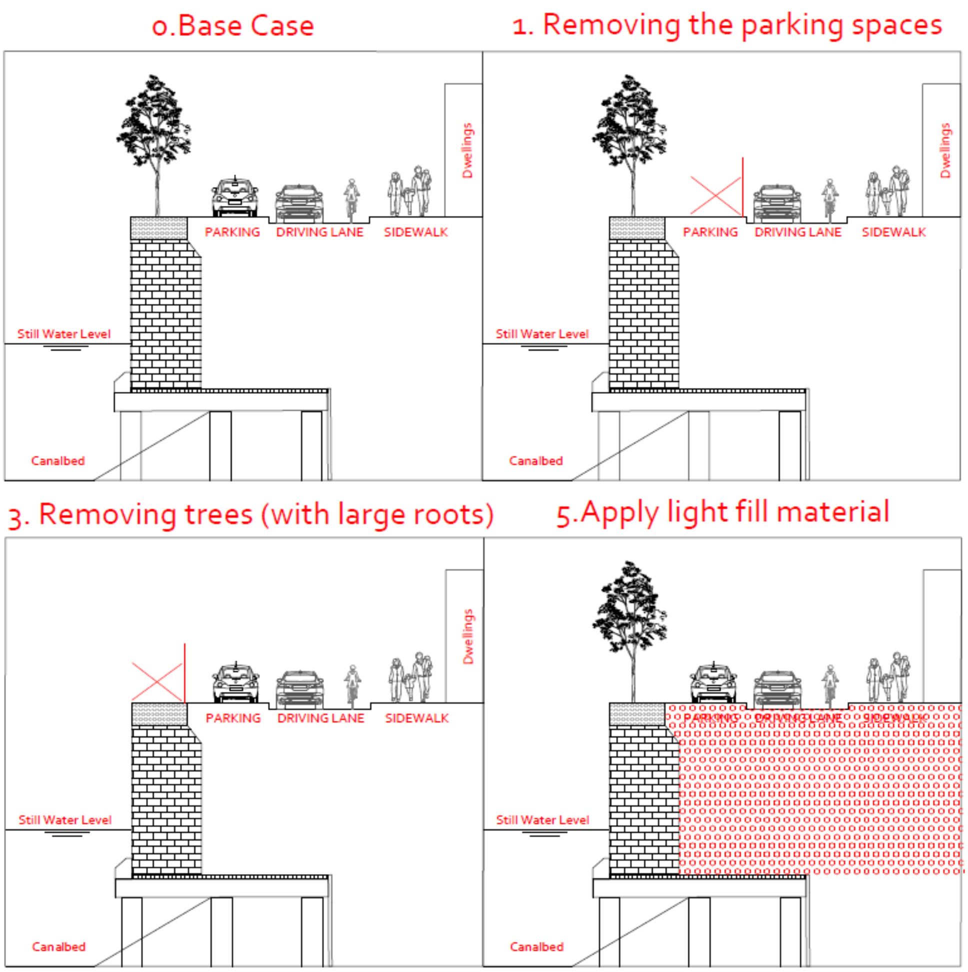

Figure 9 Intervention measures reducing the driving forces (<S) (own illustration)

4.2.1.2 Increasing the resisting forces

Increasing the overall stability of the quay wall is usually a more profound procedure than decreasing the driving forces. Measures can be taken underneath (location C) and in front (location D) of the quay wall. An overview of the intervention measures are presented in Table 3. A schematic representation of these measures are subsequently illustrated in Figure 10.

Table 4 Intervention measures increasing the resisting forces (>R)

	Description	Location	Source
1	Horizontal (grout) anchors	B	(De Gijt & Douairi, 2017; Movares, 2018)
2	Horizontal anchors with tubular pile	B	(Movares, 2018)
3	Geotextile	B	(Movares, 2018)
4	Grout filling above the floor	B	(Movares, 2018)
5	Steel vertical pile through the retaining wall	B	(Movares, 2018)
6	Grout filling riverbed	C	(Movares, 2018)
7	Application of an erosion screen	C	(De Gijt & Douairi, 2017; Movares, 2018)
8	Vertical sheet pile with sand filling	D	(Movares, 2018)
9	Vertical sheet pile with supporting beam	D	(Movares, 2018)
10	Steel pile to support the quay wall floor vertically (small)	D	(Movares, 2018)
11	Steel pile to support vertically and horizontally (large)	D	(Movares, 2018)
12	Supporting beam between two sides of the canal	D	(Movares, 2018)
13	Steel pile with supporting beam	D	(Movares, 2018)
14	Floating pontoon (deck) connected with floor through console	D	(De Gijt & Douairi, 2017; Movares, 2018)
15	Sunk pontoon with sand fill	D	(Movares, 2018)
16	Concrete floor to support the quay wall	D	(De Gijt & Douairi, 2017)
17	Concrete floor with (inclined) piles to support the quay wall	D	(De Gijt & Douairi, 2017)
18	Support quay wall from the waterside	D	(De Gijt & Douairi, 2017)

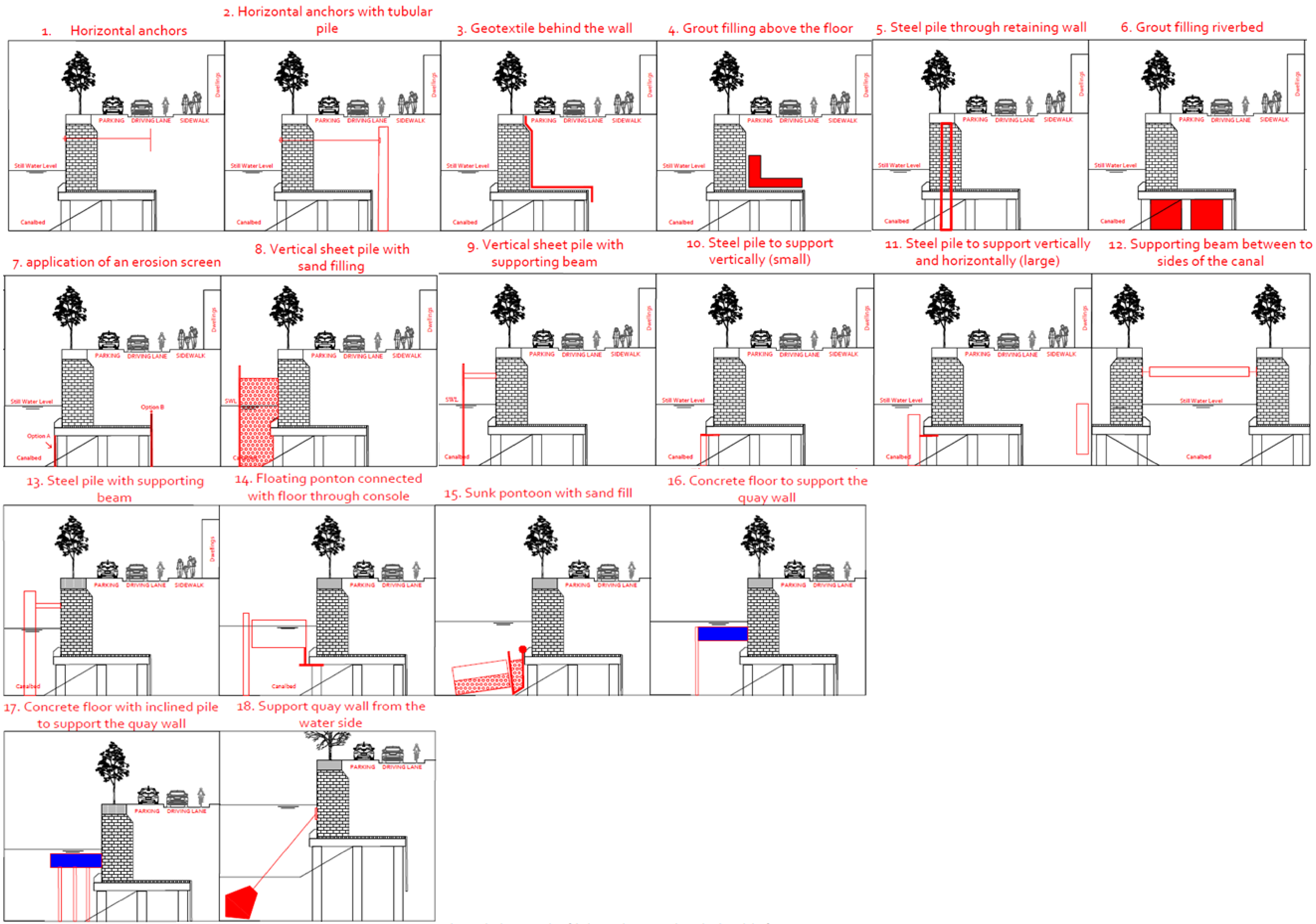

Figure 10 Intervention measures increasing the resisting forces (>R) (own illustration)

4.3 Fail to intervene in time

Failure can occur if the signals related to the failure mechanism are not detected in time. As described in section 1.1 it is unclear what the technical state is of a majority of the quay walls. The expectation is that a large number of type 2 quay walls have reach the end of their life span. This can lead to failure at any given moment, which in turn can have significant impact on the surrounding areas.

In this study the choice is made to find out what the damages will be if a quay wall section completely fails. From a pure theoretical perspective these findings can be used to make a trade-off between the other intervention measures. However, when a trade-off is made certain risks should be accepted. Identifying risks based on limited information is a difficult task. Another effect this may have is to show decision-makers how large the impact will be if the intervention measures are not implemented in time. The impact areas can be different at every location. Therefore, the specific cases should be used to determine the actual impact. In the following section first, the concept risk is discussed, then the methodology to determine the damages are explained.

4.3.1.1 Managing risks

According to the Project Management Body of knowledge (PMBok) guide published by the Project Management Institution (PMI) a project risk is an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective (PMI, 2013; Renuka, Umarani, & Kamal, 2014). The parameter that fuels risk is uncertainty. Meyer & Reniers (2016) explain that a risk should have the following components: 'hazards – exposure to hazards – losses'. A hazard is a potential that a human, machine, equipment, process, material, or physical factor to lead to an unwanted event. This can possibly cause harm to people, environment, assets, or Production (Meyer & Reniers, 2016). The term exposure explains the contact between someone or something that may suffer a loss. Losses can be physical or non –physical and can impact people, assets and the environment for instance. In the field of risk management this triangle is called the Risk Trias. If one of the three elements are missing in the risk triangle there is no risk. From a mathematical point of view risk is described as the probability/likelihood (L) that a risk may occur multiplied by the consequence (C). In formula form:

$$\mathrm{R} = L \times C \qquad \text{or} \qquad \mathrm{R} = \frac{N \times T}{Pre} \times \frac{D}{Pro} \tag{1}$$

Where N = the number of set targets (that are exposed), T=average exposure time of each target at risk, Pre = prevention measure to reduce N or T, D = the hazard of the situation and Pro = measure to increase the level of protection.

In practise (risk)managers usually focus on undesirable negative outcome of risks (Meyer & Reniers, 2016). However the postive effects of risks should not be overlooked, as it can create additional value (Hermann, 2015)

Additionally, it is also relevant to understand how people deal and react when they find themselves in risky situations. The so-called KPABC-model, which stand for Knowledge, Perception, Attitude, Behaviour and Consequence explains this attitude. It first starts with the knowledge of people. Each of the stage in the KPABC-model influences the other. The behaviour stage can be seen as a decision-making moment which results in certain consequences. An important stage in this model is the perception of people. A high perception of reality leads better understanding to interpret and efficiently deal with risk. Figure 11 is a good representation of the risk attitude in relation with the KPABC-model.

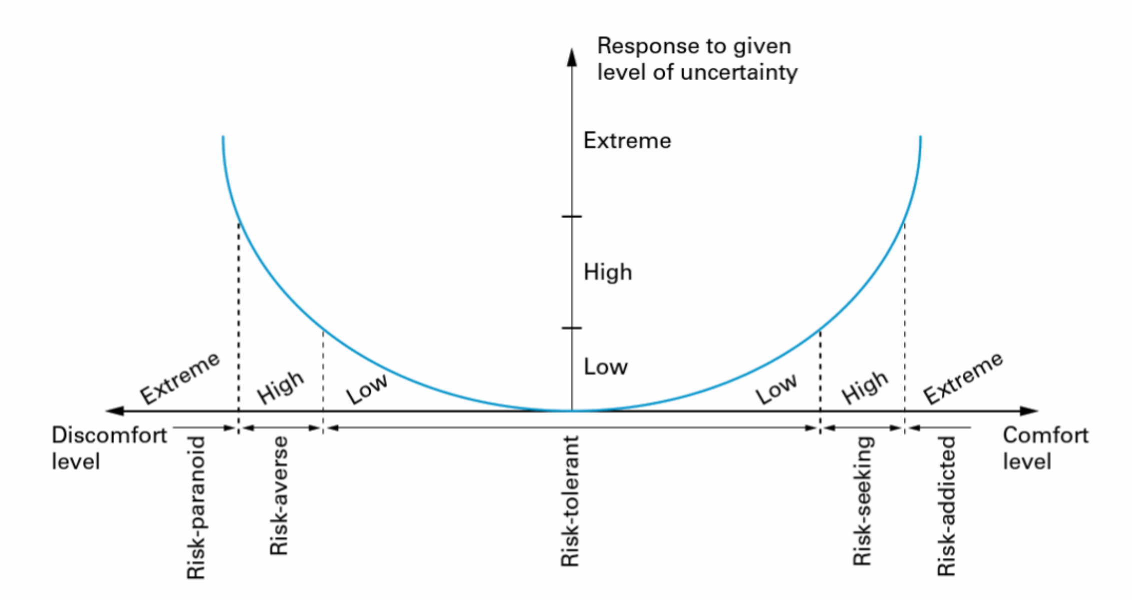

Figure 11 Relation risk attitude and response uncertainty (Meyer & Genserik,2016)

Figure 11 indicates that a high level of relevant skills, knowledge and expertise will result in a risk-seeking attitude. This means that a high reliability regarding available information is key. This will reduce uncertainty and stimulate decision-making through a risk-seeking approach. Being in control also plays an important role here. On the contrary there is a risk-averse attitude. This attitude corresponds with a perception where the probability of risk occurrence, impact magnitude and direct negative consequences are high. Uncertainty regarding information, knowledge and skills are in this case considered too high (Meyer & Reniers, 2016).

Before a certain attitude is adapted risk assessment needs to take place. There are a majority of risk assessment techniques described in the literature. These risk assessment techniques can measure risks qualitatively, quantitatively or semi- quantitatively (Hillson, 2012; Meyer & Reniers, 2016; Renuka et al., 2014). According to Meyer & Reniers (2016) risk assessment techniques can be categorized in three groups, namely basic, statistic and dynamic methods. The basic methods are usually carried out in the preliminary phases of a project. The objective is to establish what the cause of the risk is and what kind of impact it may have. The complexity of the system and the available information determines if a detailed analysis is necessary. The statistical methods have a mathematical basis in comparison with the basic model and can be applied at any given stage in a project. A downside of the statistical method is that it cannot take temporal effects on the system in to account. It shows the logical representative of the system at a given time. The dynamic methods however makes it possible to take temporal and lengthy effects in to consideration. The following project phases are identified by Nicholas & Steyn (2016) Conception (A), Definition (B), Execution (C) and Operation phase (D). After the last phase the system or asset can be improved or terminated. In case of improvement the cycle starts all over again. An indication is given during which stage the different techniques are applied.

A non-exhaustive overview of these methods and techniques can be found in Appendix B.

The different assessment techniques all follow the general framework of risk, which consists of five steps which are (Herrmann, 2015; Hillson, 2012; Meyer & Reniers, 2016; Renuka et al., 2014)

- Step 1: Identify the risk
- Step 2: Decide who or what might be harmed and how
- Step 3: Evaluate the risks and decide on precautions
- Step 4: Record your findings and implement them
- Step 5: Review your assessment and update if necessary

4.3.1.2 Damage calculations

First a distinction is made between four types of damages (Jonkman, 2007):

1. Direct tangible: Physical direct damages to assets such as dwellings, vehicles and infrastructure.
2. Direct intangible: Non-physical direct damages such as fatalities, injuries and environmental losses.
3. Indirect tangible: Indirect physical damages outside the impact area's such as displacement of victims and damages and temporary housing for victims.
4. Indirect Intangible: Indirect non-physical damages such as loss of trust in the government and social disruptions.

In this research the direct tangible and intangible damages are only assessed. To be more specific the impact on physical assets such as dwellings and the reconstruction of the quay wall. For this exposure an economical value is determined. This exposure value is an indicator for the total direct value which is exposed after failure has occurred. This implies that the analysis only takes direct damages into account. The impact of business interruption and displacement of victims is not assessed. Regarding the direct intangible damages only the fatalities are assessed in this research. This entail an assessment of loss of human life if a quay wall section fails. Also, an economic value is determined for this impact area.
A noteworthy point is that this analysis underestimates the total societal economic impact due to failure of the structure because it only takes the direct damages in to account. These two direct damages are explained below.

Direct tangible damages (physical assets)
The damages associated with physicals assets can be viewed from a variety of angles. In order to preserve transparency a non-exhaustive list is compiled and used in this research. The impact areas presented in Table 5 are assessed based on Jonkman's (2007) general classification of direct tangible and the physical aspects regarding quay walls in cities.

Table 5 Impact area's after quay wall failure

Variable	Physical aspect (Impact area)
1	Dwellings (including houseboats)
2	Quay wall
3	Means of Transportation (Motorized vehicles and bikes)
4	Trees
5	Pipelines and cables
6	Infrastructure (road and waterway)
7	Other physical location based assets

To determine the cost associated with these damages a recovery estimation is made based on the so-called 'three-point estimation' method (Steyn & Nicholas, 2016). This method is generally applied to determine the estimated outcome of uncertain values. This method uses an optimistic (a), pessimistic (b) and most likely value to estimate (m) the expected recovery cost. The following formula is used to calculate each impact area:

$$\mathrm{CE} = \frac{a + 4m + b}{6} \qquad (2)$$

To calculate the total direct tangible damages the following formula is used:

$$\mathrm{DT} = \sum_{i=1}^{7} CE_i + Estimated\ cleanup\ costs \qquad (3)$$

Where DT is the direct tangible damages and CE_i is the i-th estimated costs on the impact areas presented in Table 5. As described by Schwartzkopf & McNamara (2001) clean-up costs are an important cost item after damages. However, they cannot be classified as a physical aspect, therefore this cost item is added to the total direct tangible damages to create an overall justifiable estimation.

Direct intangible damages (fatalities)

The individual impact is described as the loss of life due to failure of a quay wall section if a unprotected individual remains fixed at one spot 24 hours a day 365 days per year (Meyer & Reniers, 2016). The literature describes two valuation methods, which are the behavioural and non-behaviour method. The behavioural valuation method uses the initial risk level as starting point to determine how much a person is willing to pay to reduce that particular risk. The perception of people and the hazard type also influences the willingness to pay. The non-behaviour valuation can be determined based on the macro-economic valuation and life quality index (LQI). The macro-economic evaluation uses the economic growth of a nation to calculate the value of statistical life. The LQI approach uses the nation's wealth to determine the values assigned to human life based on the number of years a person is expected to spend working. The LQI consists of two social indicators which is life expectancy at birth and the gross domestic product (GDP) per person (Ditlevsen & Hansen, 2007; Lentz & Rackwitz, 2004). The non-behaviour method based on LQI is used in this research because it gives a more meaningful estimation of the economic value of human life. The value of human life can easily be generalized and conceptualized through this method. The estimated value based on this method is independent of the initial risk level, hazard type and context. As described earlier it is quite difficult to determine the actual risk level of the quay walls. This is therefore are an additional reason to apply the non-behaviour method based on LQI (Janssens, O'dwyer, & Chryssanthopoulos, n.d.; Jongejan et al., 2005).

According to Jongejan, Jonkman, & Vrijling (2005) a statistical life, using the LQI approach, is usually estimated between 1 and 4 million euro's in developed countries depending on the discount rate. The formula to calculate the LQI is as follows:

$$\mathrm{LQI} = G^{q} \cdot E \quad \textit{where} \quad q = \frac{w}{1-w} \tag{4}$$

where: G = real gross domestic product per capita; q = ratio of average work to leisure time available; w = fraction of time spent working; E = discounted life expectancy averaged over the age-distribution of the national population.

This LQI methodology is then used as basis to calculate the social willingness to pay. Mathematical derivation revealed the following formula. The term C_{Δ} is described by Lentz & Rackwitz (2004) as a demographic constant. This constant consists of two demographic characteristics, namely the expected life expectancy and age average after discounting. Discounting is in included in the calculation mainly because the expected life expectancy decreases as the time increases. In Lentz & Rackwitz's (2004) study 21 developed countries (including the Netherlands) were analysed. The study revealed an average demographic constant between 5 and 20. This highly depend on the discount rate. The following formula is used to calculate the social willingness to pay for loss of life of a single individual.

$$SWTP_{LQI} = \frac{G}{q} \cdot C_{\Delta} \tag{5}$$

Total direct damages (tangible and intangible)
For a total overview of the impact assessment the direct tangible and intangible damages are combined. In the literature the damage calculations are mainly focused on flood risk assessments. These flood risk assessments use economic exposure values and so-called damage functions. Economic exposure value is an indicator for the total direct value which is exposed after failure has occurred. Damage functions indicate the relation between flood depth and the fraction of total economic exposure value which is damaged (Budiyono et. al, 2016).

In context of the quay walls in Amsterdam it is not justifiable to use the methodology used in flood risk assessments. Therefore, based on the aforementioned impact areas, the following formula is used to calculate the total direct tangible damages:

$$\mathrm{TDT} = DT + DI \quad \textit{where} \quad DI = (LQI \cdot X) \tag{6}$$

where: DT is the direct tangible damages and DI the direct intangible damages. DI is calculated by multiplying the LQI by the number of people who are exposed to the damages (Variable: X).

4.4 Concluding remarks

From a theoretical point of view there are two types of events. First a timely intervention enables managers to take two important measure, which is increasing the resisting forces or decreasing the driving forces. This chapter revealed 23 intervention measures. The second event describes the failure to intervene in time. This in turn can result in large economic damages. Literature review has revealed that damage calculations are mainly focused on flood risk assessments. These flood risk assessments use economic exposure values and so-called damage functions. Applying these methodologies in quay wall cases will result in unjust figures. Therefore a more suitable alternative is introduced based on 7 impact areas and social willingness to pay. A noteworthy point is trade-offs can be made after the failure mechanism has been determined depending on the risk-attitude. The risk-attitude depends on the knowledge, skills and expertise of managers. Risk-assessment need to performed to find out which type risk-attitude should be adopted.

5 DECISION-MAKING THEORIES & MODELS

The previous chapter revealed a variety of possible intervention measures for quay walls. Deciding which intervention fits the situation at hand is quite difficult. Literature review revealed a variety of decision-making theories and models. In context of this research it is important to understand why and how decisions are made, also to determine which theoretical basis is applied. Therefore, the following research question is answered in this chapter:

What is the state-of -art regarding the decision-making theories and models?

In this chapter the different decision-making theories and models are addressed from a theoretical perspective. First the purpose of decision-making is explained (section 5.1). Thereafter in section 5.2 a variety of decision-making theories and models are explained. Finally, in section 5.3 the different methods and tools are explained. In this research the choice was made to combine several models of authors to establish a suitable theoretical basis.

5.1 The goal of decision-making

In everyday situations people continuously make decisions. Some decisions can be more difficult to make than others because of the consequences it may have. From an engineering point of view generally two types of questions are considered relevant, namely what kind of product of system should be designed and/or what are the activities that need to be planned (Boone & Kilmann, 1991; Herrmann, 2015). For instance, the choice of materials and the shape of the design are all aspects the engineer must take in to consideration. This involves generating and evaluating different alternatives and finally selecting the best solution based on the given criteria (Saaty, 2008). In decision-making there are generally 7 steps that are taken, namely:

1. Define the problem (create awareness)
2. Set objectives
3. Search for alternative solutions
4. Compare and evaluate alternative solutions
5. Select alternative solution
6. Implement the selected solution
7. Follow-up and control

However, there are a variety of problems associated with decision-making. In cases where poor decisions are made it usually results in a loss of time, unnecessary cost and damages to reputation or relations (Herrmann, 2015; Noyes, Masakowski, & Cook, 2007) Learning from these mistakes and improving decision-making can result in a better decision-making process. A good decision-making model can save time and enables decision-makers to focus on other activities or opportunities (Boone & Kilmann, 1991; De Bruijn & Ten Heuvelhof, 2008). Decision-making models are usually based on the scientific theories.
In the literature a variety of different decision-making theories are mentioned. A majority of them are in principle similar to each other. Turpin & Marais (2004) conducted an extensive research in to the different decision-making theories. This paper is used as starting point to

create an overview of the different models and theories. Other relevant theories are added to the list if found. These theories and their descriptions are listed in Table 6.

Table 6 Overview decision-making theories

	Decision-making theories	Author(s)	Explanation
1	Rational theory	(Bekkers, 2007; Hellriegel & Slocum, 1989; Uzonwanne, 2016)	Linear step wise process towards a decision. Where choices are made based on ratio by taking long-term effects of their decisions in to account.
2	Bounded rationality theory	(Barros, 2010; Hellriegel & Slocum, 1989)	Is in concept similar to the rational theory, however there are three boundaries which influences the path to a rational decision. Which are satisfying, limited search and inadequate information & control
3	Incrementalism view	(Atkinson, 2011)	A view where a step by step process of incremental actions are followed to reach a decision. However throughout the process an open minded attitude is adopted towards adjustment. Lindblom (1959) describes this process as ''muddling through''.
4	Organisational procedures view	(Kuwashima, 2014)	From this perspective decision-making is labelled as multidimensional, which is based on a set of values and non-formal rules. Also, social elements, historically grown rules, norms and values play a central role. Decision that actors make therefore stem from the institutionalized rules.
5	Political theory	(Bekkers, 2007)	Decisions are made in an environment of multiple stakeholders, where each participant is pursuing their own agenda of objectives. It an ongoing process where allies are formed and stakeholders bargain with each other. Stakeholders with significant decision-making power are usually government bodies.
6	Garbage can view	(Cohen, March, & Olsen, 1972; Fioretti & Lomi, 2008)	The empirical foundation of this view is similar to the political theory. However, decisions are made in a plural environment which is assumed to have a chaotic nature. The difference between the political and garbage theory is that in the political theory manipulations are made deliberately.
7	Individual differences perspective	(Jackson & Kleitman, 2014)	The focus of this perspective is on the problem-solving behaviour, background and personality of the decision-maker. It aims to explain, understand and influence their decisions
8	Multiple perspectives approach	(Shubik, 1958) [1]	This approach tries to incorporate all possible perspectives on a problem to reach a decision. It is explained as unbounded systems thinking. It looks at the problem from a very broad perspective.

[1] Described as: 'Multidisciplinary approach'

The theories described in Table 6 are used as starting point to determine which theory or theories are best suited in this research. Literature review revealed which theories are applied often in infrastructural projects. Three re-occurring theories were mentioned, which are rational theory, political theory and the multiple perspective theory (Groenleer et. al, 2012; Omar, et. al, 2008). In context of this research the choice is made to look at three prominent decision-making theories, which are the rational, bounded rationality and the political theory. An iterative approach was adopted to choose the three decision-making theories. In section 7.1 these choices are explained in more detailed. In section 5.2 these theories with their corresponding model are further elaborated on.

5.2 Decision-making theories

The basis of decision-making rest on four important conditions as described by Hellriegel & Slocum (1989). First, there must be a gap between the current situation and a desired situation. This means that there need to be an urgency to achieve an alternative objective. This coincides with the second condition which is: the awareness of the gap. If there is no gap that needs to be closed it will become extremely difficult to achieve a desirable objective. Next, there must be a motivation to close the gap. Lack of motivation can hamper the decision-making process. For example, not exploring an alternative solution in more detail. Finally, resources must be available and accessible in order to act effectively.
Historically decision-making has been recognized as one of the major tasks of the managers or executives within companies (Boone & Kilmann, 1991). Therefore, the decision-making models are generally viewed from a managerial point of view. The literature describes a variety of different decision-making models. The three most important and recurring theories are the rational, rational-bounded and political model (Bekkers, 2007; Boone & Kilmann, 1991; Hellriegel & Slocum, 1989; Noyes et al., 2007; Parnell et al., 2011). These are explained subsequently.

5.2.1 Rational theory

In the rational theory, achieving goals through knowledge and information is central (Bekkers, 2007). There are central, guiding actors in this theory whose interests are known and assumed. The dominant explanatory mechanism is therefore goal rationality. It is assumed that decision-makers have unambiguous motives and make well-balanced decisions based on ratio.
Decision-makers would classify this model as ideal because it draws them closer to rationality. However this model is just an approximation of this ideal (Hellriegel & Slocum, 1989). In practice problems are usually complex and dynamic. Furthermore, practice have also shown that decision-making is usually based on professional experience, in other words based on expert judgement (Herrmann, 2015; Noyes et al., 2007).

Linear model
Typically, within this theory is the linear model (Bekkers, 2007; Hellriegel & Slocum, 1989). In this model decision-making is viewed as a cycle of successive phases. Herbert Simon was the founder of this model, he was an economist and political scientist known for his research in the field of rational decision-making. The decision-making process is seen as a series of logically successive phases with the idea that decision-making can be planned rationally. When routine decisions are made, this kind of cyclic thinking is usually performed. Furthermore, decision-makers also follow this cycle in situations where risks and (un)certainty conditions are involved. This enables decision-makers to assign probability to certain outcomes.
A central assumption made in this model which is that man is considered Homo Economicus (Bekkers, 2007). Man acts rationally and purposefully to his own advantage. This model reflects an individualistic view on decision-making. In the literature the linear model has been criticized several times (Bryson, 1988; T. L. Saaty, 2008). The main criticism of this model is that it reflects a simplistic assumption of reality. Another criticism concerns the individual character of decision- making within this model because in principle it does not take other relevant aspects in to account.

5.2.2 Bounded Rationality theory

The bounded rationally model is based on the rational model, however it is characterized by certain boundaries. Hellriegel & Slocum (1989) have identified three boundaries: satisficing (1), limited search (2), and adequate information and control (3). This type of decision-making model is seen more in day-to-day decision-making. The model is considered useful because it emphasizes the limitations regarding the rationality of decision-making. The three boundaries are explained subsequently.

1. Satisficing

In case of satisficing, decision-makers knowingly or unknowingly choose for an acceptable objective or alternative. The reason is because it is safer or easier to identify or obtain an alternative to make an decision. Simon (1955) explains that satisficing does not necessarily mean that the decision-maker is actually satisfied. This highly depends on the personal characteristics of the individual, their abilities and the organizational standards. Furthermore, he explains that time plays an important role. In a majority of companies there are certain targets that need to be fulfilled. This means that sometimes it is impossible to obtain more information in order to find the 'best' alternative or solution.

2. Limited Search

This aspect explain that is nearly impossible to search for all possible alternatives and solutions because of constraints such as time, energy and money. The main difference between the rational and bounded rationally model is that decision-makers stop searching for other alternatives after they have found an acceptable solution, in other words they limit themselves from searching further.

3. Inadequate information & Control.

The most important aspect of bounded rationally is inadequate information & control. This is explained as decision-makers having inadequate information about certain problems in order to make well balanced decisions. The reason behind this can be lack of extensive research in to the problem. Root-cause analysis can be useful in these cases.

5.2.3 Political theory

In decision-making different criteria must be weighed against each other. In this perspective it is often not the most reasonable argument or criterion that is considered important. Power is used to protect certain interests and positions (Bekkers, 2007). In contrary to the rational theory trade-offs are not made based on logical and rational decisions. In this case there is a form of permanent conflict present between actors. Where conflicts of interest play a role, the preservation of power and influence also plays a major role. In this context, power can be defined as the ability of actors to realize a certain desired behaviour or to control/influence certain decisions and outcomes (Bekkers, 2007, p.63; Hellriegel & Slocum, 1989, p.215). A concentration of power in one stakeholder is usually reflected in the final outcome of that decision. On the other hand an equal distribution of power among actors can lead to extensive negotiations and finally compromises in the end. Therefore the decision-making process in this theory is described by push and pull of actors with different powers and objectives.
In regards to information sharing decision-makers consider free disclosure of information as naïve and problematic. Decision-makers want to prevent spill of knowledge because knowledge is seen as power. The rational theory however interchanges information freely.

Actors are mainly focused on securing their own interests. In this case, a conflict can arise between their own and general/public interest. In principle every actor wants to defend their own interest. However, there are also actors who represent the so-called win-lose situations. This means that they consider the loss of another actor as their gain and the gain of another actor as their loss. In other words: My gain is your loss and your gain is my loss. This kind of mind-set can e.g. hamper decision-makers to take innovative decisions.

Arena model
The political theory is best described by the arena model, which is derived from the work of Max Weber (Fortuijn, 2003). This model assumes that groups of people organized in every society are constantly in competition with each other for the acquisition of prestige, income and power (Fortuijn, 2003). The core idea of this model is that decisions are made in a part of the society that is autonomous from the rest. In order to make these decisions an arena or fenced battle field, used as a metaphor. In such an arena a game is played based on rules that only apply in the relevant arena. Within this arena there are a variety of actors active with their own values and interests that are looking for allies to achieve their own objectives. These actors are mutually dependent on each other. The dependency relationships are different depending on the context, time, situation and the intended objective of the actor. The mutual dependency between groups makes decision-making within an arena complex. The groups have different objectives and power positions within an arena. In addition, objectives during the decision-making process can shift and thereby creating dominant positions. Another aspect that makes policy-making complex is that the interaction between groups take place at different organizational levels with intermediate links. This means that internal actors/factors can influence the interactions of external actors and vice versa. Decision-making in these kind of arena's where actors are (inter) related with each other are described by (De Bruijn & Ten Heuvelhof, 2008)

5.3 Decision-making techniques

The literature distinguishes two important decision-making techniques, which is Multi Criteria analysis (MCA) and Cost benefits analysis (CBA). MCA is applied when a more qualitatively description is desired and CBA in cases where a quantitative explanation is more suitable. These two techniques are applied most often when it comes to making trade-off's concerning public infrastructure (Abdel-malak et. al, 2017; Erdogan et. al, 2019; Jajac et. al, 2013; Noyes et. al, 2007). The literature also revealed different variants regarding the MCA concepts, however the principal is still the same. MCA and CBA techniques are described in the upcoming sections.

5.3.1 Multi-criteria analysis (MCA)

Multi-criteria analysis (MCA) is a method that can be useful for establishing preferences between options through a set of predetermined objectives. These objectives are usually translated to measurable criteria to asses to which extent the objectives of the alternatives has been achieved. It should help to identify a single most preferred option based on a rank of different options. The input used for a MCA is based on the judgement of the decision-making team. This includes the objectives, criteria, estimation the relative importance and weights. This technique brings a certain degree of structure and explanation on how the decision-maker reached the preferred option. A MCA consists of the following steps:

1) Establish the decision context

The goal in this is step is to determine the problem and knowledge needed to achieve the objective of the analysis. There should be shared understanding and necessity to conduct a MCA.

2) Identifying options

In this preliminary stage a set of options proposed in respect the current situation. In practise often ideas are introduced within the decision-making group. However certain boundary conditions are set to eliminate options which are not feasible, this can be based legal restrictions.

3) Identifying criteria and sub-criteria

In step 3 the objectives are translated in to criteria and sub-criteria. These criteria are used to determine measures of performance by which the options will be assessed. It is important to keep the number of criteria low but consistent with making well founded decisions (Noyes et al., 2007; Parnell et al., 2011). The number of criteria highly depends on the complexity of the project. After determining the criteria, it is important to group them. This can be helpful to determine the relation between the various criteria. Further it helps to calculate the weights within the group and then with each other. After a set of criteria have been determined it is recommended to assess them range quality aspects such as: completeness, redundancy, operationally, mutual independence of preferences and double counting

4) Scoring and weighting the criteria

The expected performance of each option is assessed in this step based on the criteria determined in step 3. This is done by constructing a performance matrix for each option or using weights. The options are scored based on expert judgement. In case of the application of weights different scale can be used to perform this analysis, however it should be consistent. Therefore, is recommended to check the consistency after scoring. Then, the criteria should be weight to reflect what their relative importance are to the decision.

5) Combine the weight and score for each option and examine results

An overall weighted score is determined at each level in the hierarchy to determine which option is preferred. Depending on the applied scale the preferred option can be chosen.

6) Conduct a sensitivity analysis

The last step entails a sensitivity analysis. This is necessary to take uncertainties and unforeseen events in to consideration. Sensitivity analysis can be carried out on the weights determined in step 4 to see the effects on the total scoring.

The end goal is to establish a framework linking the goals, criteria, sub criteria and alternatives with each other. Figure 12 shows an example of decision-making framework where the criteria are substituted by the interests.

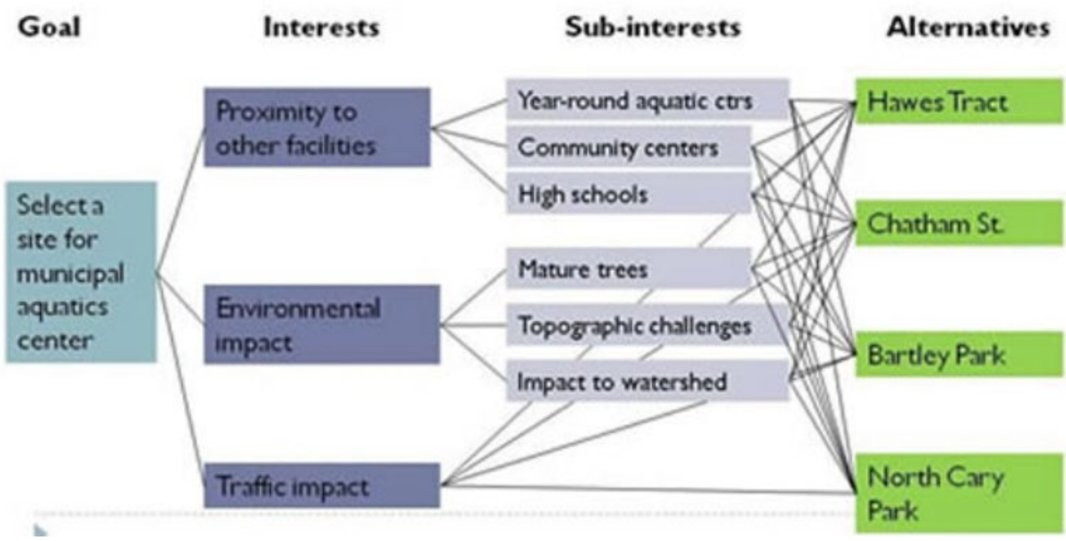

Figure 12 Multi criteria decision-making framework (NRLA, 2011)

Variants of MCA

There are different types of decision-making techniques discussed in the literature, which are based on the same principle as MCA. In context of this research two main studies are used to determine which kind of variant of MCA is generally applied in practice. The study of Kabir et. al (2014) analysed different decision-making methods applied in infrastructure projects. It was found that the top three most frequently used method were Analytical Hierachial Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE) and Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE). The study of Sabaei, et. al (2015) focused on the different decision-making methods from a maintenance point of view. The result of this study revealed the same top 3 as the study of Kabir et. al (2014). A noteworthy point is that ELECTRE preferred over PROMETHEE when it comes to decision-making from a maintenance point of view. In context of this research the AHP can be considered valuable because it is a well-known and accepted method which is applied frequently in infrastructure projects in contrast to the other two methods.

- Analytical Hierarchical process (AHP)

The Analytical Hierarchical Process is a widely used systematic approach to help decision-makers select the best suited alternative based on multiple attributes. The founder of this method was Thomas L. Saaty. It uses relative priorities based on absolute scales based on mathematical techniques. This can be analysed using discrete and continuous paired comparison in hierarchic structures (Saaty, 1987; Saaty, 2008). These comparisons may be taken from actual measurements or from a fundamental scale that reflects the relative strength of preferences and feelings.

5.3.2 Cost benefit analysis (CBA)

CBA is a policy assessment method that quantifies the value of all consequences of a policy to all members of society in monetary terms (Boardman et al., 2011, p.2). In CBA all the costs and benefits regarding the society as a whole are considered. Practitioners and experts refer to this as the social cost and social benefits. Therefore, the analysis of these benefits and cost is also referred to as social cost-befit analysis. The goal of a CBA is rationalizing social decision-making. (Boardman, et. al, 2011) distinguish two types of CBA, namely Ex ante and Ex post CBA. Ex ante CBA is compiled when a project or policy is under consideration before implementation or start. The goal is to determine whether certain resources should be allocated to a project or policy. Ex post CBA is conducted after a project or policy has been implemented. This type of CBA enables decision-makers such as project managers and policymakers to learn from previous decisions. There are 7 major steps in CBA.

1) Specify the set of alternative projects

The first step requires the analyst to determine a set of alternatives in respect to the base case. An example for road expansion: Maintaining the current situation (base case), expanding the road with one lane (alt. 1), expanding the with one lane including tolls(alt. 2).

2) Decide whose benefits and cost count (standing)

In this step the analyst decides whose benefits and costs should be included in the CBA. This highly depends on the perspective of the analyst. This can be from a local or national point of view. In the road expansion case this can be the municipality. The analyst should then consider the cost and benefits within the municipal boundaries first.

3) Identify the impact categories, catalogue them, and select measurement indicators

In step 3 the different impact categories are determined. In the example described in step 1, the following impact areas can be identified: Time and operation cost savings, alternative routes benefits, safety benefits, toll revenues, construction and maintenance. Additional impact areas are possible in this case.

4) Predict the impact quantitatively over the life of the project and monetize

In this step the impact areas are quantified and monetized. First the expended benefits and costs need to be determined, then a dollar value is assigned to these quantities to determine the overall cost. For instance, the number of life saved due to an extra lane, number of vehicle trips on the new highway and the number of accidents avoided. Monetizing impact areas can be difficult, especially placing a value on loss of life.

5) Discount benefits and cost to obtain Net Present Values (NPV) of the alternatives

Projects and policies are usually implemented for a certain amount of time, usually years. Therefore, the benefits and costs need to be discounted to obtain their present values. The different between the present value of the benefits and cost is referred to as the NPV. The NPV should be larger than zero for the analyst to proceeds with the project or implementation of the policy. In case there are more alternatives available, than the alternative with the largest NPV should be selected. This is only the case when at least one alternative has a positive NPV.

6) Optional: Perform sensitivity analysis

As discussed in step 4 it is quite difficult to determine the quantities and cost related to the impact areas, in case of high uncertainty it is recommended to perform a sensitivity analysis. Upper and lower boundaries are determined to indicate the range of the total cost.

7) Make a recommendation

The information retrieved from step 1-6 will result in a recommendation. Generally the alternative with the highest NPV (if positive) should be recommended. However the results from the sensitivity analysis should be included, as they can have an impact on the final recommendation.

A CBA explains how resources should be allocated, not how resource allocation decisions are actually made. Therefore, a CBA should be used as input for the political decision-making process. In political and bureaucratic arenas other aspects could play a bigger role than the economic impact (on the long term). An example of CBA for a road expansion (with and without tolls) is presented in Figure 13.

	No Tolls	*With Tolls*
Revenues ("Benefits"):		
Toll revenues from British Columbia residents	0	112.1
Toll revenues from non–British Columbia residents	0	37.4
	0	149.5
Expenditures ("Costs"):		
Construction	338.1	338.1
Maintenance	7.6	7.6
Toll collection	—	8.4
Toll booth construction	—	0.3
	345.7	354.4
Net Revenue-Expenditure "Benefits"	345.7	204.9

Figure 13 Example of a CBA for road expansion with or without tolls (Boardman et. al, 2011)

5.4 Concluding remarks

Critical literature review revealed three important re-occurring decision making theories, which are the rational, bounded rationality and political theories.
The rational theory is governed by the linear model, which explains that decision-making is a logical, rational and cognitive process based on a cycle of successive phases. It is assumed that decision-makers have unambiguous motives and make well-balanced decisions based on ratio. The bounded rationality theory is based on the rational theory however three boundary conditions are important, which are satisfying, limited search and inadequate information and control.
The political theory is based on the arena model. This model assumes that groups of people organized in every society are constantly in competition with each other for the acquisition of prestige, income and power (Fortuijn, 2003). The core idea of this model is that decisions are made in a part of the society that is autonomous from the rest. In order to make these decisions an arena or fenced battle field, used as a metaphor, where a permanent conflict is present between actors in order to reach a decision.
Next to these theories and models two important techniques are identified to help decision-makers make well-balanced decision, which are Multi-criteria analysis (MCA) and Cost benefit Analysis (CBA). Furthermore, literature review revealed different variants of these concepts.

6 DECISION-MAKING CRITERIA

The different decision-making theories, models and techniques revealed that in order to make well-balanced decisions objectives need to be defined. The objectives are usually translated in to criteria and sub-criteria. These criteria explain which aspects are considered important and relevant when making project-related decisions. Therefore, several theoretical decision-making criteria are discussed in this chapter. The following research question is answered in this chapter:

Which decision-making criteria related to maintaining inner-city quay walls can be identified?

In this chapter the different decision-making criteria are addressed from a theoretical perspective. These criteria are derived from studies where infrastructural projects are assessed. A recent study of Hansen, et. al (2019) is used as starting point. These criteria are presented in Table 7.

Table 7 Overview decision-criteria with corresponding authors

	Decision-making criteria	Referred to as	Author(s)
1	Safety	Operation Philosophy; Risk	(Infrastructure Australia, 2017; Queensland Government, 2015; Yadollahi & Zin, 2011)
2	Accessibility	Social issues & impacts	(Infrastructure Australia, 2017; Queensland Government, 2015; Shiau, 2014; Collins, 2015)
3	Liveability	Social issues & impacts; Operation Philosophy	(Doloi, 2012; Shiau, 2014; Wesley Collins, 2015)
4	Costs	Funding and programming; Economic issues and impacts	(Cheung & Chan, 2009; Iyer & Balamurugan, 2006; Queensland Government, 2015; Sciulli, 2008; Collins, 2015)
5	Sustainability	Environmental issues and impacts	(Huang, et. al, 2010; Collins, 2015)
6	Innovativeness	Innovation	(Goodrum, et. al, 2009)

First a theoretical description is given of the different criteria. Then, their methodologies and tools are subsequently explained.

6.1 Safety

Safety is without doubt considered as one of the most important aspects in society. This fact is underlined by Maslow's (1943) hierarchy of human needs. He divides the human needs in to hierarchy classes. After the physical basic needs such as food, drink and sleep. Safety is considered the second important class, where aspects such as protection and economic certainty is discussed. From a construction management point of view safety can be looked at from different perspectives (Jazayeri & Dadi, 2017; Meyer & Reniers, 2016). Such as safety of the structure and safety during construction. Another perspective is the environmental point of view. This means looking at the cascading effects if a structure fails or after an accident occurs at a construction site. In this research the main focus is on safety of the structure and possible effects it may have if it fails.

6.1.1 Description of safety

Assets in the Netherlands are obligated to meet minimum safety requirements. In order to meet these standards, the NEN 8700 norm explains that existing structure should have sufficient residual strength to comply with the calculated life span and the predetermined reliability indices. The NEN 8700 stipulates two fundamental criteria regarding the safety of the structure. First, the structure should withstand all loads and influences that may occur during its lifetime. This means that the probability should be large enough for the structure to withstand these loads. Secondly, it should remain suitable for its intended use. These requirements are necessary to prevent future accidents. These accidents can have a direct impact on people, tangible goods (such as buildings) and intangible goods (such as brand and image) (Jazayeri & Dadi, 2017; Meyer & Reniers, 2016). The safety level of assets highly depends in time. A representative tool to illustrate the safety of a structure in time is the maintenance-reliability model illustrated in Figure 14 (Vervoort, 2013). Figure 14 shows the life cycle of an asset using a failure rate R(t). R(t) is explained as the resistance rate which is denoted as a function of time. In the beginning, right after commissioning the condition of the asset is considered good (assuming that the asset has been built according to the current safety standards). As time passes by the resistance rate decreases (Kapur & Pecht, 2014). The objective is to stay above the horizontal line of the failure condition. This can be achieved by deploying by upgrading or renovating the structure. In this model the assumption is made that aging has a gamma distribution. This assumption is made to take uncertainties such as weather conditions, change of use and the technical properties of the asset in to account (Kapur & Pecht, 2014; Noortwijk & Frangopol, 2004). Literature review revealed that a gamma distribution is best suited for modelling time dependent deterioration (Edirisinghe et. al, 2012; Iervolino, et. al, 2013; Noortwijk & Frangopol, 2004). This distribution reflects the optimistic, pessimistic and expected time of failure. The quality and accuracy of the information regarding the quay walls determines when the expected failure will be.

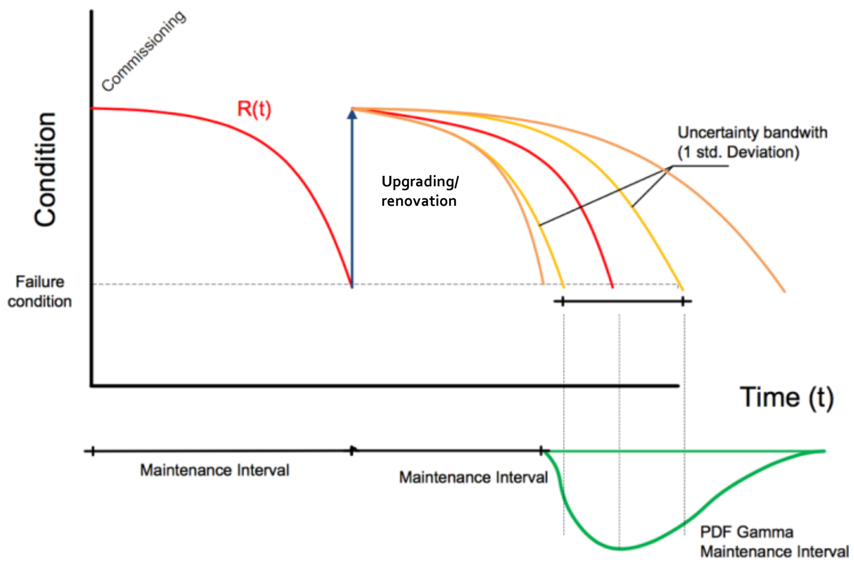

Figure 14 Maintenance - Reliability model (Vervoort, 2013)

6.1.2 Methods and tools for measuring safety

A safety margin is considered when designing a construction. This safety margin stems from the uncertainty in the load on the structure and in the strength of the construction. The load on a structure is not constant, it has a more variable behaviour. The design is used to calculate the construction that is representative of the structure, there is always a chance of exceeding that representative load. This is presented by the following formula 1, mentioned in section 3.1.

In this research two important tools for measuring safety are discussed, which are the Unity Check (UC) and Reliability index (β).

Unity check
The NEN standards contain various guidelines describing which elements of structures must be tested. These guidelines are expressed by means of a ratio between the solicitation and the resistance of the structure. The resistance of the structure must be greater than the solicitation and thereby must be less than or equal to 1. This is expressed with the following formula:

$$\mathrm{UC} = \frac{S_d}{R_d} \qquad (2)$$

When UC ≤ 1 then the structure is safe, if UC > 1 than the structure is unsafe.

Reliability Classes
The safety level of structures are expressed in Reliability Classes (RC). The reliability index is coupled with the probability of failure. Failure occurs when the solicitation is larger than the resistance. The following relation is found:

$$\mathrm{P}_f = (\mathrm{R} < \mathrm{S}) \quad \text{can be rewritten as} \quad \mathrm{P}_f = \phi(-\beta) \qquad (3)$$

Where ϕ is the standard normal distribution and P_f the probability of failure.

Each reliability class is coupled with a reliability index β. A distinction is made between reliability indices for existing structures, renovating and rebuilding (SBRCURnet, 2013). An overview of these minimum requirements are presented in Table 8.

Table 8 Reliability indices' (SBRCURnet, 2013)

	Existing structures (NEN 8700)	Renovating structures (NEN 8700)	Rebuilding structures (EN 1990)
Class	β_{15}	β_{15}	β_{50}
RC1	1,8	2,8	3,3
RC2	2,5	3,3	3,8
RC3	3,3	3,8	4,3

The reliability indices for existing and renovating structure are calculated based on a reference period of 15 years. The reference period is explained by the NEN 8700 as the time period which is chosen as a basis for statistical determination of constant, variable and extreme loads. In short, the reference period is used for statistical determination of the reliability indices. This concept is not the same as the remaining life span of an asset. The remaining life span of an asset is described as the estimated period of time during which an existing or renovated construction or element can be used for its intended purposes.

Methods for calculating and modelling structures
The literature describes three methods for calculating quay walls. The following four methods can be distinguished (CURnet, 2012; Gerritsma, 1982; SBRCURnet, 2013; Wolters, 2012).

- Hand calculation

The most straightforward way to calculate the safety of structure is by means of hand calculations. The first step is to calculate all the (horizontal and vertical) forces working on the structure and the strength of the structure itself. Then the NEN 8700 is used to check whether the structure is safe enough according the international standards

- Classic method of Blum

The Blum method is used for the calculation of sheet-pile structures. This method gives a rough estimation of the internal forces in the quay wall and can be calculated relatively easy. Because of its simplicity and user-friendly nature this method is generally applied in the draft design phase.

- Beam elastic Foundation

The beam elastic method is a more sophisticated method than Blum. The method schematized the soil as a set of elasto-plastic springs to calculate the forces. The springs are not coupled, this means that the one spring can be loaded without loading the adjacent springs. This model is frequently used in the Netherlands for the calculation of sheet piling.

- Finite element analysis

The finite element method is a more mathematical complex method. It is based on a model in which the behaviour of the structure and soil are integrated. This model includes the soils stresses and deformations into calculation. Mainly because of the complexity of this model generally a computer software is used.

6.2 Accessibility

Accessibility is an important topic for local and national governments. A good infrastructure network that provide access to people, service and goods and information are vital for economic development in cities (Rode & Floater, 2014). In cities where an efficient access is provided to these aforementioned aspects the greater the economic benefits will be. Therefore local and national governments are continuously improving their infrastructure because of these advantages but also to deal with the growing demands. These measures are mainly focussed on improving internal accessibility (Bruinsma & Rietveld, 1998). The next step is to improve the external connectivity by connecting this to the existing internal network.
From a national perspective the main goal is to provide a good transportation network to the people to full fill their needs and desires. They should be able to go from location A to B and preferably with low effort (efficiency) (Manzoor, 2014). Another issue is also the growing population in cities. This causes more people to go from location A to B, which in turn can lead

to large stresses on the infrastructure network (congestion and traffic). Lastly, new technological development also leads to new insight and sometimes to changes in the infrastructure network (Geurs & van Wee, 2004). Therefore, improving public infrastructure is an important an continuously process.

6.2.1 Description of accessibility

Literature review has shown that researchers find it quite difficult to describe and operationalize accessibility. This statement is underlined by Geurs & van Wee (2004). They explain that there are a variety of poorly defined definitions and methods to describe accessibility. At the same time they also explain that finding a theoretical and operational sound explanation is quite difficult. They explain accessibility as: 'the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)' (p.128). This definition can be broken down in to different parts by looking at accessibility from different perspectives or components (Geurs & van Wee, 2004; Litman, 2003; van Wee, 2016). Geurs & van Wee (2004) refer to this as components. Litman (2003) describes this as perspectives. They both use different terms for the same defintion.

Individual component
The individual component is related to the needs of an individual to reach a certain destination. This is influenced by different factors such as income, age and ability These factors enables people to make use of different kind of transportation modes. For instance if an individual is unable to drive a car because of physical limitation. This component is referred to by Litman (2003) as the perspective: *Users*

Transportation component
This component looks at the different ways of transportation by analysing the transportation system as a whole. There are a variety of different modes, including motorized and un-motorized modes such as public transport, car, boat, bicycle and on foot. However this perspective also includes an integrated view of the transport network by looking at connections among modes. Litman (2003) refers to this perspective as: *Mode*

Land-use components
This component uses the land-use patterns as starting point. The land use patterns show the distribution of the infrastructure network, land use mix and destinations. It looks at the different activities and facilities in an area, such as jobs, shops and recreational facilities. In Litman's (2003) study he refers to this as: *Land use*

Temporal component
The temporal component is explained by Geurs & van Wee (2004) as the temporal unavailability of participating in different activities due to a variety of constraints. This has dynamic character and can change over time. Litman (2003) refers to this as *Transport Problems* which he explains as certain barriers or risks that prevent people to reach a desired location.

6.2.2 Methods and tools for measuring accessibility

Applying methods to measure accessibility can be useful for the evaluation of (future) scenario's in urban planning. In practice traffic models are used to describe current traffic and in the near future. This enables policy-makers to take the best measures to implement. In the traffic model criteria such as traffic flow, safety and/or environmental aspects are taken in to consideration. These traffic models can be used.

There is a vast amount of traffic models types applied worldwide. These types of models are discussed below (Immers & Stada, 1998):

- Demand models

The demand model predicts the number of trips made in a network for a specific mode of transport. In other words, the scale of demand is used as function of the service level. Examples of these models are TRANSIMS and ALABATROSS. The latter is a well-known Dutch model.

- Supply models

This type of model is generally used to determine the service level which is denoted as a function of load on the network. These models are also known as time-loss functions. The model reveals the relationship between travel time or cost and the flow of traffic on the intended road sections.

- Short- and long-run equilibrium models

Both the short- and long-run equilibrium models use demand and supply data to determine the scale of traffic flows in a network. The long-run equilibrium model however looks at the changes in the infrastructure network and it relation with spatial distribution of activities. The latter model are used in cases of scenario planning to directly predict the effect of flow patterns.

- Impact models

Impact models are applied to find out what kind of impact a traffic has on the environment. For instance, on air pollution, noise pollution and safety. This can also include an analysis of an improved service level after implementation. These types of models are usually constructed for a specific case and is therefore difficult to use them in a generic setting.

Traffic models can be considered highly dynamic. An increase in traffic of (temporary) change of the infrastructure can have large consequences for the people make use of the infrastructure. This will in turn trigger changes in the activity and transport system resulting in new equilibrium after certain amount of time.

In the Netherlands the Ministry of Infrastructure and Water management distinguishes two main indicators, Vehicle Lost Hours (VLH) and 'Structuurvisie Infrastructuur & Ruimte-indicator (in short SVIR-indicator) and traffic intensity. These indicators are explained subsequently.

Vehicle Lost Hours (VLH)

This a measure to determine the total number of travel time loss (in hours) due delays on the road. Possible causes are an increase of cars on the road, traffic jams, road works and other factors that hamper the traffic flow.

The vehicle loss hours are calculated by comparing the actual travel time with the travel time needed to make the journey undisturbed and without any delays. Vehicle loss hours are used by the business community to express the economic damage caused by traffic jams and traffic congestion. National and local governments applied this concept when making cost benefit analysis.

SVIR-indicator

The SVIR indicator is introduced in 2012 by the minister of Infrastructure and environment. The objective of this new SVRI indicator was to create an integral concept which captures the ambitions of the ministry. By doing so mobility in networks and the coordination of infrastructure and spatial development can be optimized. The SVIR indicator is explained by CROW as the travel speed from one destination to another (door-to-door). The indicator gives an uniform overview of the accessibility per transport mode and shows where accessibility bottlenecks are. The goal is to locate these bottlenecks and solving them.
This indicator only looks at the travel distance and time. Other aspects such as cost, comfort and quality are excluded.

6.3 Liveability

The concept liveability is still considered an important topic. This is reflected in the political and public debates where the quality of neighbourhoods is discussed extensively. The rise of the various 'liveability parties', increasing media attention and political debates regarding these topics emphasis this phenomenon (Leidelmeijer & Marlet, 2014). The issue of liveability is also high on the agenda of the central governments. Attention to liveability is not a new phenomenon. However, it has become a more collective term for all aspects regarding the living environment of people (Leidelmeijer & Kamp, 2003).
Behind the apparently straightforward nature of the concept of liveability lies an enormous complexity. Liveability is therefore not a fixed fact, but a collective term. Its interpretation can vary from person to person and from place to place. What liveability means for one person is not the same for the other person and vice versa. People experience and appreciate places very differently. The explanation of liveability depends to a large extent on the norms and values of the individual who assesses a neighbourhood or place (Van der Werf, 2013).

6.3.1 Description of Liveability

In the literature many different definitions are used to describe the term liveability. From an international point of view the concept of liveability is described by dimension and indicators. Generally, this concept depends on two concepts which are quality of life (1) and well-being (2). The following dimensions and indicators are identified (Commonwealth of Australia, 2012; Personal et. al, 2017; VROM, 2004).

Table 9 Global description of liveability

	Dimension	Indicators
1	Quality of life	World Happiness Index Mercer Quality of Living Index The Economist Intelligence Unit Liveability Indexes
2	Global city liveability Resident-assessed liveability	The Economist Intelligence Unit Liveability Indexes Property Council of Australia City Liveability Index

	Dimension	Indicators
3	Wellbeing	Happy Planet Index
4	Equality	Early Development Index
5	Health	Life expectancy Indigenous population Walkability
6	Safety	Road safety Crime rates
7	Affordability National Centre	Mercer Cost of Living Index NATSEM Cost of Living Housing cost and affordability
8	Accessibility	Access to public transport services Active Travel Access and use of broadband internet
9	Community wellbeing	Participation in sporting, cultural and leisure activities

These international dimensions and indicators make it possible for nations to compare liveability relatively from each other. To determine the liveability from a national point of view it is customary to apply the national definition of liveability. In context of this research it is relevant to analyse Dutch perspective of liveability. This perspective is used as starting point and discussed in the following section.

A more contemporary definition used in the Netherlands is: 'the extent to which the living environment meets the conditions and needs that are set by individuals' (van der Werf, 2013, p. 126). When describing liveability authors generally refer to a set a of indicators as measurement tool (SCP, 2002). A majority of the authors mention social cohesion, safety and physical quality of the living environment as keywords (Leidelmeijer & Kamp, 2003; SCP, 2002; van Dorst, 2005).

6.3.2 Methods and tools for measuring Liveability

National and local government agencies in the Netherlands use an interactive map called the 'Leefbarometer' to measure liveability in different neighbourhoods. The Leefbarometer is made up of two sub-models. The first sub-model directly predicts the opinion of residents about their living environment (the so-called "stated preferences", also referred to as the "subjective part"). The second sub-model predicts the appreciation of residents for the living environment (the so-called 'revealed preferences', also referred to as the 'objective part'). By combining these two approaches a good picture of the quality of life is created (Leidelmeijer & Kamp, 2003; Leidelmeijer et. al, n.d.; van der Werf, 2013).

The Leefbarometer measures five important dimensions on zip-code, district and municipal level. (Leidelmeijer & Marlet, 2014; Leidelmeijer, et al., n.d.). The dimension are dwellings (1), residents (2), facilities/services (3), safety (4), physical surroundings (5). The Leefbarometer enables national and local government agencies to respond quickly and adequately to any negative developments. In addition, the Leefbarometer can be used in policy making, monitoring, evaluations and in-depth research. This tool measures liveability every two years by generalizing the opinions in a specific neighbourhood.

6.4 Costs

Project cost is one of the most fundamental subjects that is discussed when initiating a project. In the early stages of a project trade-off are generally made to find out which design or solution is the cheapest while still achieving the project goals (Smith, 2014; Steyn & Nicholas, 2016). The cost of a project stands in direct relation with the level of quality. In principle the goal is to focus on a safe technical design first. Cost is of secondary importance. should be Two other elements which also influence the quality of the project is time and scope. These three elements (cost, time and scope) are referred to as the triple constraint (Baratta, 2006). The quality is safeguarded by finding a right balance between the elements of the triple constraint illustrated in Figure 15. This approach is not only limited to the design and construction phase, but also the maintenance phase (Baratta, 2006; Rachwan et. al, 2016; Smith, 2014).

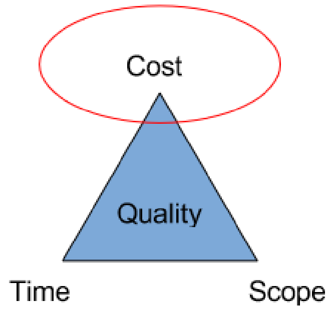

Figure 15 Triple constraint triangle (Baratta, 2006)

6.4.1 Description of Costs

In infrastructure projects there are generally two types of costs, namely the investment cost or Capital Expenditure (CAPEX) and the maintenance cost or Operational Expenditure (OPEX). The CAPEX and the OPEX are compiled as follows:

CAPEX

- Direct cost: The direct cost is directly attributable to the project items. The required materials, labour and equipment are calculated as direct costs. The direct cost includes all countable elements related to type of material, size and design of the structure, related construction procedures and quality of the intended structure.
- Indirect cost: The costs which cannot be accurately attributed to specific project items are defined as indirect cost. This is an integral part of each cost calculation. It consists of site expense, overheads, profit and preparatory works.
- Contingency: The contingency costs refer to costs that will occur as a result of uncertainties of prices. Contingency is applied to all project items and estimated as 10% of the total amount of direct and indirect costs.

The VAT is excluded in this overview.

OPEX

- Maintenance cost: Projection of maintenance and operation costs are important parts of the financial planning of the project. To determine the maintenance and operational costs a percentage of total construction cost based on expert judgement and past project experiences is used. This usually lies between 1% and 2% of the CAPEX (Steyn & Nicholas, 2016) .

Social costs (such as the effects of a project on noise and air pollution, nature and people) are excluded in this overview. They are usually assessed in a cost benefit analysis. However, public organisations need to take these effects in to account.

6.4.2 Methods and tools for measuring Costs

In order to compare different alternatives based on the cost (project)managers usually apply Life Cycle Costing (LCC). LCC is a method to compare the most effective solution by considering the capital cost (initial construction), operation, maintenance, and upgrade of the alternative. The lifecycle is looked at from the acquisition, maintenance and disposal phase (Hastings, 2015). The time value of money plays an important role in this approach because the value of money changes over time (Van den Boomen et. al, 2016). The IEC (2017) described LCC as:

''The process of performing an economic analysis to assess the cost of an item over a portion, or all, of its life cycle in order to make decisions that will minimize the total cost of ownership while still meeting stakeholder requirements''

Literature study revealed that the main objective described by the authors is to gain insight into the total cost of an asset during its lifecycle in order to make well balanced decisions (Barringer, 2003; Hastings, 2015; IEC, 2017; Van den Boomen et. al, 2016).

In context of this research it is clear that budget is an important issue. The municipality is responsible for reserving sufficient budget to improve the quay walls. The budget allocated to this issue should be spend wisely. This is because the allocated budget mainly consists of tax-payments received from the Dutch citizens. The public value efficiency play a large role here, which is described as the relation between the available resources and its outcome (Manzoor, 2014).

6.5 Sustainability

In the construction industry, many project and process managers struggle with the implementation of sustainable solutions while at the same dealing with many uncertainties, such as risks, cost overruns and delays (Hao et al., 2008). Sustainability is in particular important because of the global climate goals set by the United Nations in 2015. The objective is to improve sustainability worldwide by drastically reducing the carbon dioxide emission and other pollutants.
These goals have a large impact on the construction industry, because this sector is responsible for a high level of energy consumption and external pollution. Approximately 23% of air pollution, 50% of greenhouse gas (GHG) production, 40% of water pollution and 40% of solid waste in cities are the global pollution numbers caused by the construction industry (Wilmott Dixon, 2010)

6.5.1 Description of Sustainability

The umbrella term 'sustainability' has no unique description. Different authors give a variety of definitions. In 'infrastructure project management context' the definition of Abdulai et. al (2007) and (Mckenzie, 2004) is considered best suited. They describe sustainability as:

'The commitment to integrate social principles and the concerns of stakeholders. It occurs when the project actively supports the capacity of current and future generations to create healthy and liveable communities.

Abdulai et. al (2007) define the social principles as inclusiveness, integrity, transparency, fairness and diversity. These social principles should be safeguarded at all time and are focused on the long term. From an infrastructure point of view the environment is considered the most important aspect. There are in general a variety of human actions which can lead to large environmental impacts in the construction industry, such as the production and transportation of materials. Likewise, operating heavy machinery like cranes also has a negative impact on the environment. These environmental impacts can be classified in different categories like the impact on air, nature and water. These categories are evidently interrelated with each other (Akan, et. al, 2017)

6.5.2 Methods and tools for measuring Sustainability

In order to measure the actual impact on the environment (air, nature and water) two concepts are generally used, which is the CO_2- footprint and the social cost of carbon. The CO_2- footprint is described by Wiedmann & Minx (2007) *as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product" (p.4).* Fu, et. al (2014) describes these life stages as material production, material transportation, building construction and material disposal. To calculate the total CO_2- footprint the emission in each stage need to be determined. This is usually expressed in kg/CO_2 or metric ton/CO_2.

The social cost of carbon is applied to determine the environmental impact in monetary terms. It converts the calculated CO2 (in tons or kg) to actual cash flow. This method enables decision-makers to calculate the total project cost including the environmental impact. However, this method uses an estimated value for the cost per CO2 (in tons or kg). Several researchers, institutions and experts looked into providing a representative number for the social costs per ton. The results revealed conflicting values. This shows a large uncertainty regarding the determination of the social cost of carbon per ton CO2.

6.6 Innovativeness

Innovativeness is generally coupled with new sophisticated high-end techniques developed by research and design (R&D) departments within companies. However, innovativeness is more than developing new techniques, it also about improving processes to stimulate creativity within a society. This should eventually contribute to innovative behaviour. One of key players to that can stimulate innovativeness are the local and national governments. From a construction management point of view innovativeness can for instance be included in the procurement of services. This will stimulate organization to come up with innovative solutions. Innovativeness is also about collaboration. This means finding the right partners to team up with to reach certain objectives.

6.6.1 Description of Sustainability

Different definitions are proposed by authors to describe the term innovativeness. According to Slaughter & Member (1998) innovation is defined as: "*The actual use of a nontrivial change and intervention in a process, product, or system that is novel to the institution developing the change*". They explain that innovativeness can be viewed from five different scales, namely:

- Incremental: Small and based on existing experience and knowledge;
- Modular: A change in concept limited to the company itself;
- Architectural: a change in links to other components or systems;
- System: multiple, integrated innovations.
- Radical: Breakthrough in science or technology;

Incremental innovativeness represent a small change and radical innovativeness a major change. Slaughter & Member (1998) further explain that it depends on the predetermined goals to find out which innovative level fits.
From a construction management point of view Ling (2003) describes innovativeness as: "*A new idea that is implemented in a construction project with the intention of deriving additional benefits although there might have been associated risks and uncertainties, whereby the new idea may refer to new design, technology, material component or construction method deployed in a project*".
In context of this research and exploring additional criteria the definition of Ling (2003) is best suited. However, the different levels of Slaughter can be applied in order to explain the impact of innovative measures.

Innovativeness is used more and more as criterion when making trade-offs in the construction industry. Technical innovative solution can be useful for the governments in order to provide benefits to a wider society. According to Seaden & Manseau (2001) this can directly be linked to the economic development. Innovative measures will be important in order to take advantages of the changes in market economy, to build long- term relationship with clients, increase motivation for the project and make interventions to the system and processes (Asad et. al, 2005).

6.6.2 Methods and tools for measuring Innovativeness

The literature does not describe a clear method or tool to measure innovativeness. The main reason is that each innovative solution has his own characteristics such as implementation time, effectiveness, cost etc. The main goal is that the innovative solutions should suit the predetermined objectives or should add value to the society (as a whole).

6.7 Interdependencies between the decision-making criteria

The criteria discussed in the previous sections are interrelated. Van Wee et. al (2013) have developed a conceptual framework which can be used to described the interdependencies between the aforementioned criteria. The framework is used to describe which factors have impact on the infrastructure system. This framework is illustrated in Figure 16.

This framework introduces the factors that influence trends in accessibility, safety and the environment. It first explains the needs and desires of people. People generally prefer to live and work in an area which suits their needs and desires. For instance, students at the TU Delft prefer to live around the campus in order to be close to the university. This illustrates that accessibility is about having access to things that people think is important for them. In other words accessibility depends on what people want to do where the related activity and locations are. It is also about the mode of transportation, depending on how easy it is to travel to the desired location. Another factor is safety, which reflect how safe the infrastructure network is. Nowadays the infrastructure network is safer compared to a few decades ago. An example is that many cities and towns have bypasses so that vehicles do not cross cities and towns and therefore protect pedestrians and cyclist way better. This goes hand in hand with technology. Smart cars for instance reduce the number of serious injuries. The last factor is the environment, for example 40 years ago on many roads, especially in central urban areas, there was way less traffic. Cars and lorries are much cleaner than 40 years ago and people slowdown (due to max. speed limits) and consequently make less noise.

The framework conceptualizes these relationships and can be useful to understand why changes in any part of the transport system have several effects and thus influencing levels of accessibility, safety and environmental pressure. It for example explains that if we build a railway station it might make the nearby area more attractive for offices and houses. This could encourage/stimulate people to live there. It illustrates that if cars become more comfortable and cheaper it reduces transport resistance and more people might prefer to buy one. In turn this could influence the decision of people to accept jobs at more remote places. To summarize a change in any of the components leads to a complex chain of direct and indirect effects.

Decision-making criteria in relation to the framework by Van Wee et. al (2013)
In context of this research the component technology can be explained through the criteria innovativeness. New technological developments can for instance increase the safety level of the asset and at the same time fulfil certain needs and desires. Sustainability is partly related to the environment, risk liveability. Motorized transport affects the natural environment by the emission of greenhouse gases and air pollutants. Liveability is also addressed in this section through the built environment. This describes health noise pollution. Safety and accessibility are already addressed in this framework. The criterion cost is excluded. This is more related to available resources to improve the transportation system, which is not part of the scope of this framework.

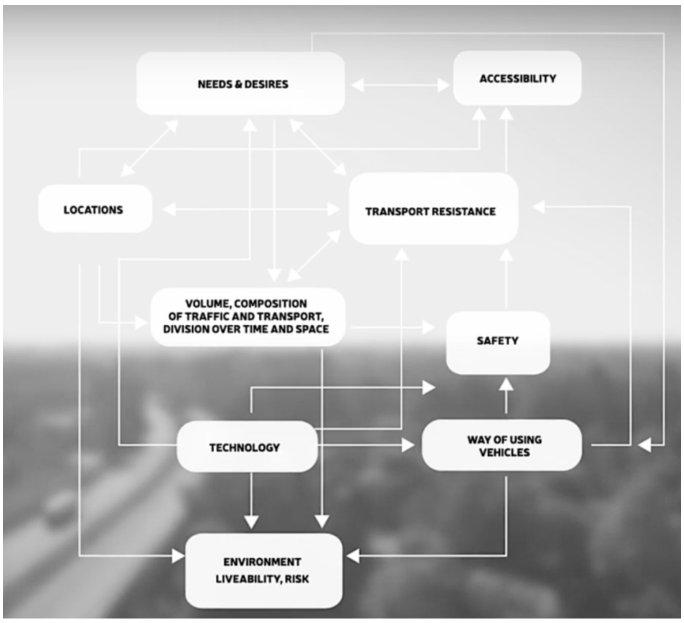

Figure 16 A conceptual framework for factors that impact the transport system (van der Wee et. al, 2013)

6.8 Concluding remarks

Literature study revealed 6 re-occurring decision-making criteria related to infrastructural projects, which are safety, accessibility, liveability, costs, sustainability and innovativeness. Safety is considered the most important criteria. An unsafe asset can result in failure and loss of function. In any case the objective is that the asset should function accordingly. Costs is also considered an important criterion. A lot of decisions are made based on total cost of the project. Accessibility, liveability, sustainability and innovativeness should also be taken in to consideration. It can be a decisive factor depending on the situation at hand. The framework of Van Wee et. al (2013) described certain dependencies between factors which have impact on the transport system, accessibility, the environment and safety. These factors can be explained through the decision-making criteria discussed in this chapter. It shows that favouring a particular decision-making criterion will have consequence on the other criteria, with the exception of costs. This criterion is described as an input in order to reach certain goals. In context of maintaining quay walls safety, accessibility, liveability and cost are the most important criteria. Sustainability and innovativeness are less important

7 CONCEPTUAL DECISION-MAKING MODEL Q-WALLS

This chapter describes the Q-wall decision-making model based on the discussed decision-making theories/models, failure mechanisms, intervention measures and criteria. The following research question is answered in chapter 7 and 8. (The answer to this question is presented in chapter 8):

What kind of theoretical conceptual decision-making model can be established for quay walls and applied in practise?

Figure 17 gives an overview of the quay wall decision-making model. In section 7.1 an explanation is given why these decision-making theories/models are applied. Section 7.2 explains the parts in more detail. Finally, in section 7.3 the decision-making moments are described.

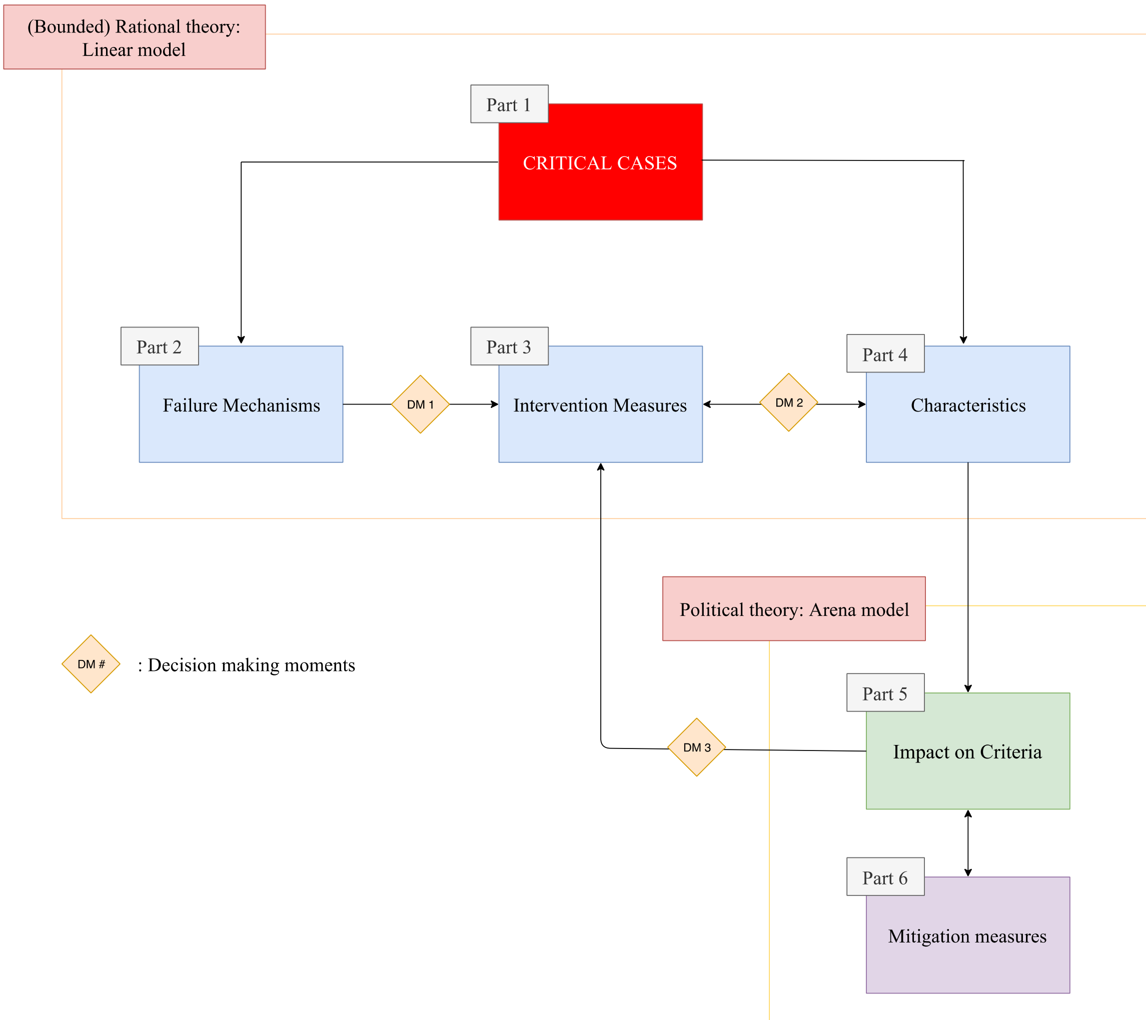

Figure 17 Conceptual decision-making model (own illustration)

7.1 Integrating decision-making theories

The bounded rationality and political theory are applied in the quay wall decision-making model. The application of these two theories in context with the quay wall decision-making model are discussed subsequently.

Application of the bounded rationality theory
As illustrated in Figure 17 the upper part of the model is governed by the bounded rationality theory. Decision-makers follow a series of logically successive phases with the idea that this will result in a rational decision. The linear character of this theory should simplify the path to a suitable decision. Therefore, this theory is considered suitable in the quay wall decision-making model. However, *inadequate information and control* regarding the quay walls show signs of bounded rationality. As discussed in section 1.1 the absence of information regarding the technical state of the quay wall makes it extremely difficult for the asset managers to deploy suitable intervention measures. This uncertainty cannot be controlled by decision-makers and will influence the results of their decisions. For example, if the failure mechanisms of the quay wall cannot be identified correctly (due to lack of information of the subsoil or foundation) wrong intervention measures will be deployed. Or it may happen that intervention measures are deployed which do not entirely cover all the failure mechanisms. In summary, the bounded rational theory is applied in order to systematically find the right intervention measure, while taking bounded rationality in to account. This is reflected by means of inadequate information which is difficult to control.

Application of the political theory
The bottom part of Figure 17 is governed by the political theory. The different intervention measures have a certain impact on the criteria. The characteristics will determine what the impact area's will be and their level of extremeness. These decisions will affect a variety of actors which have divergent objectives. In order to minimize the impact, it is important to take their objectives in to account, especially actors with large decision-making power. Dealing with a variety of interdependent actors in such an environment can be seen as an arena. In section 5.2.3 this arena is described as metaphoric environment where are a variety of actors are active with their own values and interests. In this case it is the task of the municipality to take the role as leading actor in order to find a right balance between the different interest. This means that a network of actors is set-up where interaction back and forwards between the actors is key. Mitigation measures can be deployed to minimize the impact by for instance compensating actors elsewhere. This also includes taking advantage of opportunities which can arise.

7.2 The parts in the conceptual decision-making model

In this section the parts illustrated in Figure 17 are elaborated on.

Part 1:
As discussed in section 5.1 every decision-making process starts with the identification of the problem. In this case the quay wall section which is considered critical are referred to as the 'cases'. It starts with identifying of the case, the scope and problem and the objectives. For the scope a radius of ca. 300 meters is applied in this research. In order to determine the kind of failure mechanism a set of signals are identified based on inspection classes. SBRCURnet (2013) distinguished four inspection classes, namely basic geometry (1), monitoring and visual

inspection (2), technical inspection (3) and additional inspection (4). During these inspections a variety of indicators can be determined, which in turn can question the reliability of the structure. The first two inspection classes are relatively easy to perform. These classes are focussed on desk research and visual inspection at site in order to find out the type of quay wall, built year and visual defects. Monitoring can be applied to determine if the quay wall is moving excessively in the X, Y or Z direction (in respect to the base case). The third class is focussed on gathering more technical detail regarding the condition of the quay wall. This is usually supported by calculations. Additional inspections are needed if further investigation is needed based on initial defects. These kinds of inspections are generally aimed on a specific part of the quay wall (such as dive research).

Due to lack of detailed information about the quay wall a non-exhaustive list is compiled of several key indicators. These key indicators are based on the first two inspection classes mentioned before. Furthermore, information retrieved from monitoring can also be a signal of quay wall failure. These levels are based on the policy set by the municipality in Amsterdam. The indicators are presented in Table 10.

Table 10 Signals of quay wall failure

Analysis of the physical problem (non-exhaustive)		
	Indicator	Description
1	Tears in the retaining wall	Horizontal and vertical tears of the masonry
2	(Local) settlement of the structure	Vertical settlement of the structure (can be local)
3	Bending of the retaining wall	Bending in the horizontal direction perpendicular to the wall
4	Deformation of the ground level	Deformation at ground level behind the retaining wall (parking spaces and road)
5	Sinkhole	Behind the retaining wall a hole emerges due to collapse of the surface layer
6	Loose/missing bricks	Missing bricks in the retaining wall due to loss of mortar strength or excessive horizontal pressure

In regards to the characteristics of the case five important aspects are considered in this research based on general case descriptions. A list of these aspects can be found in Table 11.

Table 11 Characteristic of the area surrounding a quay wall (section)

Analysis of the surroundings (non-exhaustive)		
	Indicator	Description
1	Buildings	Assessed depending on the distance between the quay wall and buildings
2	Houseboats	The number, size and type of houseboats present are analysed
3	Pipelines/Cables	Available sources need to be consulted to determine the location of the pipelines and cables. In the Netherlands the Kadaster can provide this information.
4	Trees and plants	Municipal departments provide information about the number of trees and their condition. Sometimes this information is made public by local governments.
5	Service	This part describes the available services such as shops, bars and other public or private services people make use of.
6	Roads and waterways	All available information regarding the waterway and road is described, such as the depth, width and the type of users.
7	Other physical exceptions/projects	Other additional physical aspects are described in this part. Such as public toilets and poster columns. Furthermore, planned and project in execution are described here. This can have significant impact on the quay wall.

Part 2:
After the problem is identified the next logical step is to translate the problem in to failure mechanisms based on the observed issues. The failure mechanisms need to be identified in order to take appropriate measures against them.

Part 3:
In this part the different failure mechanisms are coupled with the intervention measures. The failure mechanisms determine which intervention measure is best suited.

Part 4:
In part 4 the characteristics of the intervention measures and the cases are described. For the characteristics of the intervention measures a detailed description is given of the activities needed to implement the measure. In order words: what do we need to do in order to implement the selected intervention measure. Another input in this part is to look at the characteristics of the surroundings, which is described in part 1. The objective is to couple the characteristics of the intervention measure and the surroundings in order to determine what the impact will be on the criteria which will be used in part 5.

Part 5:
Part 5 looks at the characteristics which are determined in part 4 to measure the impact on the criteria. If the impact is considered too high, then an alternative intervention measure should be deployed. Another option is stick with the intervention measure but implement mitigation measures to reduce the impact (part 6).

Part 6:
In this last part mitigation measures are proposed in order the minimize the impact on the criteria.

7.3 Decision-making moments

In Figure 17 three decision-making moments are illustrated. These decision-making moments are described subsequently.

Decision-making moment 1:
In the first decision-making moment a choice of intervention measures is made based on the perceived failure mechanism(s). As discussed in section 4.1 there are two possibilities, namely intervening in time and failing to intervene in time. This will result in appropriate intervention measures or damages. A trade-off can be made to accept certain risk or to implement intervention measures.

Decision-making moment 2:
The second decision-making moment takes the physical surrounding of the quay wall in to consideration and the failure mechanism(s) determined in the first decision making moment. The characteristics of the specific intervention measures are reflected against the characteristics of the surroundings. The goal is to make a well-balanced decision based on intervention measures together with location specifics surroundings.

Decision-making moment 3:
In the last decision-making moment, the characteristics of the surroundings and suitable intervention/prevent measures are explained through the predetermined criteria. This will

reveal what the impact of the prevention or intervention measure will be. If the impact of a certain prevention or intervention is considered too high the decision can be made to revisit other prevention or intervention measures. Or mitigation measures can be introduced to reduce the impact level. Decision-making should involve actors such as the local (and national) government, organizations and residents.

8 CASE STUDY: QUAY WALLS IN AMSTERDAM

In this chapter Amsterdam is used as case study for the application of the conceptual decision-making model. The same steps as followed in the theoretical frame work applies here. The following research question is answered in this chapter:

How can a theoretical conceptual decision-making model be established for quay walls?

In this chapter background information of the quay walls is given. First in section 2.1 a brief introduction is made of the quay walls in Amsterdam. In the following sections the different functions (sections 2.2) and typologies (section 2.3) of the quay walls are further elaborated on.

8.1 History of quay walls in Amsterdam and state of art

The city of Amsterdam was formed in 13th century after the construction of the dam in the Amstel canal. Shortly thereafter in the middle ages the first canals where built (Damrak and Rokin). In the 16e and 17e century the major of Amsterdam decided that the city should be expanded to provide housing for the growing population. To expand the city the marshland needed to be drained. During this process a network of canals in arch-like shapes where constructed. These walls and the prestige's buildings alongside the canals are considered to be iconic and unique in its kind and are part of the Unesco World Heritage. Figure 18 gives an overview of the canals in Amsterdam throughout the centuries.

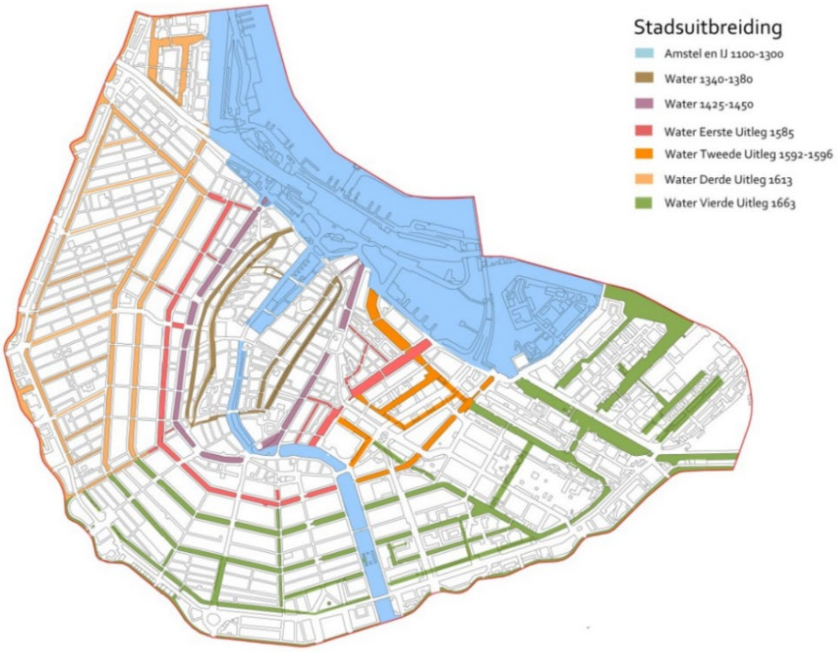

Figure 18 The growth of the waterway network up to the 17th-century (amsterdam.nl)

Within the municipal boundaries more than 900 kilometres of quay walls and banks are situated. The municipality of Amsterdam is responsible for the management and maintenance of approximately 600 kilometres of these quay walls and banks. The remainder has other owners, such as Waternet, Province of North Holland and the Port Authority. Green banks and other soft banks are not counted as part of the quay walls, leaving a length of 200 kilometres of quay walls that need to be managed by the municipality of Amsterdam.

Type 2 quay walls (retaining walls on wooden piles) are most common in the city centre of Amsterdam. These quay walls have different functions. The most important functions are retaining, mooring, protecting and bearing (CURNET, 2005; Wel, 2018). These inner-city quay walls were initially constructed to withstand a smaller amount of load than in the present day. This is mainly due to the increase of (heavy) traffic in these area's (Gemeente Amsterdam, 2018). Furthermore, natural decay (because of aging) of these walls increases the sense of urgency (Vervoort, 2013).

Throughout the years a lot of information regarding existing quay walls have become unavailable. This has a variety of reasons. The absence of this information makes it extremely difficult for the municipality of Amsterdam, which is the asset owner, to determine the current technical state of their quay walls. Relatively expensive inspections need to be carried out along hundreds of kilometres of quay walls. This puts the municipality of Amsterdam in a difficult dilemma. Doing nothing is a risky option because it only increases the probability of failure. Renewing all the quay walls in Amsterdam at the same is nearly an impossible task, it is a time consuming and costly procedure. Furthermore, renewal means that (a significant part of) the city of Amsterdam will not be accessible for a long period of time.

The main goal of the municipality is to make sure that the quay walls do not fail until the moment of renewal. Intervention and prevention measures need to implemented to maintain the quay walls. However, the implementation of these measures is a complex task due the densely built area and the stakeholders with divergent interests.

8.2 Failure mechanisms

The most common type of quay wall which are retaining walls on wooden pile (see Figure 5) is used as starting point to describe the failure mechanisms in Amsterdam. The municipality of Amsterdam identified a variety of failure mechanism based on SBRCURnet (2013) and observed failure mechanism in practise. These failure mechanisms are summarized in Figure 19.

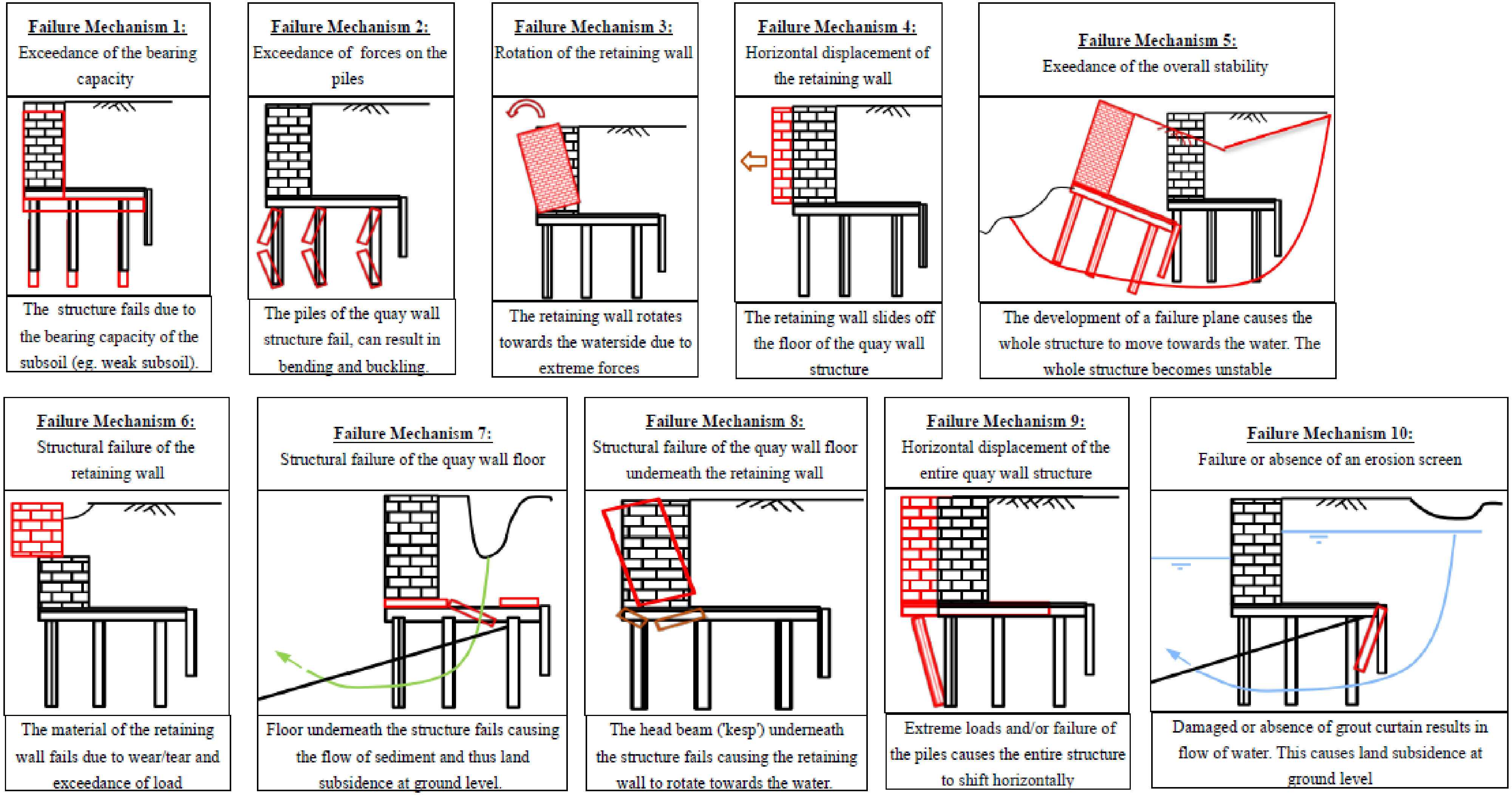

Figure 19 Failure mechanisms type 2 quay walls Amsterdam (amsterdam.nl; adapted)

There are certain failure mechanisms which occur in practise more often than others. An analysis of the situation in Amsterdam revealed 16 location where a quay wall (section) has 'failed' due to one or more failure mechanisms. An overview of the probabilities regarding these failure mechanisms are presented in Table 12. These probabilities are integrated in to a fault tree for type 2 quay walls. The fault tree, calculations and the assumptions made to determine the probabilities can be found in appendix C.

Table 12 Overview observed failure mechanisms in practice and their probabilities

ID	Frequency	Probability of Occurrence	Min value	Max value
FM1	0	0,00	0,00	0,34
FM2	1	0,03	0,03	0,37
FM3	5	0,16	0,16	0,50
FM4	6	0,19	0,19	0,53
FM5	1	0,03	0,03	0,37
FM6	0	0,00	0,00	0,34
FM7	3	0,10	0,10	0,44
FM8	6	0,19	0,19	0,53
FM9	5	0,16	0,16	0,50
FM10	4	0,13	0,13	0,47

The figures presented in Table 12 show that FM 8 (Failure of the head beam, in Dutch: 'kesp') and FM 4 (Horizontal displacement of the retaining wall) occur more frequently than others. The input used to determine these figures are mainly based on results from dive research. From a theoretical point of view these findings where expected. In respect to FM 8 the head beam is situated at a vulnerable location. This part of the structure is also responsible for transferring the vertical and horizontal loads to the piles (and subsoil). FM 3 was expected to occur more often due the increase of horizontal and vertical loads acting on the retaining wall. These loads occur because of an increase of traffic consisting of relatively heavy vehicles.
On the other side FM 1 (exceedance of the bearing capacity) and 6 (Structural failure of the retaining wall) have not been observed yet in practise. In regards to FM 1 it is quite difficult to the determine if the subsoil is the cause of vertical displacement of the structure. In order to establish this additional research is needed (for instance a cone-penetration test). The absence of FM 6 was expected from a theoretic/scientific point of view. As discussed earlier in this section research revealed that the masonry has a significant amount of residual strength.

8.3 Intervention measures Amsterdam

As discussed in section in 4.1 there are two possible events after a failure mechanism has been identified, namely intervening in time and failing to intervene in time. Intervening in time resulted in 11 interventions measures for the situation in Amsterdam. These are selected based on the likelihood of application in practice. This is determined by performing a quick scan regarding the feasibility of the measures in Amsterdam. First the measures related to reducing the driving forces are discussed, followed by the measures related to increasing the resisting forces. Again, retaining walls on wooden pile (see Figure 5) is used as starting point.

8.3.1 Reducing the driving forces

At location A

- Removing the parking spaces

The parking spaces along the canals have a major effect on the forces acting directly on the quay wall. These spaces are generally occupied most of the time and can be seen as permanent loads. Therefore, this measure can have significant impact on the quay wall. This measure is relatively easy to implement with low costs. First preparation take places, which include research in to alternative route and communicate with residents. Then, signs and fences need to be placed in order to show that parking is prohibited. During the period of this intervention measure enforcement is needed to check whether people comply with it.

- Removing trees (with large roots)

Trees with large roots can have a large impact on the forces working on the quay wall. The roots of trees can increase the horizontal forces and cause tears and shearing of the quay wall. Removing trees is not an easy procedure because a lot of trees in the city have a monumental status and/or a significant value for the people in the surrounding area. It is considered a straight forward procedure, however the interest of the stakeholders need be aligned in order to secure quick implementation.

- Reducing the amount of (heavy) traffic

Reducing the amount of heavy traffic can be divided in to different categories by looking at the weight of the vehicles passing the quay wall. A distinction is made between three categories. This division is made based on presumable allowable q-load which is derived from the technical state and age of the quay walls.

1. For pedestrians and cyclist only (avoid large groups) (max q-load: 2,5 kN/m^2)
2. For pedestrians, cyclist, car and motor user (max q-load: 10 kN/m^2)
3. For pedestrians, cyclist, car and motor user and heavy vehicle such as garbage trucks, touring cars and fire (trucks) (q-load around: 20 kN/m^2)

At location B

- Apply light fill material

This measure can be implemented if the horizontal forces working on the retain wall are relatively high. By excavating the soil directly behind the quay wall and replacing it with light material such as EPS, Flugsand or Bims.

Table 13 gives an overview of the activities of the different measures.

Table 13 Overview of intervention measures to reduce the driving forces for Amsterdam

	Measure	Activities
LOCATION A		
1	Removing the parking spaces	» Preparation[1] » Assemble and signs and fences » Enforcement (check with frequency)
2	Removing trees (with large roots)	» Preparation (Informing residents and other stakeholders) » Set-up site: (equipment and materials) » Remove tree » Clean-up site
3	Reducing the amount of heavy traffic	-
3a	▪ Category 1	» Preparation » Assemble and signs and fences » Enforcement (check with frequency)
3b	▪ Category 2	» Preparation » Assemble and signs and fences » Enforcement (check with frequency)
3c	▪ Category 3	Current situation
LOCATION B		
6	Apply light fill material	» Preparation » Set up site » Removing pavement at ground surface » Excavating soil behind quay wall » Replacing soil with light fill material » Place pavement and clean-up site

[1] The preparation includes desk research, analysis of the surrounding, informing stakeholders and when needed monitoring. In some cases, it is necessary to perform additional research such dive inspection or trial trenching.

8.3.2 Increasing the resisting forces

At location B

- Applying geotextile at the floor

Geotextile is placed behind the quay to prevent the soil to wash away. This measure is usually applied when the quay wall floor is damaged. The soil at land side need to excavated until the floor is visible. Thereafter geotextile is placed to close-off the damaged quay wall floor. The excavated soil is placed back and the pavement is restored. This is a quite extreme measures which can cause a lot of hinder for the people working and living around this location. The street need to be closed-off in order to implement this measure.

- Vertical steel pile through the retaining wall

A vertical steel pile is driven through the retaining wall to improve the connection between the retaining wall and floor. It also acts as additional pile to transfer the vertical loads. However, it is quite difficult to implement this measure due possible damages to the wall and floor. In the preliminary stage the situation around the quay wall (section) should be examined in detail (such as the (remaining) strength of the bricks and floor. Mainly because of this it can take relatively long to implement this measure. Before implementing this measure it is important to locate the pipeline and cables to prevent damages.

At location C

- Erosion screen

An erosion screen can be placed in front and behind the quay wall. In case the erosion screen is placed in front of the quay wall a good connection between the quay wall floor and retaining wall is needed in order to prevent leakages. Placing an erosion screen behind the quay wall is more difficult. First the end of the quay wall at the landside need to be located, this means that the soil needs to be excavated. This can cause a lot of hindrance. Secondly the connection between the erosion screen and quay wall needs to be secured, which is a time-consuming procedure. Lastly applying an erosion screen close to the adjacent buildings can cause complication to the state of the foundation of these buildings. Therefore, placing an erosion screen in front of the quay wall (waterside) is preferable.

At location D

- Placing a sheet pile with sand fill

For this measure a sheet pile is vertically driven in to the canal. Thereafter the space between the quay wall and (newly placed) sheet pile is filled with sand. An option is to add a horizontal beam between the quay wall and sheet pile. This measure reduces the clearance width of the canal but it considered a robust measure to stabilize the quay wall. The measure can be implemented easily and quickly via the canal. A noteworthy point is that placing

- Steel pile with console to support vertically and horizontally

This measure is applied to transfer the horizontal and vertical loads by means of a steel pile with console. The console is placed between the floor of the vertical beams of the quay wall and the wooden pile. The forces are transferred via the console to the newly placed steel pile. Implementing this measure can take time because of the dry working environment that needs to be created in order to place the console correctly.

- Supporting beam between two sides of the canal

This measure is useful when two quay walls at opposite sides of each other are moving towards the canal. By placing a horizontal beam the two quay walls can be stabilized. The vertical beam is placed against purlins which is mounted against the brickwork of the retaining wall. The purlins are placed to distribute the horizontal forces on the whole length of the retaining wall.

- Concrete floor with piles

In front of the quay wall a new structure is placed, which consists of a concrete floor on piles. The structure can be placed under or above the water level. In case the concrete floor is placed above water a new area is created in front of the quay wall. The new area can be used as second quay wall. However this measure narrows the clearance width of the canal. Waternet, which is the organization responsible for the water levels in the canals, need to be compensated elsewhere due to water storage issues.

Table 14 gives an overview gives an overview of the activities of the different measures:

Table 14 Overview of intervention measures to increase the resisting forces for Amsterdam

	Measure	Activities
LOCATION B		
1	Applying geotextile at the floor	» Preparation[1] » Set up site » Removing pavement at ground surface » Excavating soil behind quay wall » Placing geotextile behind the quay wall » Placing excavated soil back » Place pavement and clean-up site
2	Vertical steel pile through the retaining wall	» Preparation » Set up site » Partly removing pavement at ground surface » Install steel piles » Check and monitor underwater situation » Placing excavated soil back » Place pavement and clean-up site
LOCATION C		
3	Erosion screen (can be placed at water- or landside)	» Preparation » Set up site » Waterside: press-in sheet pile in front of the structure » Check underwater situation after placement » Clean-up site
LOCATION D		
4	Vertical sheet pile with sand fill (and supporting beam)	» Preparation » Set up site » Waterside: press-in sheet pile in front of the structure and create dry working environment » Apply geotextile and sand fill » Clean-up site
5	Steel pile to support vertically and horizontally	» Preparation » Set up site » Waterside: press-in sheet pile in front of the structure and create dry working environment » Install steel piles and console » Clean-up site
6	Supporting beam between two sides of the canal	» Preparation » Set up site » Place H-profile on the quay wall (both sides) » Place horizontal beam on both sides of the quay wall » Clean-up site
7	Steel pile (with or without supporting beam)	» Preparation » Set up site » Place supporting beam on the quay wall » Waterside: steel pile » Connect supporting beam with steel pile » Clean-up site

[1] The preparation includes desk research, analysis of the surrounding, informing stakeholders and when needed monitoring. In some cases, it is necessary to perform additional research such dive inspection or trial trenching.

8.3.3 Alternative intervention measures

In this section two alternative intervention measures for Amsterdam are introduced, namely lowering the quay wall and the application of geotextile encapsulated sand elements in front of the quay wall. These measures are determined based on interviews and past projects. The two measures will be examined in more detail by means of hand calculation to check whether the structure is considered safe. Detailed calculations regarding the assumptions, starting points, dimension of the structure and input parameters can be found in appendix D. In this section of the report only the summaries of the results are presented.

8.3.3.1 Lowering the quay wall

This alternative intervention measure is focussed on reducing the driving forces on the quay wall at location A (see figure Figure 8). This measure can be extremely effective in case of high retaining walls.
For successful implementation of this measure it is necessary to determine the minimum height of the 'new' retaining wall. The profile of the canal depend on three factors which are the hydraulic conditions of the canal (1), the number of lanes (2) and the dimensions of the passing vessels (3).
The hydraulic conditions are related to meteorological conditions. This means that a change in weather conditions can cause fluctuations of the water level. A distinction is made between low, mean and high water level.
Next, the number of lanes mainly determines the width of the channel. A modern channel has at least two lanes. However there are channels which only consists of one lane. Furthermore, the dimensions of the lane have an influence on the manoeuvrability, steerability and speed of the vessels passing. An example of a two-lane channel is presented in Figure 20 to illustrate the ratio between the safety and sailing lanes.

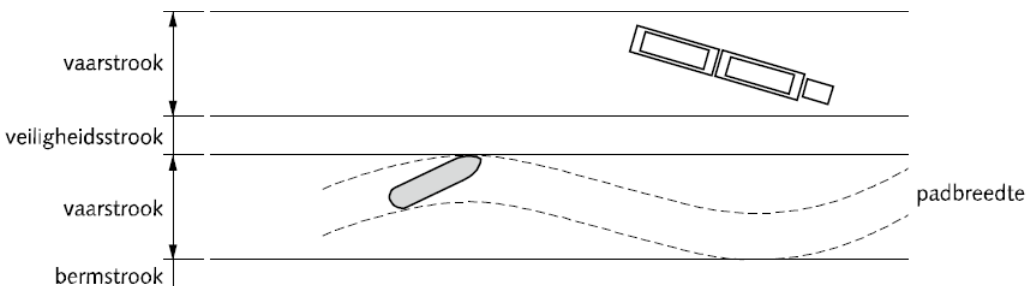

Figure 20 Example safety and sailing lanes (Rijkswaterstaat, 2011)

The most important factor is the dimension of the passing vessels. The width, length and depth of the passing vessels determines the profile of the channel. These passing vessels are categorized in to different classes based on their dimensions. When determining the minimum dimension, the largest passing vessel should be used as reference point.

Rijkswaterstaat (2017) has determined guidelines for designing hydraulic structure for waterways. In the Netherlands a distinction is made between two functions for waterways, which is recreational and commercial shipping. In practice, recreational and commercial shipping often go together. In those cases, the guidelines for commercial shipping should be used as reference to determine the dimension of the waterway. A distinction is made between a normal profile (2-lane) and a tight profile (1-lane). In case of a normal profile, the depth of the waterway (D) must be at least a factor of 1.4 times the loaded draft of the largest vessels which is allowed to pass the canal. For the tight profile a factor 1.3 applies. The depth of the waterway mentioned here must be present at all times. This means that the maintenance depth or dredging depth must be greater than or equal to the waterway depth. The factor is established by taking the energy height of passing vessels in to consideration. This is based on historical data.

In Amsterdam a vessel with the following maximum dimensions are allowed on a vast majority of the canals:

- Width: 4,25 m.
- Length: 20 m.
- Height loaded ship: 2.1 m (D_g)

There are a few locations where a smaller vessel is allowed. These locations are excluded from this analysis. Based on these parameters and a marge for high water levels a minimum height of 2.94 metres in respect to still water level should be present. This margin is considered to be extremely high and does not give a representative figure for the current situation of Amsterdam. Therefore, the table below (see Table 15) is used to determine the minimum height of the retaining wall. These figures are compiled based on past data gathered by the municipality of Amsterdam.

Table 15 Dimensions retaining wall Amsterdam

Dimension retaining wall			
Top part [m NAP]	Bottom part [m NAP]	Height [m]	Width [m]
+ 0,40	- 0,90	1,30	0,55
+ 0,70	- 0,90	1,60	0,66
+ 1,00	- 0,90	1,90	0,77
+ 1,30	- 0,90	2,20	0,88
+ 1,70	- 0,90	2,60	0,99
+2,00	- 0,90	2,90	1,10
+2,30	- 0,90	3.20	1,21
+2,60	- 0,90	3,50	1,45

Results calculations

For the calculation an average height of 1,9 m is used as starting point. This means that the retaining height can be reduced to a minimum height of 1,3 m. The structure is checked against sliding and rotation mainly because the retaining wall is the only element where adjustment are made. All other elements of the structure is assumed to be safe. Also, due to lack of detailed information about the wooden foundation only the retaining wall is assessed.

The following values where found for the case of a retaining height of 1,9 metres and a width of 0,77 metres. The figures represent the forces acting on the retaining wall and not the whole structure:

Horizontal forces = 24 kN
Vertical forces = 30 kN

The retaining height is then reduced to a minimum height of 1,3 metres but maintains the same width of 0,77 metres. This gives the following values:

Horizontal forces = 13 kN
Vertical forces = 21 kN

This results in a relative difference of 38% in respect to the base case. As mentioned, two relevant criteria must be checked. The structure needs to be safe against sliding and rotation of the retaining wall. For determination of these factors the Unity Check (UC) (see section 6.1.2) is applied.

Table 16 Unity check lowering the quay wall (from 1,9 m)

Unity check lowering the quay wall (from 1,9 m)		
Retaining height [m]	UC (against sliding)	UC (against rotation)
1,9 (base case)	1,29	0,802
1,3 (new situation)	0,98	0,608

The results presented in Table 16 revealed that the retaining wall is safe against sliding when the retaining height is reduced to 1,3 meters, in contrary to the base case.

This intervention measure is considered to be effective in cases of relatively high retaining walls. Therefore the same calculation is made for the retaining wall with the largest dimension (h:3,5 w:1,45) in Amsterdam (see Table 15). The following results were found (see Table 17. The values in-between can be determined through linear interpolation (see appendix D)

Table 17 Unity check lowering the quay wall (from 3,5 m)

Unity check lowering the quay wall (from 3,5 m)		
Retaining height [m]	UC (against sliding)	UC (against rotation)
3,5 (base case)	0,26	0,66
1,3 (new situation)	0,13	0,32

As expected a lower unity check is found as the retaining height decreases. This is mainly due to the fixed width of the retaining height and the reduction of the active soil forces. This intervention could there be considered a valuable solution from a technical (safety first) perspective. However, each quay wall has its own set of parameters and should therefore be tested. Additionally, when reducing the quay wall measures should be taken to prevent damages to the rest of the structure. The assumption is made that after implementation of this measure the road will be only made accessible for cyclists and pedestrians if this is not the case already. In this case the land-use plan needs to be adjusted. Therefore, the goal is to apply this measure at locations (with high retaining walls) where the foundation is in bad condition without needing to change the land-use plan.

The activities regarding this measure is presented in Table 18. An illustration of the intervention measure is shown in Figure 21.

Table 18 Overview of an additional intervention measure: Lowering the quay wall

	Measure	Activities
LOCATION B		
1	Lowering the retaining height of the quay wall	» Preparation » Set up site » Removing pavement at ground surface » Excavating soil behind quay wall » Removing the masonry work of the quay wall » Placing excavated soil back » Place pavement and clean-up site » Announce change of function (only for cyclist and pedestrians)

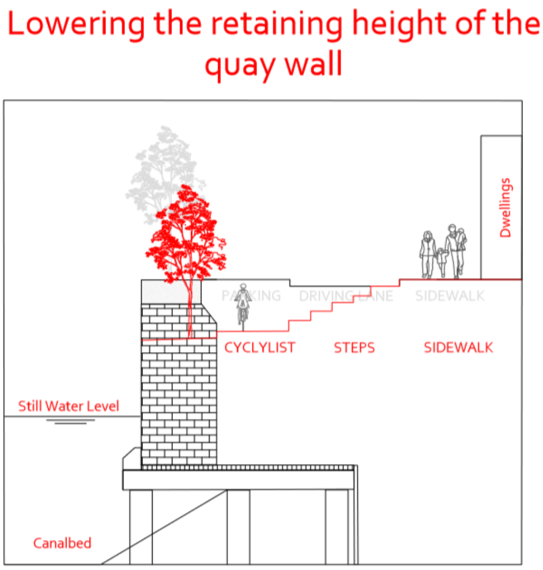

Figure 21 Example illustration: Lowering the quay wall (own illustration)

8.3.3.2 Application of geotextile encapsulated sand elements

The application of big bags in front of the quay wall is to increase the stability of the structure from the waterside by applying geotextile elements filled with sand (location D). In this case the application of geosystem technology will be looked at in more detail. The application of geosynthetics structures are increasingly being applied in coastal protection projects (Lee et. al, 2014). In the geosystem technology there are four variants, which are presented in Figure 22.

Figure 22 Geotextile encapsulated sand elements (Bezuijen & Vastenberg, 2013)

Geotextile Bags:
These are generally described as 'big bags' which can be filled mechanical or manual. Size range between 0,3 and 10 m^3. They are usually applied for channel repairs, scour holes, beach groynes and as soil and bank protection.

Geotextile Matresses:
The mattresses consist of two layers of geotextile which are filled with sand or concrete. Between the two layers compartments are made in the form of tubes or cells. This should facilitates an even distributions of the fill material. The mattresses are usually applied in nature development areas and as soils and bank protection.

Geotextile Tubes:
The Geotextile tubes consists of geotextile that is permeable only for water. The fill material is usually sand or a similar granular material. The diameters vary from 0,5 to 4 metres and can

be 25 to 100 m[1] long. They can be used for dewatering of dredged material, groyne, breakwaters and for land reclamation.

Geotextile Containers:
The geotextile container is a large sand bag with a volume between 100 to 600 m^3. The container is filled and transported by a hopper with a split barge. After it reaches the desired location it is discharged (dumped) on the sea or river bed. They can be used for artificial reefs, breakwaters, land reclamation and toe stability.

A summary of the application areas are presented in Table 19.

Table 19 Application areas of geotextile-encapsulated sand elements

Application areas of geotextile-encapsulated sand elements				
Application	Geotextile bag	Geotextile mattress	Geotextile tube	Geotextile container
Beach groyne	X		X	
Breakwater	X		X	X
Hanging beach	X		X	X
Dune toe protection	X		X	
Channel repair	X	X	X	X
Land reclamation			X	X
Underwater reef	X			X
Bed protection	X	X		
Bank protection	X	X	X	
Temporary dams	X		X	X
Sediment management	X	X	X	X

Based on the field of application the geotextile bags are best suited in the case Amsterdam. The geotextile bags can be placed more accurately and moreover likely to applied based on the dimensions. The CUR 217 is used as guideline for designing with geotextile bags.

Results calculations
When applying the geo bags in 7 conditions must be checked (see appendix D). For the situation in Amsterdam revealed 3 important criteria where considered relevant. These are rupture of the geotextile due to insufficient seam strength (1), instability of the geotextile bags through water current over the structure (2) and foundation failure and deformation (3). These results are presented subsequently.

Rupture of the geotextile due to insufficient seam strength (1) and instability of the geotextile bags through water current over the structure (2)
These two failure conditions are analysed simultaneously because the stability (condition 2) depends on the dimension of the bags, which has a direct relation with the required tensile strength (condition 1).
The stability of geotextile bags depends on the slope of placement, tensile strength and dimension of the bags. To establish the required dimensions iterations where performed to find out if the geotextile bags are stable when subject to overtopping in combinations with the required tensile strength. The results are presented in Table 20. The dimension of the geotextile bags with a slop 1:3 is used as starting point because it the most common profile found in Amsterdam. The width of the bag has the largest contribution to the required tensile strength. The length and the height are variable. Values between 0,1 and 1 meter can be chosen for the length and for the height values between 0,1 and 0,93 for the height. For the dimension of the bags see Figure 23.

Table 20 Minimum requirements of the geotextile bags

Minimum requirements of the geotextile bags				
Slope	Tensile strength [kN/m]	Dimensions [m]		
		L	W	H
1:5	19,72	-	11,48	-
1:4	23,66	-	9,45	-
1:3	30,16	0,1-1	7,25	0,1-0,93
1:2	41,67	-	5,04	-
1:1	61,3	-	3,2	-

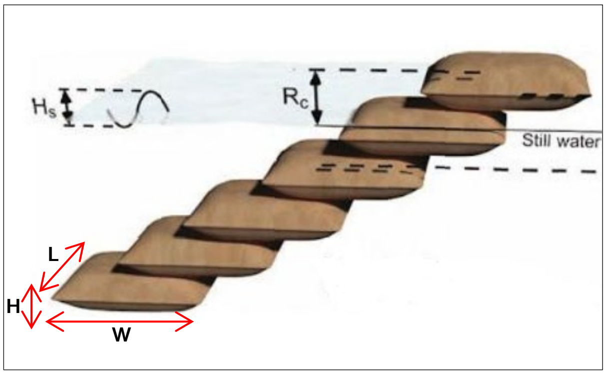

Figure 23 Dimensions of the geotextile bags (Bezuijen & Vastenberg, 2013)

Foundation failure and deformation(3)

The subsoils in the canals of Amsterdam consists of dredged material and soft layers (clay and peat). Therefore calculations are made to determine the total settlement after the geotextile bags are placed. These calculations are based on the formula of Terzaghi and Koppejan. The results are presented in Table 21. The results show that a total settlement of 0,6 m[1] is to be expected after a period of 730 days (=2 years). This means that extra layer of 0,62m[1] geotextile bags need to be added during settlement.

Table 21 Settlement geotextile bags

Settlement Geotextile bags			
Layer	Primary Settlement [m]	Secondary Settlement [m]	Total settlement [m]
Clay & peat	0,30	0,20	0,50
Clay	0,09	0,03	0,12
Clayey sand	0,03	0,01	0,03
Clay & peat	0,01	0,00	0,02
		Total settlement	**0,6**

The activities regarding this measure is presented in Table 22. An illustration of the intervention measure is shown in

Table 22 Overview of an additional intervention measure: Geotextile encapsulated bags

	Measure	Activities
LOCATION B		
1	Applying geotextile bags in front of the quay wall	» Preparation » Set up site » Dredge 0,5 meters » Fill the geotextile bags with sand » Place filled geotextile bags under water with a grabber or hydraulic crane (monitor placement under water) » Place mooring poles, steel piles or other structure (to prevent boats to moor) clean-up site

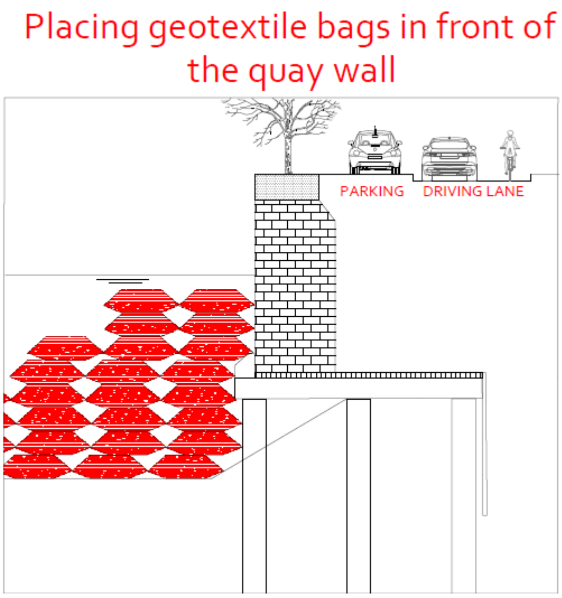

Figure 24 Example illustration: Application of geobags (own illustration)

8.3.3.3 Concluding remarks alternative intervention measures

After analysing and interpretation of the results the following conclusion are drawn:

Lowering the Quay wall
The application of this intervention is possible in theory. It reduces the horizontal forces while still maintaining the robustness (width) of the original retaining wall. However, in practise this can be considered a very cumbersome measure. It means that the entire area behind the quay wall need to restructured, by means of stairs, road for cyclist and replanting of trees. Cables and pipelines also need to be located and if necessary redirected. Furthermore, it has a large impact on accessibility. Motorized vehicles are in this case not allowed to park or pass this area. However there are locations were a change of land-use is not necessary. To conclude, from a theoretical 'safety perspective' it can be considered a valuable solution.

Geotextile encapsulated elements (bags)
The calculations revealed that 0,6 m additional bags need to be placed during a settlement period of 2 years. This is almost as high as the initial height of the geotextile bags (1 m). This is an undesirable situation. Additionally, the dimensions of the bags related to a slope of 1:3 are extremely large. A width of more 7 meters is required for 1 bag. Placing such large bags in the canal is undesirable and will hamper nautical traffic. The goal of this measure was to prevent the structure (specifically the retaining wall) from tilting and sliding. If the forces working on the geotextile are large enough tilting and sliding cannot be prevented because of presence of soft soil. The geotextile bags need to find stability from the underground. Soil improvement technique can stabilize the bags. However, large bags are still needed.

To conclude, after analysing the two intervention measures from a theoretical and practical point of view they are considered not feasible. The option of lowering the quay would preferably be possible in contrary to the application of the geotextile bags. This is viewed purely from a theoretical point of view.

8.4 Decision-making criteria Amsterdam

Literature review revealed that there are three important decision-making criteria in Amsterdam, which are safety, accessibility and liveability (Coalitieakkoord Amsterdam, 2018). These three areas are considered the most important cornerstones by the municipality of Amsterdam and should always be safeguarded. Safety is the most important cornerstone followed by accessibility and liveability, all three cornerstones are interrelated with each other (Coalitieakkoord Amsterdam, 2018).

In addition, costs are also considered a decisive factor. The municipality is responsible for reserving sufficient budget to improve the quay walls. The budget allocated to this issue should be spend wisely. This is because the allocated budget mainly consists of tax-payments received from the Dutch citizens. The public value efficiency play a large role here, which is described as the relation between the available resources and its outcome (Manzoor, 2014).

First the three important decision-making criterion in Amsterdam are discussed in this section. These three criteria are explained an operationalized in the upcoming section. Next an analysis is made regarding the interdependencies of these criteria.

8.4.1 Safety

Safety is the most important criterion regarding the maintenances and renew of public assets in Amsterdam. Section 6.1 described that public assets are obligated by law to meet minimum reliability levels. The quay walls are no exception, especially given the current situation.
The municipality of Amsterdam is currently dealing with two main problems. Which are: lack of knowledge regarding the technical state of the quay walls and secondly time constraint. The combination of these two factors have shown in practice that quay walls in Amsterdam can fail at any moment, which in turn, can have large (financial) consequences. Failure occurs if the load or solicitation (S) is larger than the resistance (R) of the structure (Kapur & Pecht, 2014; Wel, 2018; Wolters, 2012).

To secure the safety of the people working and living in Amsterdam a so-called safety-first principle is introduced by the aldermen. This means that safety cannot be considered a trade-off under any circumstance. This political choice means that safety should be considered a boundary condition rather than a trade-off criterion. A change can only be made after the approval of the council of aldermen.

8.4.2 Accessibility

One of the objectives of the municipality of Amsterdam is to improve the accessibility of the city. On the other hand measures are currently been carried out to close-off parking spaces and reducing the number of (heavy) vehicles alongside the narrow canals (Coalitieakkoord Amsterdam, 2018). These two conflicting objectives make it even more challenging to address accessibility. In this analysis only, boat- and car-users are considered. The impact on these target groups will be higher compared to other road-users. Pedestrians and (motor)cyclist for instance need a smaller passage, in addition it is very common to provide an emergency solution for these target groups. Boat- and car-users usually operate larger vehicle's, therefore alternatives routes are generally needed to safeguard the accessibility and to minimize blockages.

Section 6.2 has revealed a variety of indicators for accessibility. In this analysis two indicators are used to determine the impact on accessibility, namely travel time and travel cost. The travel time will reveal how much additional time is needed to travel from location A to B (by car and boat. The travel cost will express the loss travel time lost in monetary term in order to show the level of impact.

In Amsterdam the traffic model VMA is used (stands for Verkeersmodel Amsterdam). This is a urban traffic model used for strategic road and transport studies. It is mainly used to asses the impact of policy changes and infrastructural projects in the city. This type of model can be categorized under the impact model as discussed in section 6.2.2.

8.4.3 Liveability

One of the responsibilities of the municipality of Amsterdam is to take care of the public interests. This can be achieved by taking the opinion of their citizens in to consideration when making decisions. This aspect is discussed extensively in the report of the Coalitieakkoord Amsterdam (2018). They acknowledge the problems related to liveability. The main problems they identified are street littering and nuisances due to increase of tourism. Furthermore, the crime rate should be reduced significantly. Budget is made available to increase liveability in appointed areas.

The importance of liveability is also reflected in this research. The different preventions and intervention measures can have a significant impact on liveability. Actors, such as local businesses and residents are usually the one who are faced with these problems and are also considered the focus group in this research. The following indicators for liveability are identified in context of this research (Kees Leidelmeijer et al., n.d.; van der Werf, 2013; VROM, 2004).

Table 23 Indicators of liveability

Indicators of liveability (non-exhaustive)		
	Indicator	Dimensions
1	Disruption of public space	Safety
2	View (of inland waterways and roads)	Public spaces
3	Sound pollution	
4	Green spaces	

Air pollution could also be considered a valuable indicator in context of this research. However, this indicator is extensively described and operationalized in the criteria: sustainability. Furthermore, a more sophisticated approach is needed to measure the effects regarding air pollution.

8.4.4 Interdependencies

Safety, accessibility and liveability are criteria which are interrelated with each other. In context of this research the scheme in Figure 25 illustrates their dependencies.

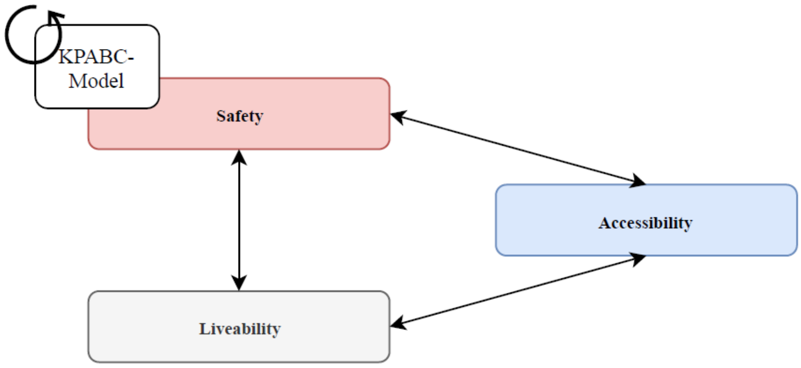

Figure 25 Overview of interdependencies safety, accessibility & liveability (SAL) (own illustration)

As mentioned safety is considered one of the most important criterion in Amsterdam. The quay walls should be safe enough for its intended use, this means that the load should not exceed the resistance. The reliability of the structure can be related directly to liveability, an unsafe environment can have a negative impact on liveability (van der Werf, 2013). The assessment of a unsafe environment is closely related to the perception of people. This is governed by the so-called KPABC-model (Meyer & Reniers, 2016) (Knowledge - Perception - Attitude - Behaviour – Consequences). It first starts with the knowledge people have. The more knowledge a certain individual has, the better he/she can assess 'risky situations and unsafe situations'. This in turn influences their perception. The higher their perception of reality is, the better their ability becomes to understand, interpret and assess the situation. In the next stage their attitude and behaviour are influenced by their perception. The actions which are coupled with their behaviour result in certain consequences. These consequences can be either positive or negative. This model shows that people's perception of safety highly influences liveability. For instance people with lack of knowledge about the safety of the quay walls do not directly consider themselves living in an unsafe area. This model also shows that knowledge regarding the quay walls is important for the municipality in order to react adequately.

Accessibility is a concept that is generally mentioned when assessing liveability. As discussed in section 6.2 accessibility can be viewed from different perspectives, for instance reducing the parking spaces and the amount of cars alongside the canals can have a negative impact the liveability. Removing this possibility can be viewed as an negative or positive impact depending on the perception of the people living in the surrounding area. In addition safety has a direct impact on accessibility. If the quay wall is considered unsafe there is a possibility that the area need to be closed off, which in turn has impact on liveability.

In section 6.7 the dependencies between the different decision-making criteria are explained through the study of Van Wee et. al (2013). The situation is Amsterdam underlines these dependencies. It revealed that there is mutual dependency between the criteria. In respect to Amsterdam the factor knowledge plays a prominent role.

In practice the municipality aim to find a right balance between these three criteria. However it turns out to be a difficult task to make well-balanced decisions that satisfies a large amount of the public. Furthermore, there are also other criteria which need to be taken in to consideration, which is costs. Improving each of the three elements comes at a certain cost. It is almost impossible to continuously invest all three criteria at the same time, unless there are unlimited resources to do. This is also the case in Amsterdam. The allocated budget cannot cover all three aspects at the same time.

To summarize safety can not be considered a trade-off because assets are required by the law to meet certain minimum requirements (see section 6.1.2). In order to deviate from the mandatory safety levels, a policy change is necessary. For instance, if accessibility has a higher importance level than safety, a (temporary) new legalisation should be made. Sufficient (widely-based) support needs to be created at all administrative level for this new legislation. As of now this change of policy is not effective.

8.5 Application of the model on a case

In this chapter the established model is applied on a case in Amsterdam study First a list is compiled of the critical quay wall sections based on the available information. Thereafter a quay wall section is chosen randomly. This resulted in the following quay wall section LLG0201, which is located at the LELIEGRACHT

A systematic approach is applied to the case. The steps described in the quay wall decision making model are used as guideline. This resulted in the following steps:

1. In the first step detailed information is given regarding the characteristics of the cases. This mainly includes the location, the scope and technical details.
2. In the second step (possible) failure mechanisms of the quay wall are identified based on the signals related to failure of the quay wall.
3. The third step describes the two possibilities, which are: fail to intervene in time and intervene in time. Regarding failure an economic analysis is made if the quay wall actually collapses. Next an analysis is made by coupling the failure mechanisms to possible intervention measures.
4. The fourth step combines the characteristics of the intervention measures with the characteristics of the quay wall surroundings. Then a decision is made which intervention measure is best suited.
5. In step 5 the impact of the chosen intervention measure on accessibility and liveability are determined. Safety is as mentioned earlier not a decision-making criteria. If the impact is considered too high, mitigation measures must be deployed.

8.5.1 Case study – LELIEGRACHT

The quay wall section LLG0201 is 86 m long and located in the city district: Centrum. The quay wall section is situated between bridge 52 and 62, Figure 26 shows where the quay wall is located. A visual representation is added to create an overall overview.

General information LLG0201

Identification no.:	LLG0201
Adjacent canal:	Leliegracht
Adjacent street:	Leliegracht 38 t/m 60
Total length quay wall:	86m
Construction year:	Unknown

Figure 26 Overview of the quay wall LLG0201 (data.amsterdam.nl)

Technical information

The construction year of the quay is unknown. Desk research did not reveal any information regarding the type of quay wall. It is therefore difficult to find out the type of quay wall. However, as discussed earlier in this research most of the quay walls in the city centre of Amsterdam are type 2 quay walls, which are retaining walls on wooden piles. Based on the physical appearance of the quay wall it is presumable that this a type 2 quay wall. A standard cross section of this is illustrated in Figure 27.

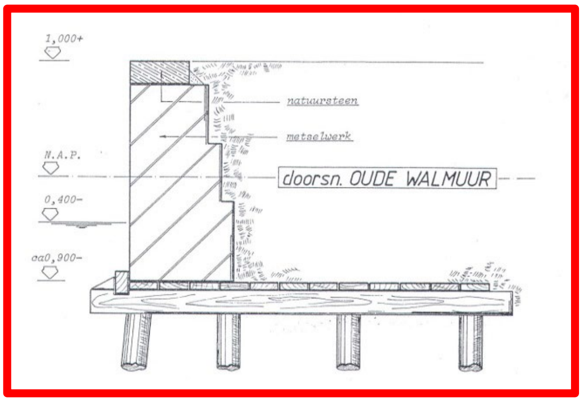

Figure 27 Presumable cross-section type 2 quay walls (Amsterdam.nl)

In order to find what the technical state is of the quay wall inspection reports are compiled. These are discussed in the next section.

1. *Technical inspection (2017)*

In 2017 a technical inspection is carried out by an engineering company conform CUR-recommendation 72, class 1.2. The results of the inspection are determined based on the NEN2767-4. An overview of these results are presented below.

A. Broken capstone (nearby house number 50)
B. Shearing of the retaining wall (nearby bridge 52)
C. Horizontal and vertical tears in the retaining wall (nearby house numbers 36, 38, 42, 48 and 56)

Based on the NEN 2767 classification the inspection report concludes that the quay wall is in reasonable condition. This means that aging has start locally and that defects are visible. However the function of the quay wall is not in danger.

The available information regarding the quay wall LLG0201 is limited. Additional research (such as dive research) is needed to give more technical detail about the quay wall section.

<u>The area surrounding the quay wall</u>

The quay wall is situated in the city centre of Amsterdam which is densely populated and built. Therefore it important to find out what kind of factors play a significant role in a particular area. The list presented in Table 11 is used as guideline to describe the area surrounding the quay wall. These factors are described subsequently.

1. Stakeholders

The stakeholders that will be analysed in this section are the people living/working adjacent to the quay wall LLG0201 and the actors responsible for the road, waterways and underground infrastructure.

- People working and living near LLG0201

According to the 'Basisregistratie Adressen en Gebouwen' (BAG) there are 36 independent units, of which 28 are classified as residents and 8 units are used for other functions (such as shops and restaurants). These other functions are situated at ground level.

Figure 28 gives an overview of the different functions in the street.

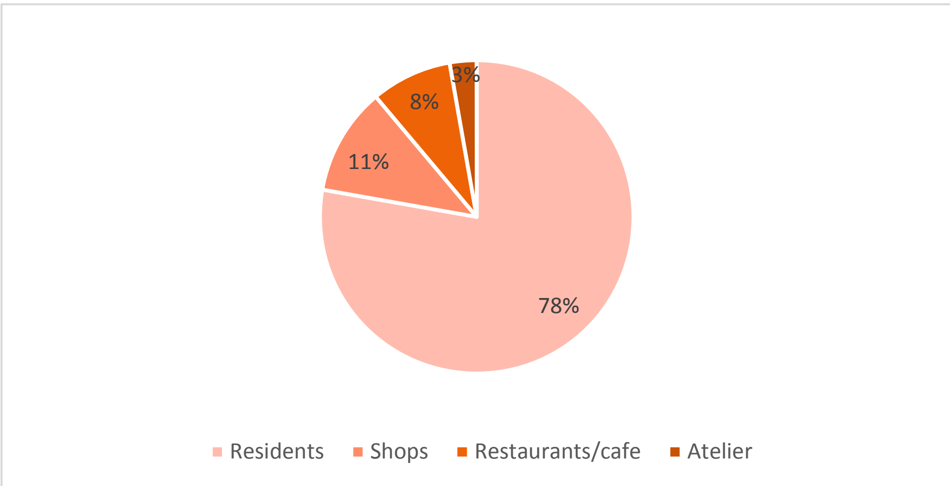

Figure 28 Function use of the buildings along LLG0201 (own illustration)

In respect to type of people working and living in this area The Central Bureau of Statistics (CBS) can be consulted. Below an overview of several important topics related to the people living in the area 2017 is the most actual reference year and therefore used in this analysis.

- Amount of residents: 80 (45 male; 35 female)
- Distribution of age: 17 % (25 years and younger); 59 % (25-65 years); 24 % (65 and older)
- Orgin: 60 % (Dutch) 40 % (western); 10% (non-western)
- Car-usage per household: 0,5

- Buildings

According to the 'Basisregistratie Adressen en Gebouwen (BAG) there are 13 building adjacent to the quay wall. The average construction year of these buildings is around 1905. There are several buildings which are renovated in 1997. Furthermore these buildings are labelled as Protected City views by the National Government (in dutch: Rijksbeschermende stadsgezichten).

- Houseboats

In the canals of this quay wall section there are no houseboats situated. However in the canal next to bridge 52 (Prinsengracht) there are houseboats situated.

- Pipelines/Cables

Information is not yet available.

- Trees and plants

On the quay wall 6 trees are situated, 2 of these trees have a monumental value. An overview of these trees and their characteristics are presented in Table 24.

Table 24 Analysis of the trees situated at the Leliegracht Amsterdam

Tree no.	Location	Tree height [m]	Plant year	Monumental status?
342322	Leliegracht no. 60	18-24	1920	Yes
342282	Leliegracht no. 58	15-18	1980	No
342330	Leliegracht no. 56	9-12	1980	No
342325	Leliegracht no. 52	18-24	1920	Yes
342319	Leliegracht no. 48	15-18	1980	No
342310	Leliegracht no. 44	18-24	1960	No
342307	Leliegracht no. 38	15-18	1960	No

- Service

The services are described in the functions situated alongside the canal.

- Roads and waterways

The road on top of the quay wall is a 30-km road with parking spaces and a sidewalk for pedestrians. The 30-km road is used for motorized vehicles, cyclists. Next to the parking spaces there are also bicycle stands, lanterns and a terrace which is used by one specific bar/restaurant. The distance between the quay wall and the buildings at landside is approximately 12 meters.

The canal LLG0201 has passage width of 13m and passage depth of NAP - 2,2m according to the Waternet (responsible for managing the waterways in Amsterdam). This corresponds with a passage profile code B. Which means that a vessel with a maximum width of 4,25m and length of 20 min is allowed to pass this canal.

- Other physical exceptions or related projects

The quay wall LLG0201 is different in comparison with the standard quay wall section in Amsterdam, mainly because it has two different width's. The corridor is more narrow after 40m (viewed from bridge 52 to 62). This means that two large vessels with a width of more dan 6,5 m cannot cross at the same time. According to experts this could be a former sluice.

This quay wall is situated nearby the 'Oranje Loper'. This is the corridor from the Raadhuistraat until the Mercatorplein. This corridor, including the bridges and adjacent quay walls, is scheduled for renewal. It can therefore be interesting to look at this quay wall section from a broader perspective. Furthermore, the quay wall section on the opposite site of the canal LLG0202 is in the same technical state as LLG0201 based on the available inspection reports. Also, LLG0101 and LGG0102 which is situated below bridge 62 is currently being stabilized by means of sheet piles (with sand fill).

8.5.2 Fail to intervene in time

In this section an analysis is made if a critical part of the quay wall fails. In this case the part next to bridge 52 is used as starting point because of the observed shear at this location. The formulas described in section 4.3.1.2 are used to determine the tangible and intangible damages. An analysis is made if a length of approximately 15m from bridge 52 on-words fails. Figure 29 gives an overview of the damages as function of the number of exposed people. The values in between can be determined through interpolation. Detailed calculations can be found in appendix E.

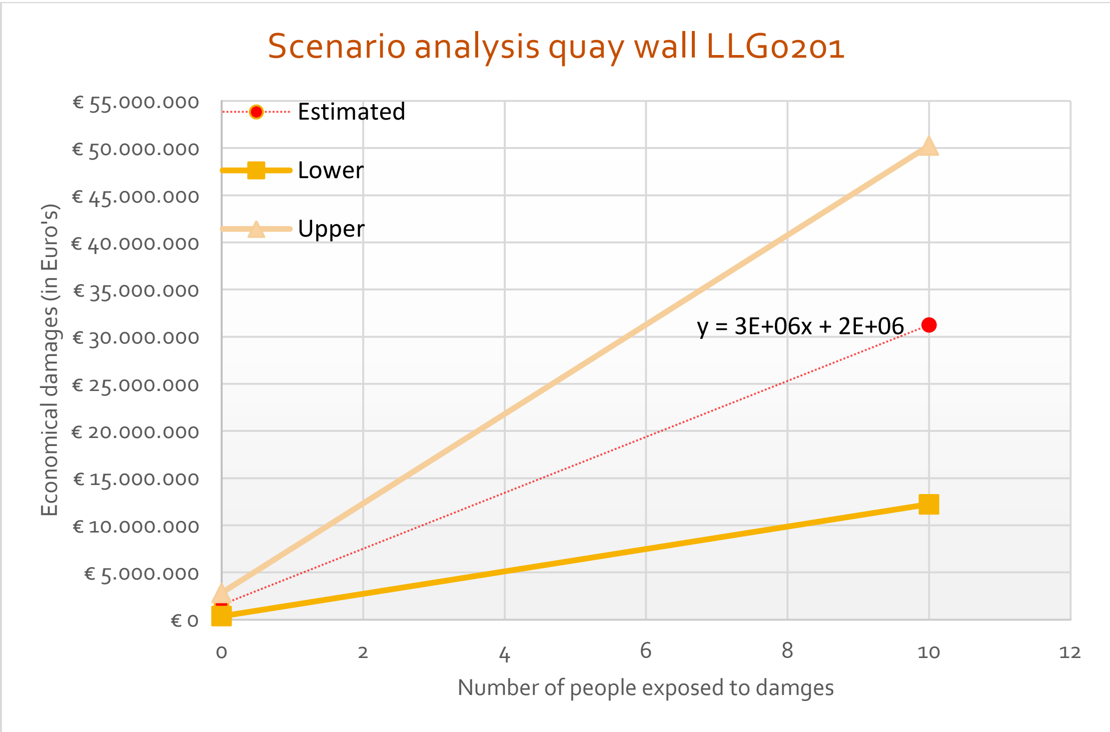

Figure 29 Scenario analysis quay wall failure Amsterdam (own illustration)

The scenario summary revealed significant damages depending on the number of people present at the location. This analysis can be used to determine the potential damages if timely intervention does not take place. Further the results can be used to make trade-off regarding the implementation of intervention measures after a (potential) failure mechanism has been identified. Ethically seen making this trade-off can cause a lot of political issues. A choice can therefore be made to close the area near the quay wall section to prevent loss of life. The analysis revealed that the major cost driver are damages related to loss of life.

8.5.3 Intervene in time

In this section the best suited intervention method is chosen. The three decision-making moments are described in respect to the case. For the determination of the best suited intervention measure the model is used. See appendix E for a full overview of the steps towards the decision-making moments

Decision-making moment 1:
Based on the signals (shear and horizontal and vertical cracks) the following failure mechanisms can be identified

- Failure mechanism 3: rotation of the retaining wall;
- Failure mechanism 4: Horizontal displacement of the retaining wall;
- Failure mechanism 5: Exceedance of the overall stability;
- Failure mechanism 8: Structural failure of the quay wall floor horizontal beam;
- Failure mechanism 9: Horizontal displacement of the entire quay wall structure.

This analysis is solely based on visual inspection. It is therefore difficult to pinpoint which failure mechanism has a dominating role. Additional research in the form of underwater inspection (dive research) can narrow this list down. At the moment this piece of information is not available.

Based on these failure mechanisms the best suited intervention measures are:

1. Removing the parking spaces;
2. Reducing the amount of (heavy) traffic;
3. Apply light fill material;
4. Placing sheet pile with sand fill;
5. Supporting beam between two sides of the canal.

Decision-making moment 2:
The second decision-making moment takes the surrounding and the activities related to the intervention measure in account (radius ca. 300 m). There is no change in respect to the first decision-making moment. However intervention 3 and 4 cannot be implemented until the location of pipelines and cables are determined. This location of these assets has a large impact on the choice of intervention measure. Damages to the pipeline and cables can have large consequences for the citizens. The implementation of these measure should

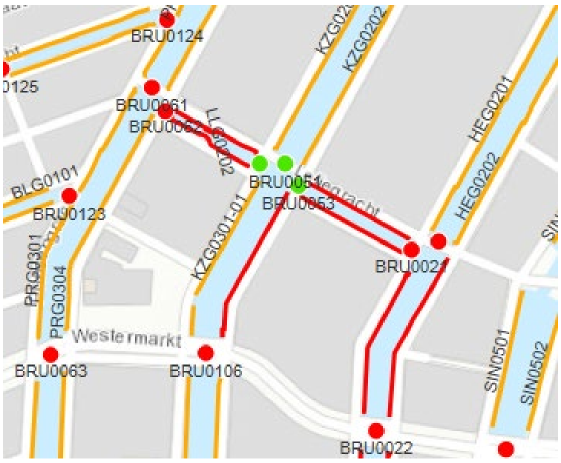

Figure 30 Scope LLG0201 radius ca. 300 m (Amsterdam.maps.arcgis.nl)

not influence the sewer system for instance or the electricity supply. This should stay operational by any means necessary. Figure 30 shows where the critical bridges and quay walls in the surrounding area are situated. This shows that the bridges at the end of the street are critical (marked red). The orange marked quay walls are neither critical nor completely 'safe'. The green marked bridges are relatively in good condition. Alternative routes can be taken in case the quay wall is completely closed-off.

Decision-making moment 3:
The last decision-making moment is included to determine the impact on accessibility and liveability. As discussed earlier safety is not considered a trade off in Amsterdam and is therefore excluded. However the project cost can be a decisive factor. Stakeholders play a central in this decision-making moment. A noteworthy point is having sufficient capacity to carry out the intervention measures. This means within the municipality and external (contractors and engineering firms). Also, the municipality is obligated to adhere to the procurement laws. This can cause delays regarding the implementation of intervention measures.

For a total overview of the assessment see appendix The results revealed that the first three intervention measures are not considered a suitable option because the impact on accessibility is too high. Along the quay wall there are a lot of commercial business owners. Closing of the quay wall for motorized vehicles will result in social and political tension. Therefore, the last three options are considered feasible. Due to the uncertainties regarding the location of the pipelines and cables intervention measure 6 is best suited in this case. Additionally is takes care of two problems at the same time, which is stabilizing two quay walls with one measure. This conclusion shows that information regarding the location of pipelines and cables is crucial.

This intervention has a major impact on the nautical traffic, therefore mitigation measures need to be in place in order to reduce the impact on accessibility. A possible measure is to implement this intervention measure in the winter to minimize the impact. Additionally, there are alternative routes nearby that can facilitate the vessels that want to pass the blocked corridor.

8.6 Concluding remarks

This conclusion is based on the results from chapter 7 and 8.

A conceptual decision-making model is established by integrating two decision-making theories, which are the rational bounded and political theory. The rational bounded theory is chosen because of limited information regarding the quay walls. Furthermore, this theory uses logical successive steps to reach decisions.
To reach a suitable intervention measure the failure mechanisms and physical surrounding are considered important and need be assessed through a step by step approach. The political theory is focussed on the social aspect. At this stage stakeholders need to be included in the decision-making. They can have significant decision-making power and can therefore have a negative or positive impact on the project.
Three decision-making moment are identified. During the first decision-making moment an intervention measure is chosen solely on the failure mechanism(s). The second decision-making moment takes the failure mechanism(s) and the physical surroundings in to

consideration. The last decision-making moment takes the failure mechanism(s), physical surroundings and the social aspect (stakeholders interest) in to account.
The application of the model on the case revealed that model gives the best results if two crucial pieces of information are available, which the results of the dive research and the location of the cable and pipelines. The absence of this information makes it extremely difficult to narrow the number of failure mechanisms and thus intervention measures. The information in respect to the location of the pipelines and cables should be available. Certain intervention measures are not considered feasible due to lack of information, while in principle it could have been suitable measures.

9 CRITICAL ANALYSIS OF THE QUAY WALL DECISION-MAKING MODEL

In this chapter the conceptual decision-making model applied on the Amsterdam case is evaluated. This assessment is done by reflecting on the conceptual decision-making model and its application to the case. Another part which is included in this section are the interviews conducted at the different municipalities in the Netherlands. The following research question is answered in this chapter:

How can the conceptual decision-making model be updated?

9.1 Reflection on Amsterdam as a case study

The application of the model revealed two interesting topics. First information (in the form of inspection, dive research and location of pipeline and cables) need to be available in order to get accurate results. This is also described as the 'rubbish in – out rubbish out' principle. The next topic is that an additional outcome is found at decision-making moment 1, which is: waiting until additional research has been carried out. The factor time plays an important role here. If it takes too long before intervention takes place the quay wall can still fail at any moment. However, making decisions based on available information and observed failure mechanisms can result in unjust decisions. In this case a valuable tool is to monitor the quay wall. This can be used as an indicator to find out when and if extreme deformation occur. The changes are presented in Figure 31 and marked red. A new line is added to show that waiting too long can results in a feedback loop.

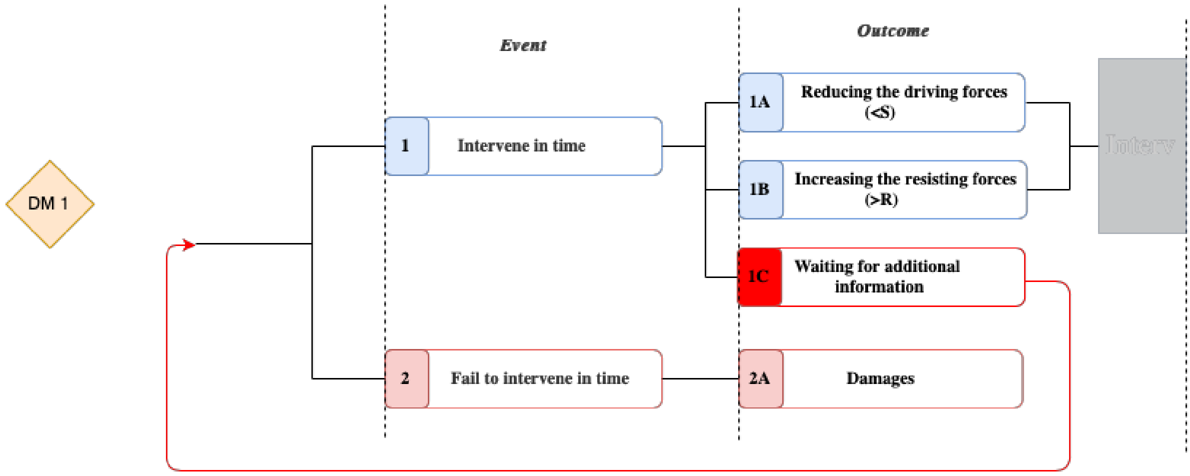

Figure 31 Possibilities after identifying failure mechanisms (adjusted) (own illustration)

Another outcome of the case is allocation of resources and capacity. Implementing intervention measures is not a straight forwards task. Sufficient resources should be made available within the municipal organisation. Furthermore, the municipality is a public organisation, therefore they are obligated to adhere to the procurement law. This can result in delays. The allocation of resources and having sufficient capacity also applies to the contractors implementing these measures.

9.2 Interview results municipalities

The interview were conducted according to list of topics (see appendix F) Four topics were considered valuable. First background information was retrieved from the municipalities to find out what the state of art is regarding their inner-city quay walls. Secondly, the different failure mechanisms related to the type of quay walls were identified. This part was included to determine if there are other relevant failure mechanisms or to find out which failure mechanism occur more often than others. Another objective was to find out how decisions are made when intervention measures need to be implemented. Lastly, the decision-making criteria are discussed in more detail to determine which criteria is considered more value than other and how trade-off between these criteria take place.

The following organizations and representatives were interviewed (see Table 25):

Table 25 List of interviewees and their respective organisations

Respondent	Function(s)	Organization	Date
A	Project manager & Asset manager civil structures	Municipality of Utrecht	20/05/19
B	Project manager maintenance civil structures	Municipality of The Hague	29/05/19
C	Technical manager civil structures (quay walls)	Municipality of Rotterdam	05/06/19
D	Asset manager civil structures	Municipality of Breda	04/06/19
E	Technical manager construction and ports	Municipality of Dordrecht	02/07/19
F	Advisor groundwater (urban area climate adaption)	Waternet	27/02/19

First a short summary is given of the interviews (see Table 26). Then the most important findings during the interview are elaborated on subsequently. This entails differences or similarities in approach, views and recommendations.
Table 26 is divided in to five subjects. Underneath each subject a question is formulated which captures the main objective, this is based on the interview protocol that can be found in appendix F. In the overview each question is answered based on the interview results from the respondents. To create an overall view Amsterdam is added to the table. For the last respondent another set of questions were asked through an informal conversation to find out what their perspective is on the current problem. These results are described separately in this section.

Table 26 Summary of interview results

	Quay wall	Failure mechanism	Intervention measure(s)	Decision-making criteria	Decision-making
Respondent	What type?	Which?	Which method based on failure mechanism	Which are most important (1-n)	Which entity decides?
- (Amsterdam)	» Retaining wall on wooden piles (type 2)	Type 2: » [4] » [8] » [7] » [10]	» Sheet pile with sand » Removing the parking spaces » Removing the amount of heavy traffic	» Safety (1) » Accessibility (2) » Liveability (3)	» Asset manager[2]
A	» Retaining wall on wooden	Type 2: » [8] » [10]	» Sand supplement » Sheet pile with sand	» Safety (1) » Liveability (2) - Trees[3] » Accessibility (3)	» Steering committee

	Quay wall	Failure mechanism	Intervention measure(s)	Decision-making criteria	Decision-making
Respondent	What type?	Which?	Which method based on failure mechanism	Which are most important (1-n)	Which entity decides?
	piles (type 2)		» Injection erosion screen	(Tourism)	
B	» Retaining wall on wooden piles (type 2)	Type 2: » [2] » [7] » [10]	» Sheet pile with sand » Horizontal (grout) anchors » Steel vertical pile through the retaining wall	» Safety (1) » Liveability (2) – Trees[2] » Water management (3) » Accessibility (4)	» Asset manager
C	» Retaining wall on wooden piles (type 2) » Sheet piles (type 4)	Type 2: » [7] » [10] Type 4: » Appendix A: Failure mechanism 8	» Removing the parking spaces » Removing the amount of heavy traffic » Removing other permanent loads	» Safety (1) » Liveability (2) - Trees	» Asset manager
D	» Sheet piles (type 4)	Type 4: » Appendix A: Failure mechanism 8	» Removing the amount of heavy traffic » Geotextile	» Safety (1) » Economy (2) » Cost (2)	» Asset manager
E	» L-wall on (wooden) piles (type 3)	Type 3: » Appendix A: Failure mechanism 6 and 8	» Removing the parking spaces	» Safety (1) » Accessibility (2)	» Asset manager

[1]The assetmanager is responsible for the final decision. However prior to selection the intervention measures are discussed extensively with the asset-, technical- and areamanager.

[2] Relative to the other municipalities trees is considered a very important topic in the respective municipality.

The topics described in the interview protocol are further elaborated on:

Maintenance and management

Maintaining assets is an ongoing cyclic process. In the theoretical section of this report (chapter 2.4) it was found that in respect to quay walls asset managers are currently applying a more reactive type of management. This statement is repeatedly underlined by respondent D during the interview. He stated: 'An asset which has just been completed is usually classified as category A. After a certain amount of time the asset deteriorates (due to normal wear and tear) and falls in category B. Usually it stays in B if (periodic) maintenance is carried out. However, a lot of our assets are now in category C, mainly due to budget issues. If this continues after a certain amount of time you slowly lose control'. He further explains that they recently started to adopt a risk-based maintenance strategy. This means that they prioritize their assets based on the risk profile. The higher the risk profile the earlier it will be scheduled for maintenance or renewal.

The results of the interview revealed that background information about the quay walls (such as age and cross-section plans) are in all cases limited with the exception of the municipality of Dordrecht (respondent E). In cases where the original plans are present trial trenches are carried out to verify the structure (respondent B). Therefore, the municipalities are currently trying to determine the technical state of their asset. This is usually done through visual inspection (within the municipality or external), dive research and monitoring. Respondent C explained that the situation in Rotterdam is more or less under control. This stems from the strict maintenance strategy which was already in place for years. This means that all the quay walls are monitored each year. Depending on the type of construction an inspection is carried out every 5 years. In addition to the technical inspection also maintenance of non-constructive elements is carried out. Respondent E describes a similar maintenance strategy. They started in 1999 with monitoring their quay walls and subsequently performing a quick scan. This resulted in a prioritization list, which is used for programming the renewal of the quay walls until 2025. Respondent E further explains that the quay wall are used intensively in their municipality, therefore a strict inspection regime needs to be in place. This consists of an inspection every 5 to 7 years (above and under water), weekly visual inspection (to locate damages). A log-register is kept to establish an overview of the defects of each quay wall section. If certain defects re-occur a rout-causes analysis is performed to prevent similar damages in the future. A noteworthy point is that all of the respondents emphasised that the task ahead of them is relatively small compared to Amsterdam. Mainly because the number of quay walls that need to be maintained or renewed is significantly larger compared to their own quay walls.

Failure mechanisms
The most common type of quay walls found in the city centre are the retaining walls on wooden piles (see Figure 5). In 2 out of the 5 cases the (concrete) sheet piles were the most common. In respect to retaining walls the most common type of failure mechanisms are: structure failure of the quay wall floor and absence of failure of the erosion screen (see Figure 19 for the failure mechanisms). The signals related to this failure mechanism are sinkholes. Three of the respondents (C, D and E) explain the difficulties related to detecting this signal. Respondent C stated: 'There was a situation a few years ago that we did not expected. Behind one of our quay wall a sinkhole the size of a Fiat 500 was found!' This is considered a dangerous failure mechanism where the sand underneath the pavement washes away towards the canal side. In the case described by respondent C the pavement itself was constructed out of cobblestones. The connection between the cobblestones was so sturdy that it did not collapse by itself. In the case of respondent D a large crane fell in to a sink hole unsuspectedly. A similar situation occurred here as in the case of respondent C, only the sand found its way through the locks of the sheet piles. It usually fails after a vehicle passes by and can even happen after a long period of time. Respondent E explains that the most recent failure (when the quay wall collapsed entirely) was in in 1982. However, in 2011 a failure mechanism occurred in form of sinkhole. A bicycle rack fell in a hole of 2 metres deep during the Sinterklaas parade unexpectedly. Fortunately, no one was injured. These examples emphasized the danger behind this failure mechanism. A reduction of the bearing capacity of the piles underneath the quay wall is also considered a common and critical failure mechanism by respondent E.

Next to the sinkholes the failure of the wooden piles underneath the quay wall is also very common. The piles in the front of the quay wall are usually in bad condition. This can result in a bad connection between the pile and the head beam/floor. The signals related to this failure mechanism is horizontal and vertical displacement of the structure. The respondents all agree that it is a sensitive area. Due to fluctuations in water level and potential damages that may occur by vessels. A well-known problem is that a majority of the foundation is affected by an unknown bacterium (Respondent B). This phenomenon also contributed to the further deterioration of the wooden foundation.

A more process related cause of a quay wall failure is explained by respondent B. There was a case with a quay wall that was in critical state. Within in the engineering department the situation surrounding this specific quay wall was known. However, a permit was granted by another department within the municipality for the crane to work on this section. This caused the quay wall to fail. This shows that communication within such a large organization is vital.

In respect to all the failure mechanisms a plausible statement was given by respondent C. He explains that tears and cracks in the retaining wall should be look at with caution, it could also be the cause of a collision by a vessel. He further states: 'I often think that it is a chain of events that results in different failure mechanisms. We should not only asses one failure mechanism.

Intervention measures

The interviews revealed intervention measures for type 2 and type 4 quay walls. A vast majority of these intervention measures were already discussed in chapter 4.2. The most frequently applied intervention measure is a sheet pile with sand fill. All respondents mentioned two important issues related to this measure. First the application of a sand fill can cause negative skin friction. This means that the weight of the sand compresses the soft layers in the ground. As a result, the soft layers stick to the piles and creates an additional vertical weight downwards.

Another issue is the possibility that the piles (especially the front row) is horizontally pushed away by the sand. This can cause instability and thus rotation of the structure. In the cases described by the respondents they explained that these two issues have not occurred. Therefore, the assumption can be made that the effects of these two issues is minimal. Additionally, two exceptional intervention measures are mentioned. First respondent A explained that they used a kind of polyurethane based fill material to inject the erosion screen in case of failure. They applied this to a piece of quay wall that was planned for renewal in order to find out if the material would cover the hollow spaces. Unfortunately, it was difficult to establish in practice. They could not say with certainty that the function of the erosion screen was fully restored because it was only tested for a short period of time.

Another intervention measure is the application of tubular piles in front of the quay wall (respondent B). This method was not applied because it was not considered safe enough by the in-house engineers after calculations. Also, placing this pile can cause damages to the quay wall itself if it is not placed with care. However, he explained that it has been applied in other cities. So, it is a possibility, but they find it a 'tricky' measure. Placing anchors was also described by the same respondent as a viable option. Although they had a case where they placed these anchors for a long period of time. This caused the anchor to break which resulted in tears and cracks in the retaining wall. Eventually the wall consisted of loose elements and they were forced to close-off the quay wall. This example illustrates that duration of the implementation measure plays a very important role.

In relation to combining and restoring intervention measures there were interesting ideas mentioned by the respondents. One of the respondents (B) mentioned a 'recovery scheme'. This means that the starting point is safety. Based on safety and lack of information the decision is made to close of entire quay wall until additional information about the technical state is gathered. So, in the case that parking spaces are removed and heavy vehicle are denied, is it possible to slowly restore the use (if for instance monitoring results show that the situation is stable). This poses a certain dilemma. This dilemma is explained by respondent B as followed: 'Suppose you close off the quay wall based on visual inspection and expert judgement and the quay collapses, then you know that you have acted properly. On the other hand, it may also happen that you have caused unnecessary nuisance if it does not fail'. The problem is not that the quay wall will collapse when someone passes by, but rather the scenario what if someone passes by and it collapses. This has to do with the fact that it is unclear what the chance is that a particular quay will actually collapse.

Therefore, respondent C proposes the following measure: 'I think many of the problems stems from the loads acting on the quay wall. If we reduce the loads and bring them back to their

initial design values, a lot of problems can be avoided. Despite that, we all know that a majority of the quay walls have reached (or in some cases surpassed) the end of their lifespan'. He finishes his statement by saying: 'Renewal is key'.
Respondents E is more interested in intervention measures to prevent internal erosion by repairing the erosion screen. As discussed earlier this is the most common failure mechanism in Dordrecht, also there are cases where the rest of the structure is in good state with the exception of the erosion screen. Respondent E further explains that in order to implement this measure information about the quality of the erosion screen is vital. He states: 'My ideal situation is to have an overview of the erosion screen of a specific quay wall with the weak spots. Depending on the quality level local repairs can be carried out'. This type of intervention measure can prolong renewal of the quay significantly, without completely renewing the structure.

Decision-making criteria and trade-off's
Questions related to decision-making criteria's and how trade-off are made were difficult to answer by all respondents. However, all the respondents conclusively agreed that safety is the most important decision-making criterion. Two respondents (A & B) emphasized the importance of liveability through the concept of trees. Trees are considered of great value. Respondent A explains that generally the surroundings is taken in to consideration when implementing intervention measures. In their case the trees have a very high priority. Some are monumental or have a certain distinctive value, therefore we need to find alternative ways to replace or maintain the quay wall. In fact, within the municipality there is a policy in place regarding the removal of trees. First the council must be informed when a tree is scheduled for removal. Next, the goal is to always preserve the tree. If this is not possible the following steps must be followed: Preserve (1) – Move tree, grow at a different location and replant (2) – if the tree cannot be replanted then it planted somewhere else in the city (3), If this is not possible than the tree is removed and completely (4). These steps show how valuable trees are for this municipality. Another specific aspect in Utrecht is that in front of the quay wall lies a sewer system in longitudinal direction. It is of utmost importance that this remain in function. Furthermore, tourism also plays a role in all the cases. Exceptional was the situation explained by respondent D. He explained that when determining the safety level of a structure external engineering parties are consulted. In case of trade-off's life cycle costing of the asset is considered important. Next, the impact of constructions alternatives is weighed against the economic impact. Questions such as: does the measure influence businesses or hamper economic growth are key. Finally, he stresses that a trade-off is made based on the costs and dynamics of the city. For example, if an area is going to be renewed then the activities related to maintenance or renewal are combined with development of the area. Liveability is not considered an import aspect in this case. Overall the respondent explain that the impact related to the type of measure is generally assessed through scenarios.

In almost all the cases the asset manager is responsible for the final decision. The engineering department within the municipalities have an advisory role on the technical state of the quay wall. However, practice has shown that it is quite difficult to convince the decision-makers that option A for instance is the safest option, because they also need to take other aspects in to account. This is corroborated by respondent A through the following statement: 'The decision-makers are hard to convince, as long as nothing happens they assume that everything is safe. In the case of the trees, for example, we must convince them that we have done everything to preserve them'.
Another example related to trade-off's is explained by respondent B. There was a project initiated to construct a new road for cyclist. After the project was delivered it became clear that the quay wall adjacent the new road was in bad condition. The situation escalated and

the measures needed to be taken. The trade-off in this case was image loss or safety. Safety is paramount so the new bicycle road was closed off.

Watermanagement
In the region of Amsterdam Waternet is responsible for managing the waterways. Waternet is a foundation which is funded by the municipality of Amsterdam and the water board (in Dutch referred to as: Waterschap Amstel, Gooi & Vecht). They are in principle responsible for providing (drink)water to household, the waterways and canals and purification of pultaed water. The tasks of respondent E are mainly focused on groundwater in Amsterdam.

In respect to issues related to the quay walls their main concern is preserving the current water flow between the canal and the groundwater at landside. He further explains that in Amsterdam a lot of sheet piles are being placed to stabilize the quay wall. When doing so it is important to maintain the function of waterflow at two sides (canal and land). Rainwater which falls at land side should find his way to the canal. In case the sheet pile is made watertight (no flow of water is possible) then it gets too wet in winter and too dry in the summer. High water levels also increases the water pressure at land side which act on the retaining wall. Another effect it can have is that the basements of the adjacent dwellings are flooded. A lot of these basements are not watertight. In principle the owner is responsible for his own asset. On the other hand, during dry periods the wooden foundation of the dwellings behind the quay wall can be affected. The foundation should be kept wet for it to preserve its function.
Another aspect he stressed out is the flow of water in the canal itself. Placing sheet piles with sand fill above the still water level minimizes the room for water storage. He further explains that working on a large number of quay wall projects at the same time can cause upstream in the lower lying backlands. However, no research has been carried out to determine the maximum number of acceptable projects to prevent a possible upstream. These issues are related to the quantity of water. The quality however is another issue. They frequently test the quality of the water levels (on E.colli, oxygen levels and algae).

The main conclusion is that stability in the environment and subsurface is important. The stability of the environment is related to adjacent dwellings. He explains this with the following statement: Tackle the problem from an integral perspective, look outside the construction area. From a technical perspective (buildings and civil works) but especially from hydraulic point of view.

Additional interesting comments related to maintaining and renewal of quay walls
This part addresses certain relevant issues related to maintaining and renewal of the quay walls which was mentioned by the interviewees. These issues are addressed from the perspective of the respondent.

- When we just started renewing the quay wall a monitoring (of the quay wall and adjacent buildings) period of approx. a month was common before starting construction activities. Now we apply one year to determine the natural settlement behavior of the quay walls and buildings. Mainly to show stakeholders (residents and business owners) how the construction activities impacts their buildings. In Amsterdam a period of 2 years is prescribed. We think that 1 year is enough because it takes all the seasons in to account. We then measure the quay walls, adjacent buildings, water levels (monitoring well) and measure vibrations during construction (respondent B).

- A risk session could be valuable to determine which intervention measure should be implemented. Based on the risk-acceptance level a trade-off is unwillingly made between the decision-making criteria (respondent E).
- For maintaining quay wall and detecting sinkholes there are two possibilities. First it is important to search for hollow spaces in case of brick pavement. In uncertain situations an iron bar (in dutch: stootijzer) can be used to detect hollow spaces. Another option is the use of ground radar. This machine is used on land to detect which areas under the ground surface show discrepancies. As soon as the soil material has insufficient density, spots appear on the radar. The soil can then be grilled to check whether a sink hole can occur. This machine measures up to 2-3 meters deep (respondent E).
- A good idea can be to involve universities like the TU Delft to collectively think about innovative intervention measures. Just to maintain the quay the wall before renewal (respondent F).
- We have restrictions for projects as we use pontoons during construction. The situation in our city is different from others. In the Hague we have a problem regarding the water management system. We have one main waterway which circles the city centre. The water is first pumped from the lower lying polders (the Vliet) to the city of The Hague. After the water has travelled through the narrow canals it is finally pumped in to the sea. However, with heavy rainfall, the water system in the centre works like a bottleneck. The water from the lower-lying areas cannot be transported to the pumping station fast enough. This is due to the relatively narrow canals in the city centre. This resulted in a policy that prohibits us to narrow the waterways and compensate somewhere else in the city. Water flow is big issue here.

Finally, all respondents agreed that every case is different with its own set of parameters and this needs to be assessed each time. Additionally, the choice of intervention measure highly depends on the political environment. For instance, in Utrecht liveability is a very important topic mainly because Groenlinks is the largest political party in Utrecht. One of their core business is preserving nature and trees. This is even reflected by one of their slogans which is: 'Green stays Green'. The same relation can be found in Breda. VVD is the largest political party in this region. Constant stimulation of their economy is therefore one of their main objectives. This also reflected in the interview.

9.3 Concluding remarks

The conceptual model can be updated by analysing the case study and determining which parts can be improved. Results revealed that at least dive research and the location of the cables and pipeline should be presented in order to selected a suitable intervention measure. Next, interviews with other municipalities should enrich model with additional failure mechanisms and intervention measures. The interviews revealed no additional failure mechanisms or intervention measures. However, valuable information regarding the maintenance protocol and future developments were addressed. Furthermore, the decision-making process in other municipalities can also give a new perspective on the model. In this case the decision-making process where similar to each other.

10 Discussion

This chapter contains the discussion of this research. The purpose of this chapter is to interpret the research results, and discuss the implications and limitations. First the decision-making model is addressed in general, then the limitations regarding the input variables of the model are discussed. Concluding with the relevance of this study.

The decision-making model quay-walls
This research is aimed to establish a conceptual model for improving decision-making when implementing intervention measures. The model proved to be a good tool to structure decision-making in critical quay wall cases. The validation through cases and interviews increased the reliability of the model. It also provides a checklist to determine if the theoretical and practical intervention measures have been taken in to consideration (coupled with the failure mechanisms), the physical surroundings and the relevant stakeholders. This model could also be considered useful for maintaining other assets such as bridges and viaduct on the short-term. However, the applicability still needs to be tested.

Unfortunately, there are a few limitations regarding the effectiveness of this model. The case study and interviews revealed that a standardized approach to choose the best intervention measure is necessarily not the best approach. It can be considered too theoretical and therefore not practical. Each case should be viewed separately because it is governed by its own set of parameters. Variant and/or combination of intervention measures could also be possible and viable solutions.
Another important observation is that implementing rigorous intervention measure is not always the best solution from a cost benefit point of view. As discussed in the introduction, quay wall in Amsterdam were initially built to withstand a significant smaller amount of load than in the present day. Therefore, it could be more beneficial to reduce the loads until there is budget and capacity to renew the quay wall.

Input variables
There are a few uncertainties regarding the input variables that need to be addressed. As in every model input parameters are crucial for obtaining just results. In the case of quay walls in Amsterdam this is extremely difficult due to lack of detailed information. Therefore, limited information can lead to a range of divers' possibilities. This should be viewed with care. Next, the failure mechanisms are a decisive factor for determining which improvement measure is best suited to ensure safety of the structure. This research revealed that there are dependencies between the failure mechanisms. Therefore, identifying all the perceived failure mechanisms can lead to unjust figures. The intervention measures are determined based on theoretical and practical information. This is a non-exhaustive list. There are additional intervention measures however they are considered too extreme that it would not be vital solution. Nonetheless, there could still be innovative out-of the box measures. The dynamic behaviour of stakeholders cannot be predicted or explained through the model. It gives an indication of the possible stakeholders which can hamper the decision-making. By identifying them early on in the process suitable intervention measures can be chosen prior to implementation.
This high level of uncertainty calls for a integration of a risk-based asset management approach.

Relevance of the study

Reflecting on the theoretical, practical and social relevance of this research it can be found that there is scientific relevance. As discussed early in the research there is lack of scientific literature regarding the interdependencies of decision-making criteria. This research revealed that the proposed framework of Van Wee et. al (2013) describes the dependencies between factors which have impact on the transport system, accessibility, the environment and safety. Additionally, this research revealed that the perception of safety an important aspect is. The KPABC model explains how people react when they find themselves in a risky or uncertain situation. This could be considered a valuable addition to the framework of Van Wee et. al (2013). The other scientific relevance was the absence of specific methodologies to calculate the quay wall failures in city centres. The proposed methodology in this research is considered to be a good starting point for creating awareness for possible failure of the quay wall and the associated consequences.

The practical relevance was briefly described. This model enables the municipality of Amsterdam and other municipalities to systemically determine which intervention measure is best suited based on the perceived failure mechanisms and physical surrounding. It also provides insight in to the relevant stakeholders and what their stakes could be. early involvement can increase the probability of successful implementation. This should improve the internal processes within the municipality.

The social relevance is addressed indirectly. By improving the decision-making surrounding the implementation of quay walls intervention measures, resources can be allocated efficiently. Additionally, a safer environment also increases the trust of the citizens in the municipality. However, it remains a political choose to implement intervention measures now or in future. Each municipality deals with this in their own way.

To summarize, the decision-making model for quay walls has proved to be useful and even applicable to other assets. However, there are certain limitations and uncertainties. The most important part is to keep in mind that it provides a good starting point for determine which intervention is best suited. Input variables should be chosen as specific as possible.

11 Conclusion

The main objective at the beginning of this research was to provide a decision-making model to determine which intervention method is best suited for a particular location while considering the impact on certain predetermined criteria. In order to reach this objective a research question and sub-questions were formulated. In this chapter the sub-questions and main research question are answered subsequently.

1. **What are currently the failure mechanisms related to quay walls?**

Regarding inner city quay walls the SBRCURnet (2013) distinguishes four types of quay walls. Which are: retaining wall constructed directly on the load-bearing layer (type 1), retaining wall on piles (type 2), L-wall on piles (type 3), Sheet piles (type 4). Each type of quay wall has own set of failure mechanisms. Literature review has revealed that it is important to analyse the ultimate limit state of quay wall before assessing the failure mechanisms. Two limit states are identified namely the Ultimate limit state (ULS) and Serviceability Limit State (SLS). The first limit state describes the actual failure of the structure (collapse). The latter explains that the quay wall does not need to collapse entirely for it to lose its function. Regarding the ULS there are five main area's identified in order for the quay wall to collapse which is failure of the soil (1), failure of the construction (2), loss of equilibrium of the elements (3), loss of equilibrium due to water pressure (4) and piping and cracking (5). For each type of quay wall a variety of failure mechanisms are identified which are all related to the five areas. Furthermore, the SLS, which expresses the loss of function of the quay wall, should also be considered when assessing the failure mechanisms.

2. **What are the possible consequences or intervention measures for inner-city quay walls after a failure mechanism has been determined?**

From a theoretical point of view there are two types of events after a failure mechanism has been determined. First a timely intervention enables managers to take two important measure, which is increasing the resisting forces or decreasing the driving forces. In this research 23 theoretical intervention measures were identified. The second event describes the failure to intervene in time. This in turn can result in large economic damages. Literature review has revealed that damage calculations are mainly focused on flood risk assessments. These flood risk assessments use economic exposure values and so-called damage functions. Applying these methodologies in quay wall cases will result in unjust figures. Therefore, a more suitable alternative is introduced in this research based on seven impact areas and the social willingness to pay. A noteworthy point is that trade-offs can be made after a failure mechanism has been determined depending on the risk-attitude. The risk-attitude depends on the knowledge, skills and expertise of managers. Risk-assessment need to performed to find out which type risk-attitude should be adopted.

3. **What is the state-of-art regarding the decision-making theories and models?**

In this research six decision-making theories are discussed in context of infrastructural projects to establish a theoretical basis for the decision-making model. Critical literature review revealed three important re-occurring decision making theories, which are the rational, bounded rationality and political theory. The rational theory is governed by the linear model, which explains that decision-making is a logical, rational and cognitive process based on a cycle of successive phases. The bounded rationality theory is similar to the rational theory however three boundary conditions are important, which are satisfying, limited search and inadequate information and control. The political theory is based on the arena model. This model assumes that groups of people organized in every society are constantly in competition with each other In order to make decisions an arena or fenced battle field, used as a metaphor, where a permanent conflict is present between actors in order to reach a decision. Next to these theories and models two important techniques are identified to help decision-makers make well-balanced decision, which are Multi-criteria analysis (MCA) and Cost benefit Analysis (CBA). Furthermore, literature review revealed different variants of these concepts.

4. **Which decision-making criteria related to maintaining inner-city quay walls can be identified?**

Literature study revealed six re-occurring decision-making criteria related to infrastructural projects, which are safety, accessibility, liveability, costs, sustainability and innovativeness. Safety is considered the most important criteria. An unsafe asset can result in failure and loss of function. Costs is also considered an important criterion. A lot of decisions are made based on total cost of the project. Accessibility, liveability, sustainability and innovativeness should also be taken in to consideration. It can be a decisive factor depending on the situation at hand. The framework of Van Wee et. al (2013) describes dependencies between factors which have impact on the transport system, accessibility, the environment and safety. These factors can be explained through the aforementioned decision-making criteria. It shows that favouring a particular decision-making criterion will have consequence on other criteria, with the exception of costs. This criterion is described as an input in order to reach certain goals. In context of maintaining quay walls safety, accessibility, liveability and cost are the most important criteria. Sustainability and innovativeness are less important.

5. **What kind of theoretical conceptual decision-making model can be established for quay walls and applied in practise?**

A conceptual decision-making model is established by integrating two decision-making theories, which are the rational bounded and political theory. The rational bounded theory is chosen because of limited information regarding the quay walls. The political theory is focussed on the social aspect. At this stage stakeholders need to be included in the decision-making. They can have significant decision-making power and can therefore have a negative of positive impact on the project. Three decision-making moment are identified. During the first decision-making moment an intervention measure is chosen solely on the failure mechanism(s). The second decision-making moment takes the failure mechanism(s) and the physical surroundings in to consideration. The last decision-making moment takes the failure mechanism(s), physical surroundings and the social aspect (stakeholders' interest) in to account. If the impact on the decision-making criteria is too high then specific mitigation measures need to be deployed.

6. **How can the conceptual decision-making model be updated?**

The application of the model on the case revealed that model gives the best results if two crucial pieces of information are available, which are the results of the dive research and the location of the cable and pipelines. The absence of this information makes it extremely difficult to narrow the number of failure mechanisms and thus intervention measures. Certain intervention measures are not considered feasible due to lack of information, while in principle it could have been suitable measures. Next, the application of the model on the case revealed an additional outcome at decision-making moment 1. This moment consists of two events, which is intervening in time (1) and failing to intervene in time (2). The first event initially had two outcomes. The application of the model on case revealed an additional outcome (1c). This resulted in a final overview of outcomes which are: reducing the driving forces (1a), increasing the resisting forces (1b) and waiting for additional information (1c). The latter outcome results in a feedback loop. During the case-study two other intervention measures where proposed for the situation in Amsterdam. The results revealed that one of the two measures where considered valuable from a safety perspective, which is lowering the quay wall. However, looking at the other criteria in Amsterdam it could be a cumbersome solution. In respect to the failure mechanisms interdependencies were found. It is therefore important to identify these dependencies and determine the root cause of the failure mechanisms. Based on the observed failure mechanisms probabilities were derived which were used as input for the quay wall fault tree in Amsterdam.

Interviews with other municipalities did not result in additional intervention measures or unknown failure mechanisms. A noteworthy point is that internal erosion is considered a risky failure mechanism because it is difficult to detect but can have extreme consequences. A majority of the municipalities explain that they have a clear picture of the technical state of a large part of their quay wall. The main reason for these results is that the urgency of the problem is relatively smaller than in Amsterdam due to the amount of quay wall they manage and own. The results revealed that each municipality has his own set of decision-making criteria. Accessibility and costs, next to safety, are considered important decision-making criteria in all municipalities. The choice and type of intervention measure highly depends on the political environment. The entities responsible for water management in the municipalities are fulfilling a more active role in light of the implementation of intervention measures. Their main concern is water storage and waterflow. No additional changes were proposed regarding the decision-making model, although relevant issues related to maintenance and renewal of quay walls were discussed.

How can a decision-making model be applied to determine which intervention measure is best suited for maintaining inner-city quay walls while considering decision-making criteria?

This research revealed six important topics which need to be incorporated in to the decision-making model, which are the critical cases (1), failure mechanisms (2), intervention measures (3), characteristics of the physical surrounding and the intervention measures (4), decision-making criteria (5) and lastly mitigation measures (6). Additionally, three decision-making moments are identified. The model is based on the bounded rationality theory and the political theory. In Figure 32 an overview is given of the final decision-making model after validation through case-study and interviews. DM 1 is considered to be most crucial part of the model. The factor time plays an important role here. If it takes too long before intervention takes place the quay wall can still fail at any moment. However, making decisions based on available information and observed failure mechanisms can result in wrong decisions. Monitoring the quay wall on possible deformation can prevent failure to intervene on time.

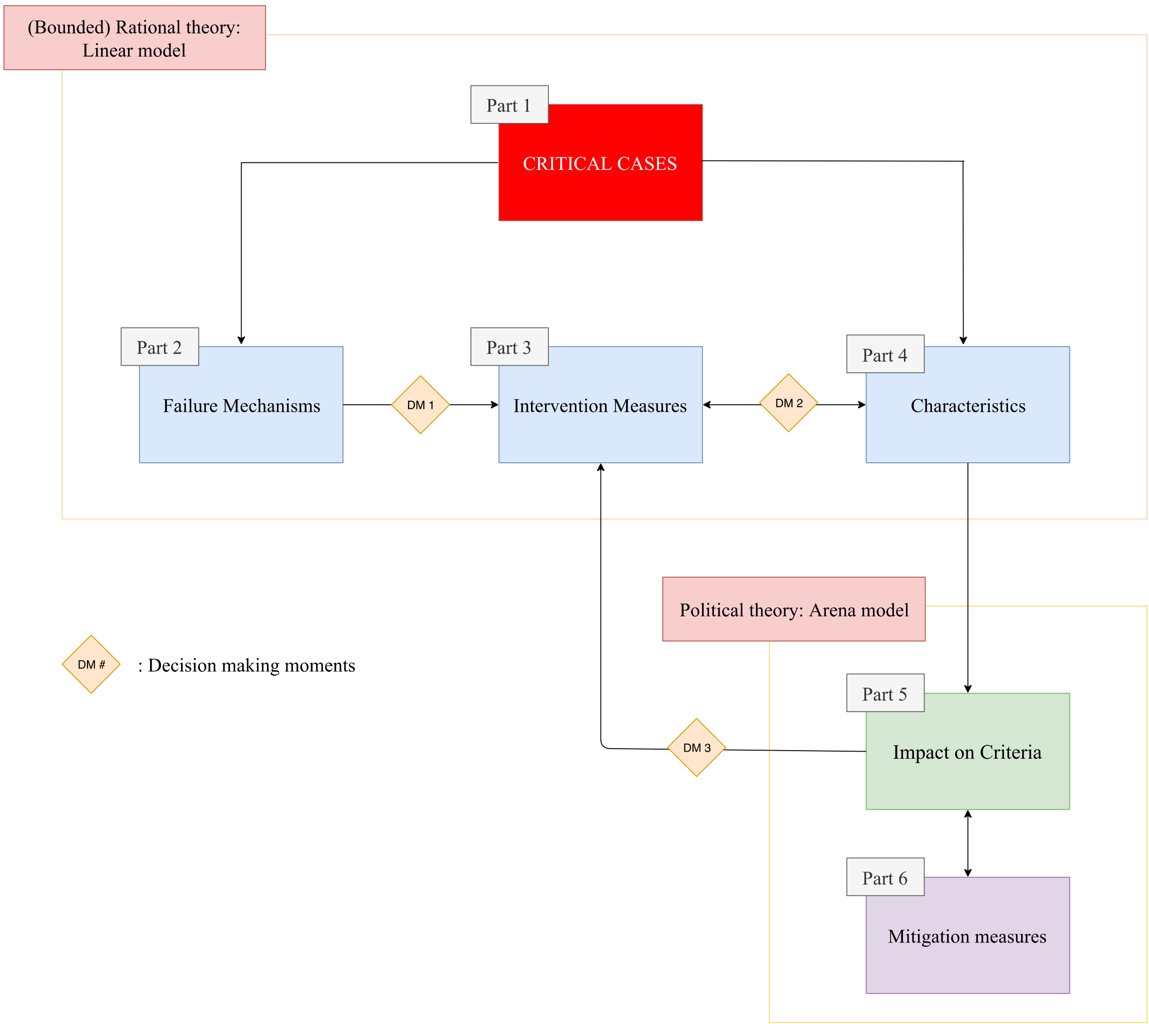

Figure 32 Conceptual decision-making model (own illustration)

12 Recommendations

This chapter consists of two sections. First the recommendations are given for further research based on the research results. The second part contains recommendation related to maintaining and renewal of quay walls. The latter were mainly derived from interviews.

12.1 Recommendation for further research

A very important topic is determining the residual strength of the quay wall. Due to lack of detailed information quay walls can fail at any moment. A methodology to estimate the residual strength of the quay wall through (past) data can prevent future failure. Furthermore, a more systematic approach can be taken to renew the quay wall. The quay wall which are considered to have sufficient residual strength based on the current use can be renewed on the long-term. This increases the flexibility and efficiency

Next, this research revealed certain interdependencies regarding the failure mechanisms. Also, based on a set of data, an estimation is made of the failure mechanisms which are more likely to occur than others. It can be valuable to update these numbers based on the observed failure mechanisms in practise. This can be helpful for estimating the probability of failure if new quay wall sections are analysed. Furthermore, the suggestion is to conduct more in-depth research in to these failure mechanisms and their dependencies. Probability updating using a Bayesian Network can be considered valuable.

As mentioned in the discussion there could be out-of the box intervention measures which can help maintain the quay wall for a number of years. This research identified 23 intervention measures and proposed two out-of box measure, of which one was not considered feasible from a safety perspective. Nonetheless, there could be other innovative, sustainable or cost-efficient measures. Therefore, the construction and education industry could be valuable sector to expand these possibilities.

The model used in this research could also be considered useful for other assets. However, the elements within the model should be re-evaluated. The failure mechanisms, interventions measures and physical surrounding are usually not similar. This model can be used to test its applicability on other assets.

An interesting topic which emerged during this research are costs. For example a comparative research can be conducted to determine the total cost to renew the critical quay walls now and what the cost would be if maintenance was carried out from the start. In other words what if the design was made 50 or 100 years ago and 2% of the initial construction was reserved for maintenance each year, in contrast to costs made now. This will show how much additional cost is made or saved.

12.2 Recommendation related to maintaining and renewal of quay walls

- Asset in the Netherlands are (by law) required to meet certain minimum requirements. A majority of these quay walls do not comply with the current safety standards. Strictly viewed the municipality is in violation. As stressed by the municipality the goal is to upgrade/renew the quay walls in order to meet these requirements. However, other aspects such as accessibility are given priority in some cases. In order to deviate from the mandatory safety levels, a policy change or new (temporary) legislation is necessary. It is recommended to reach a consensus on this topic which is supported at all relevant administrative/political levels before deviating from the mandatory safety requirement.

- Before renewal of the quay walls actually takes place in Amsterdam a minimum period of 2 years of monitoring is mandatory. These rules are stipulated in the 'Bouwprotocol of Amsterdam'. This research revealed that other municipalities only take max. 1 year in to consideration. They consider 1 year to be enough because it takes all the seasons in to account. Not only the quay walls are monitored but also, adjacent buildings, water levels (monitoring well) and vibrations during construction. An exception could be opted by the municipality to speed up the process of renewal of their quay walls.
- A risk session could be valuable to determine which intervention measure should be implemented. Based on the risk-acceptance level a trade-off is unwillingly made between the decision-making criteria.
- For maintaining quay wall and detecting sinkholes there are two possibilities. First it is important to search for hollow spaces in case of brick pavement. In uncertain situations an iron bar (in Dutch: stootijzer) can be used to detected hollow spaces. Another option is use ground radar. This machine is used on land to detect which areas under the ground surface show discrepancies. As soon as the soil has insufficient density, spots appear on the radar. The soil can then be drilled to check whether a sink hole can occur. This machine measures up to 2-3 metres deep.
- Alternative measures instead of sheet pile with sand should be considered in Amsterdam. Placing sheet piles with sand fill above the still water level minimizes the room for water storage and thus the flow of water.

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14 Appendices

Below an overview is given of the topics discussed in the appendices.

- Appendix A – Failure mechanisms Quay walls
- Appendix B – Overview Risk assessment techniques
- Appendix C – Fault tree
- Appendix D – Calculations alternative intervention measures
- Appendix E – Case study Leliegracht
- Appendix F – Interview Protocol

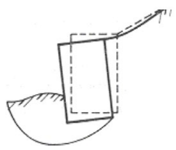
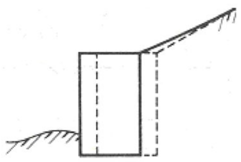
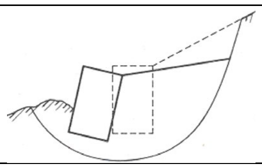
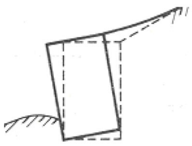
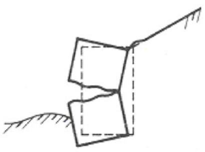
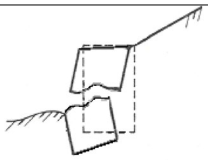
Appendix A - Failure mechanisms Quay walls

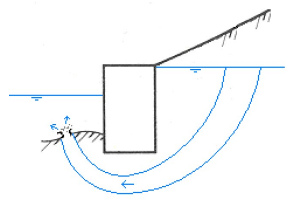
This chapter gives an overview of the failure mechanisms related to the four types of quay walls. The following type are discussed subsequently in this section. Type 2 and 3 are combined because the failure mechanisms related to these two types can be considered similar. The relevant ultimate limit states discussed in section 3.1 are coupled.

- Type 1: Retaining wall (constructed directly on the load-bearing layer)
- Type 2: Retaining wall on piles
- Type 3: L-wall on piles
- Type 4: Sheet piles

Type 1: Retaining wall (constructed directly on the load-bearing layer)

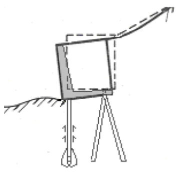
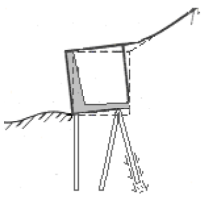
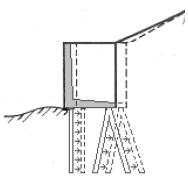
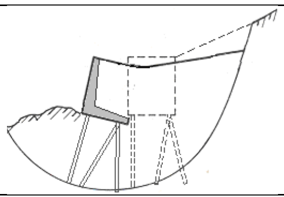
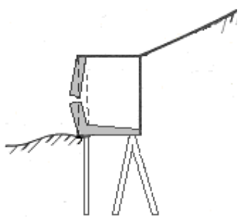
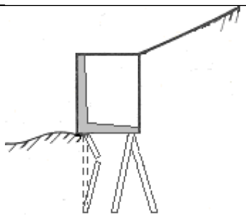
Table 27 Failure mechanisms type 1: retaining wall constructed on the load-bearing layer

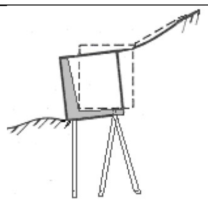
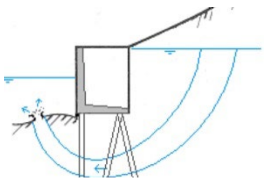
#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
1		Exceedance of the vertical bearing capacity of the subsoil. In drained and undrained situation. Mainly vertical displacement of the structure.	X				
2		Exceedance of the horizontal bearing capacity of the subsoil. In drained and undrained situation. Horizontal displacement of the structure.	X				
3		Equilibrium is lost. The whole structure slides over the failure plane.	X				
4		Horizontal displacement of the structure due to extreme active forces.			X		
5		Structure fails. Loads exceeds the resistance of the structure		X			
6		Structure fails. Loads exceed the resistance of the structure. In this case the large deformations are located at the foundation		X			

#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
7		Change in groundwater level. Hydraulic heave, internal corrosion and/or piping occurs.					X

Type 2 and 3: Retaining wall and L-wall on piles

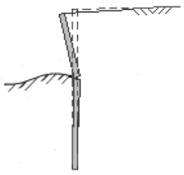
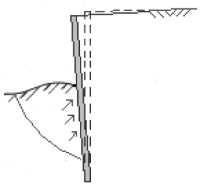
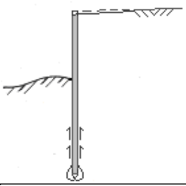
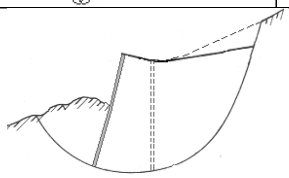
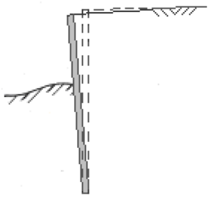
Table 28 Failure mechanisms type 2 and 3: retaining wall and L-wall on piles

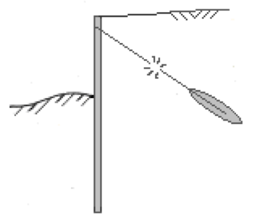
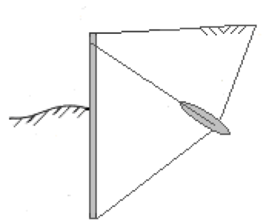
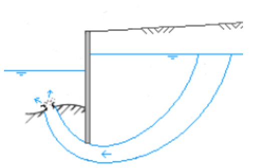
#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
1		Exceedance of the vertical bearing capacity of pile(s). Mainly vertical displacement of the structure.	X				
2		Exceedance of the tensile strength of the pile(s). horizontal bearing capacity of the subsoil. Mainly vertical displacement of the structure.	X			X	
3		Failure of the soils due to large horizontal forces. Horizontal displacement occurs.	X				
4		Equilibrium is lost. The whole structure slides over the failure plane.	X				
5		Structure fails. Loads exceeds the resistance of the structure.		X			
6		Failure of the piles. Due to horizontal or vertical forces.		X			

#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
7		Structure fails. Loads exceed the resistance of the structure. In this case the large deformations are located at the foundation.		X			
8		Change in groundwater level. Hydraulic heave, internal corrosion and/or piping occurs.					X

Type 4: Sheet piles

Table 29 Failure mechanisms type 4: Sheet piles

#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
1		Exceedance of bearing capacity of the wall. Due to large horizontal forces or rapid decline of bearing capacity (corrosion). Deformation visible at the top.		X			
2		Exceedance of the passive soil resistance strength. Entire sheet pile moves horizontally.	X				
3		Failure of the soils due to large vertical forces. Vertical displacement occurs.	X				
4		Equilibrium is lost. The whole structure slides over the failure plane.	X				
5		Rotation of the structure due to failure of the entire wall or partly.		X			

#	Failure mechanism	Description	GEO	STR	EQU	UPL	HYD
6		Failure of the anchor. This can occur when tensile strength of the anchor is exceeded or change of ground water level.	X	X			
7		Equilibrium is lost. The anchor fails over the failure plane.	X		X		
8		Change in groundwater level. Hydraulic heave and/or piping occurs.				X	X

Appendix B - Overview Risk assessment techniques

Table 30 Risk assessment techniques

Techniques[4]	Project phase	Procedure	Advantages	Disadvantages
BASIC METHODS				
PHA	A	Identifies hazards, assesses the impact of potential accidents and determining measures to reduce the risks	(1) Quick analysis can be made (2) Qualitative description of the risk is determined – can be used to rank and prioritize risks	(1) Interaction between risks are not easily recognized (2) Follow-up research is needed (3) Outcome highly depends on the knowledge of the team
FMECA	A, B	Determines whether components or process can have some failures	(1) Provides a foundation for availability and reliability management (2) Extremely useful in maintenance engineering	(1) Time consuming (2) not able to deal with cross system effects
What-if	A	Checks for potential hazards by asking what-if questions	(1) Fast in searching consequences	(1) Very basic tool (2) Cannot determine causes
Checklist	A, B	A list is applied to determine consequence and safety actions	(1) Useful to get an overview of the risks	(1) Time consuming
HAZOP	A,B	Identifies and evaluates process deviations in the process industry	(1) Improves operability in the process industry	(1) Experienced team leader required (2) Time consuming
STATISTICAL METHODS				
RBD	All	Uses a graphical and mathematical to determine the reliability of the components and thus the whole system	(1) An overview of a logic connected components is established	(1) Functions can be omitted during the process of reducing the RBD (2) There is usually limited information available regarding the physical condition of a system
FTA	All	Structures consequences back to causes with a graphic tool	(1) Gives a graphical representation of the events using AND or OR-gates to unravel above lying causes	(1) Based on binary logic, event fails or not (can perform very badly but in the system, it is considered as a success) (2) judgements are usually subjective, which can lead to inaccurate information
ETA	All	Structures causes back to consequences with a graphic tool	(1) Quantitatively illustrates all possible outcomes resulting from an event	(1) Multiple failures cannot be analysed, only one initiating event
DYNAMIC METHODS				
Bayesian Networks	C,D	Network composed of node and arcs to establish an overview of relationships between causes and effects of a system	(1) possibility to apply probability updating (2) Can calculate dependent failures	(1) Computationally intensive tool and thus time consuming

[4] PHA, Preliminary Hazard Analysis; FMECA, failure mode, effect and criticality analysis; HAZOP, hazard and operability studies; RBD, Reliability block diagram; FTA, fault tree analysis; ETA, event tree analysis.

Appendix C – Fault tree

A fault tree is systematic framework containing events which lead to a undesired top event, through logical succession (Jonkman et. al, 2016). It was initially development in 60's in the field of aviation. It gives an overview of the system, its relations and if known their probabilities. It is a top down deductive technique where the perspective is on failure of the system. There are generally two types:

- Qualitative analysis

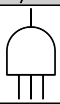
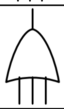
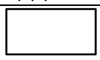
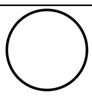
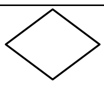
Focused on the identification of the various combinations of event which can lead to the top event

- Quantitative analysis

In addition to the qualitative analysis, probability of occurrence is added of the events and top event.

A fault tree consists of the following basic symbols:

Table 31 Elements of the fault tree

Fault tree elements			
	Symbol		Explanation
1		**AND** GATE	An output event occurs only when all the input events occur.
2		**OR** GATE	An output event occurs if at least one of the input events occurs.
3		**RESULTANT** EVENT	A fault event resulting from the logical combination of other fault events.
4		**BASIC** EVENT	An independent basic fault or component. The analysis ends with basic events.
5		**INCOMPLETE** GATE	an event that has not been fully developed because of lack of knowledge or significance.

A fault tree is compiled to determine the probability of occurrence of the elements. The fault tree for sheet piles which are discussed in the CURNET (2005) is used as starting point. Through theoretical and practical knowledge an adjusted fault tree for retaining walls on wooden piles (type 2) is compiled. To determine the probabilities a range is used due to uncertainties. The input used is based on 12 locations. The objective is to update this tree when more information is available.

For the determination of the probabilities certain assumptions are made. These are described below:

- The probability of occurrence is described as the probability that a certain failure mechanism may happen in practise.

- The figures presented in Table 12 are only based on 16 locations. These probabilities need to be updated continuously after additional failure mechanisms have been detected. This will increase the accuracy of these numbers.
- A standard deviation of 34% in respect to the observed value is applied. Assuming each variable is the mean value of a normally distributed function. This assumption is made because at this stage it is difficult to determine the lower and upper boundaries. Therefore, they are considered to occur equally. Only discrete values are relevant in this case.
- The mean value (=probability of occurrence) is similar to the min value if the calculated minimum value is less than the mean value.
- The study revealed interdependencies between the failure mechanisms. These dependencies are not taken in to consideration. (For instance, FM 8 can cause FM 3 to happen).
- The failure mechanisms which have not occurred should also be taken in to account. Therefore, a max value of 34% chance of occurrence is determined.
- With the help of software programs DIANA and ATENA an extensive sensitivity analysis has been carried out with regard to the masonry of the abutment of bridges (influence of parameters on the failure safety of the brickwork). The masonry and foundation are similar to quay walls. Based on the sensitivity analyses and the calculations, it has been found that the masonry has a significant amount of residual strength. The main cause is the pressure (through arching) caused by the structure of the bridge. However, in respect to the quay walls it is expected that other structural components such as the wooden foundation and piles are more critical. For now, these findings are not included in this analysis.

Table 12 is used as input for the fault tree. To determine the probabilities a point estimation (third column) is used. FM 1 and 6 were not observed in practise and therefore excluded in the overview. FM 3 and 9 are a combination of different failure mechanisms and are also excluded in this overview. FM5 occurs due to a variety of different failure mechanisms and is considered critical. In practise this failure mechanism was observed once, the piles under the structure however did not fail. It is therefore debateable if this should be classified as FM 5. The fault tree is presented in Figure 34. For calculating the top event Figure 33 is used.

system	gate	operator	components		
			mutually exclusive	independent	fully dependent
series	OR	$\cup$	$\sum_{i=1}^{n} P_i$ (upper bound)	$1-\prod_{i=1}^{n}(1-P_i)$	$\max\{P_i\}$ (lower bound)
parallel	AND	$\cap$	0 (lower bound)	$\prod_{i=1}^{n} P_i$	$\min\{P_i\}$ (upper bound)

Figure 33 Formula for calculating top event (Jonkman et al., 2016)

Top event = (Lack of equilibrium **U** Superstructure fails **U** Grondwaterflow too high)

- Lack of equilibrium:

$$0.03$$

- Superstructure fails:

$$1-(1-0.10)(1-0.19)(1-0{,}19)(1-0.03)(1-0.13)=\ 0.51$$

- Groundwater flow too high:

$$0$$

Top event = $1-(1-0.03)(1-0.51)(1-0)=\ 0.52$

Based on the available information there is a chance of 52% that the quay wall can fail. Uncertainty bounds are not taken in to consideration.

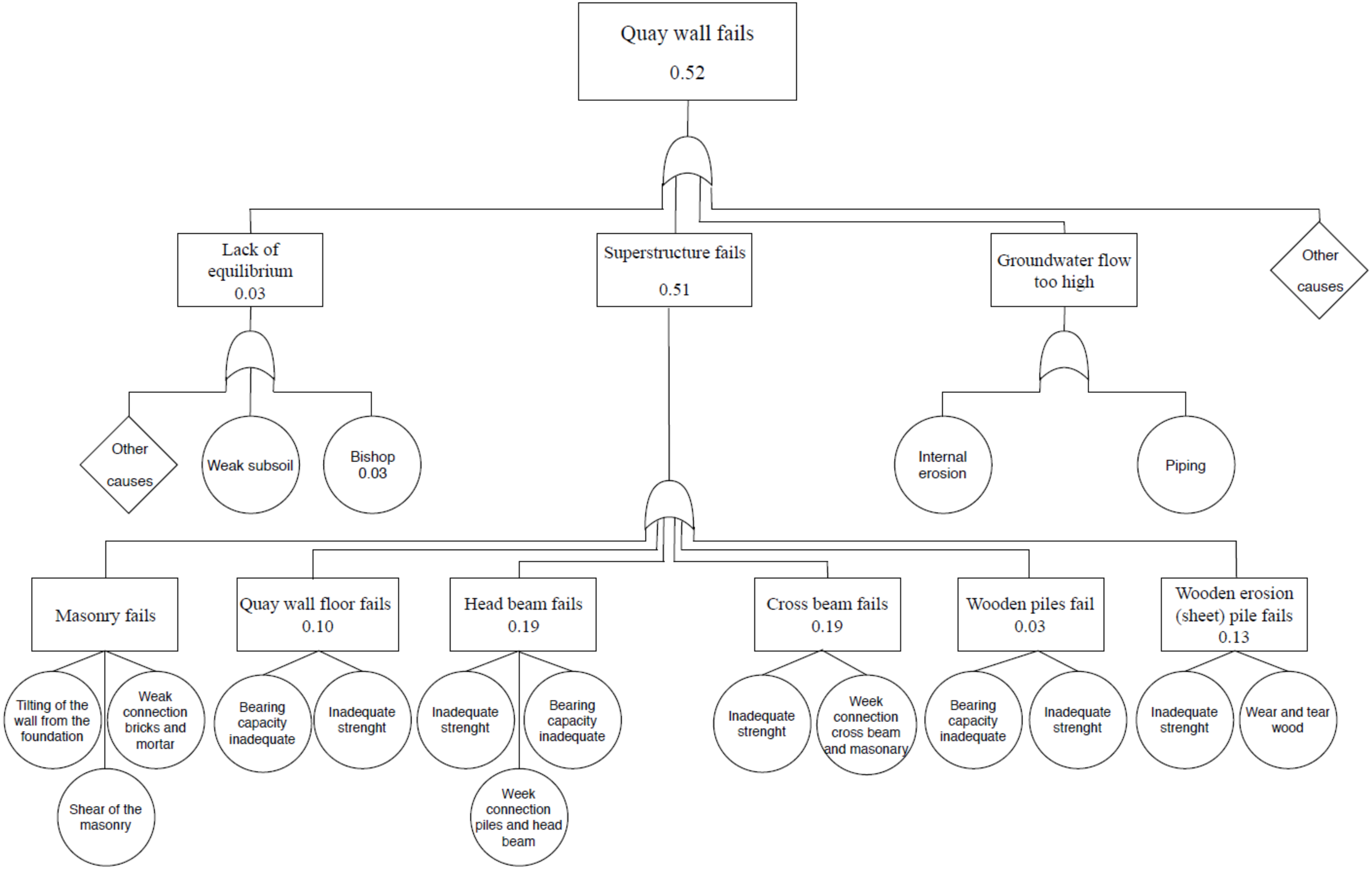


Figure 34 Fault tree type 2 quay walls Amsterdam (own illustration)

Appendix D – Calculations alternative intervention measures

This section consists of three parts. First the input parameters used to calculate the two alternatives are presented. Then the two alternatives measures (lowering the quay wall and the application of geo-encapsulated sand elements) are discussed subsequently.

D1: Input variables and starting points

The input variables (see Table 32) used to calculate the alternative intervention measures are based on a principle cross section of type 2 quay walls in Amsterdam (see Figure 35). For the soil parameters average soil characteristic values are used.

Table 32 Input parameters alternative intervention measures

General			
Symbol	Description		Unit
γ_w	Mass density water	10	kN/m³
	Waterline	-0,4	m (NAP)
	Top of the quay wall	1	m (NAP)
	Bottom of the quay wall	-0,9	m (NAP)
	Loads acting on the quay wall		
L_p	Parking	5	kN/m²
L_T	Heavy traffic (max)	14	kN/m²
	Density wood (dry)	3,5	kN/m³
	Canal bed	-2,6	m (NAP)
	Slope	1:35	
	Friction (wall and floor)	0,62	[-]

Quay Wall						
Symbol	Description		Unit			
b1	Width	0,77	m			
a	Height	1,9	m			
γ_{kd}	Mass density quay wall (dry)	20	kN/m³	b	1,4	m
γ_{kw}	Mass density quay wall (wet)	23	kN/m³	c	0,5	m
d	Thickness floor	0,25	m			
b2	Width behind the quay	1,4	m			
b3	Behind the capstone (width)	0,155	m			
h5	Behind the capstone (Height)	0,25	m			
h6	Behind the quay wall at cover stone (Height)	0,2	m			
h7	For the quay wall above the water drain (Height)	0,323	m			
h8	For the quay wall at the height of the water drain (Height)	0,106	m			
b4	For the quay wall at the location of the water drain (width)	0,187	m			
b5	Total floor (width)	2,361	m			

f	Height bottom floor and pile	0,56	m			
e	height bottom floor and bottom	1,05	m			
g	Water level and bottom floor	0,75	m			

Soil			
Symbol	Description		Unit
ϕ	Angle of internal friction sand	30	Degrees
γ_{sd}	Soil bulk density (dry)	18	kN/m3
γ_{sw}	Soil bulk density (wet)	20	kN/m3
K_a	Soil pressure factor active	0,4	[-]
K_p	Soil pressure factor passive	2,5	[-]

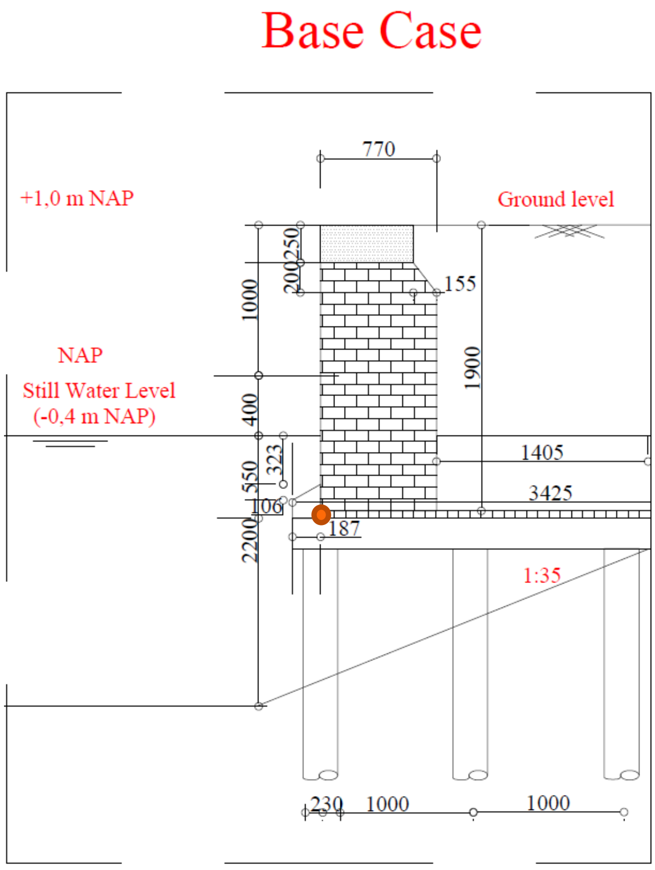


Figure 35 Principle cross section quay wall Amsterdam (own illustration)

Starting points:

- The water level is considered to be constant behind and in front of the quay wall. It is however important to note that during high water and/or rainy events the horizontal pressure will be significant higher.
- The horizontal water and soil forces acting on both sides of the piles in the base case cancel each other out.

- The serviceability limit state is applied to calculate the load combinations for renovating structures.
- The method of Boussinesq is used to calculate the horizontal forces of the loads at ground level (permanent and variable forces).
- Characteristic values (stipulated in the NEN 8700 series) are used based on the standardized soil profile in Amsterdam;
- The assumption is made 0,5 meter of agricultural soil will be dredged before placing the geotextile bags.
- A layer of 1 meter of geotextile bags will be placed (initially). The geotextile bags will stay below still water level for a period of max. 2 years.
- The weight of the geotextile (= 800 g/m^2) is not taken in to consideration. Therefore, 20 kN/m^3 is used as volumetric weight of the sand fill.

D2: Alternative intervention measure 1: Lowering the Quay wall

This intervention is aimed at reducing the forces on the structure (soil reduction) and the structure itself. An important condition for the application of this measure is that the piles and head beam (=kesp) are good in condition. The dimensions described in Table 15 are used as starting point to determine the maximum and minimum retaining height. In this section the retaining height of 1,9 m (base case) and 3,5 (max. height of quay walls in Amsterdam) are analysed. Two important failure mechanisms are checked in both cases (1,9m and 3,5m), namely:

- Safety against rotation (ratio solicitation and resistance)
- Safety against sliding (ratio solicitation and resistance multiplied by friction number wall and floor)

The following horizontal and vertical forces are calculated:

Resistance

Self-weight of the retaining wall

Formula: γ_{kd} * b * b1 + γ_{kw} * c * b1

Solicitation

Horizontal soil pressure (sum of all forces)

Formula: 0,5 (γ_{kd}) * b^2 * K_a (triangular) or (γ_{kd}) * b^2 * K_a (rectangular)

Horizontal forces from heavy traffic

Formula: L_T * K_a

Horizontal forces from parking

Formula: a * L_T * K_a

For the case with a retaining height of 1,9 m the following results were found:

Table 33 Unity check retaining height of 1,9 metres

Retaining height of 1,9 m				
Height retaining wall	Resistance structure	Solicitation	Rotation	Sliding
[m]	[kN]	[kN]	UC	UC
1,3	21,18	12,87	0,61	0,98
1,9	30,42	24,4	0,80	1,29

For the case with a retaining height of 3,5 m the following results were found:

Table 34 Unity check retaining height of 3,5 metres

Retaining height of 3,5 m				
Height retaining wall	Resistance structure	Solicitation	Rotation	Sliding
[m]	[kN]	[kN]	UC	UC
1,3	39,88	12,87	0,32	0,13
1,6			0,37	0,15
1,9			0,41	0,17
2,2			0,46	0,18
2,6			0,52	0,21
2,9			0,56	0,23
3,2			0,61	0,24
3,5	103,68	67,79	0,65	0,26

The analysis of two cases show that a lower unity check is found as the retaining height decreases. This is mainly due to the fixed width of the retaining height and the reduction of the active soil forces. The values in between are determined through linear interpolation. To illustrate the differences between the horizontal forces an overview is given in Figure 36 for lowering the quay wall from 3,4 m to 1,6 m. The red line represents the horizontal soil pressure. The yellow horizontal line indicates the centre of gravity of the respective forces.

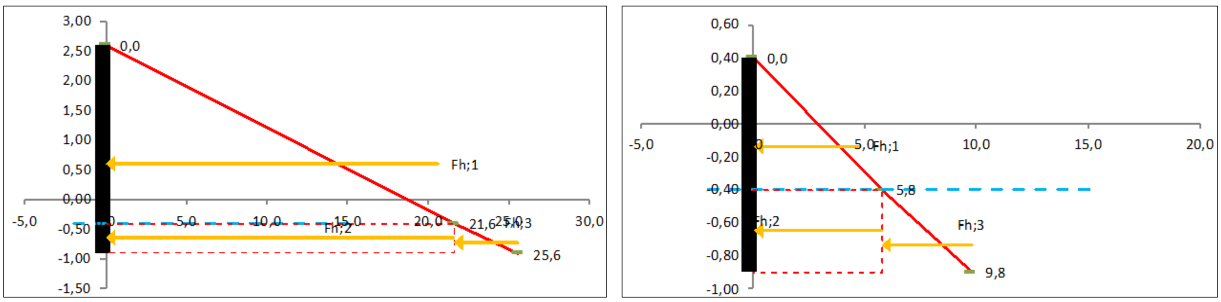


Figure 36 Illustration of the horizontal earth pressures (own illustration)

Concluding remarks:

- The active forces are larger in case of a higher retaining wall due to additional (saturated) soil;
- The distance between the point of rotation and the centre of gravity of the respective forces is smaller. This means that the probability of rotation of the retaining wall reduces.

D3: Alternative intervention measure 1: Application of geotextile encapsulated sand elements

There are four geotextile encapsulated sand element described by Bezuijen & Vastenburg (2013), namely

- Geotextile bags
- Geotextile mattresses
- Geotextile tubes
- Geotextile containers

As discussed in section 8.3.3.2 geotextile bags are best suited in Amsterdam. The CUR 217 is used as guideline for designing with geotextile bags. For the application of geotextile bags there are certain boundary conditions set. Furthermore, the bag should be safe enough considering its own failure mechanisms. 8 failure mechanisms are found in context of the application of geobags, however not all failure mechanisms are relevant in this case. The bold marked failure mechanisms are analysed in more detailed subsequently. For the other failure mechanisms reasons are given why they are excluded.

1. **Rupture of the geotextile due to impact on the bed;**
2. **Insufficient seam strength;**
3. Instability of the geotextile bags through wave attack (no wave attack in the canals);
4. Instability of the geotextile bags through water current along the structure (low flow of water and bags are not placed in the longitudinal direction);
5. **Instability of the geotextile bags through water current over the structure;**
6. Instability of the geotextile bags due to wave attack (no wave attack and water flow less than 1,5 m/s);
7. **Foundation failure and deformation;**
8. Liquefaction of the geotextile bag fill (no danger due to slope less than 1V:3H)

For the determination of the required dimension, strength and shape of the geotextile bags an iterative approach is necessary. The following ‘standardized’ input parameters are used as starting point.

Table 35 Input parameters geobags

Symbol	Site data		Unit
n	Porosity geotextile bag fill	0,45	[-]
ρ (s)	Density of sand	20	kN/m3
ρ (w)	Density of water	10	kN/m3
δ	Friction angle (Geobags and soil)	20	°
α	Slope angle	1 op 3	°
R_c	Distance crest and still water		m
μ	Max. water velocity along the slope	1,5	m/s
z	Water depth	2,7	m

Symbol	Geotextile bags		Unit
B_g	Width	2,5	m
L_g	Length	1,5	m
H_g	Height	0,75	
PP	Material: woven Polypropylene		
T_m	Geotextile strength	30,16	kN/m
ε_m	Geotextile strain at max. tensile strength	0,14	
C_t	Correction for theoretical strength seams	70%	

- **Rupture of the geotextile due to impact on the bed (1) and insufficient seam strength (2)**

To calculate the required tensile strength the following formula applies:

$$T_{seam} = \sqrt{2 \times \frac{H_g\, V}{b\, s} \times \frac{J}{Cd} \times \left(\frac{\rho - \rho_w}{\rho_w}\right) \times \rho g}$$

where:
T_{seam} = tensile load in the geotextile [N/m]
b = width of the geotextile bag [m];
s = circumference of the geotextile bag (perpendicular to the longest axis) [m];
J = tensile stiffness of the geotextile;
Cd = drag coefficient (for which 1 may be assumed) [–]
ρ = density of the geotextile-encapsulated sand element [kg/m3];
ρ w = density of water (1,000 for freshwater 1,030 for saltwater) [kg/m3];
g = acceleration due to gravity (= 9.8) [m/s2];
H_g = height of the geotextile bag [m3].
V = volume of the geotextile bag [m3].

$$J = \frac{T_m}{\varepsilon_m}$$

The bag is considered safe if the following formulae yields an outcome large than 1.

$$\frac{T_m}{\left(\frac{T_{seam}}{C_t}\right)} > 1$$

- **Instability of the geotextile bags through water current over the structure (5)**

The following dimensionless relation is found to check whether the structure is stable against overtopping:

$$\frac{u_{cr}}{\sqrt{g\Delta_t D_k}} \leq F$$

where:
u_{cr} = maximum allowable flow velocity over the crest of the structure [m/s];
F = stability factor [−] , in the Netherlands a factor between 0.5 and 1 is used.
Δ_t = $\left(\frac{\rho-\rho_w}{\rho_w}\right)$ (Relative density of the geotextile-encapsulated sand element)
D_k = effective thickness of the geotextile-encapsulated sand element [m]. Dk is determined based on the installation geometry as illustrated in Figure 37.

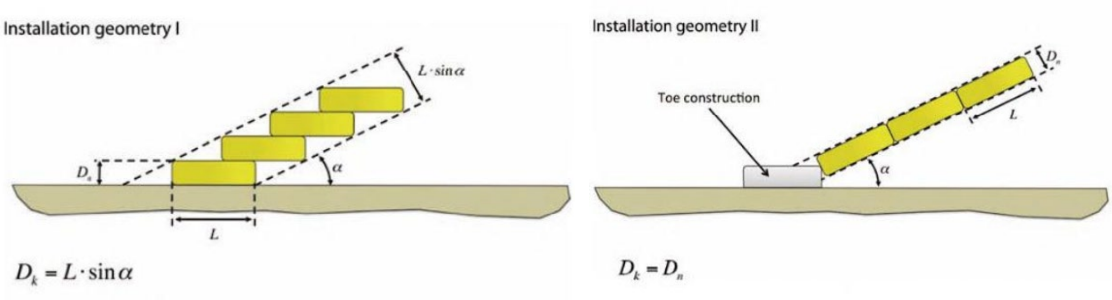


Figure 37 Installation geometry sand bags (Bezuijen & Vastenburg, 2013)

Installation geometry 1 is used in this analysis because a toe constructie is usually applied in case of high water flows and wave attacks.

Results (1), (2) and (5)
In order to determine the dimensions of the geo bags and tensile strength an iterative approach is needed. The results show that the bags are stable against overtopping and have the minimum required tensile strength if the following dimension are used.

Tensile strength: 30 kN/m
Length [m]: 0,1 $\leq L \geq$ 1
Width [m]: 7,25
Height [m]: 0,1 $\leq H \geq$ 0,93

The width of the geo bag and the tensile strength are leading factors.

- **Foundation failure and deformation (7)**

The subsoils in the canals of Amsterdam consists of dredged material and soft layers (clay and peat). Therefore, calculations are made to determine the total settlement after the geotextile bags are placed. To calculate the total settlement the formula presented in the NEN 9997 is used, which is shown below. S1 calculates the primary settlement and S2 the secondary settlement. The input parameters can be found in Table 36. A cross section of the soil layers are presented in **Fout! Verwijzingsbron niet gevonden.**.

$$S_1 = \sum_{j=0}^{j=n} \frac{1}{C'_{p:j}} \times d_j \times \ln\left(\frac{\sigma'_{v;z;0;d} + \Delta\sigma'_{v;z;d}}{\sigma'_{v;z;0;d}}\right)$$

$$S_2 = \sum_{j=0}^{j=n} \frac{1}{C'_{s:j}} \times d_j \times \log\frac{t}{t_0} \times \ln\left(\frac{\sigma'_{v;z;0;d} + \Delta\sigma'_{v;z;d}}{\sigma'_{v;z;0;d}}\right)$$

Where:
$C'_{p:j}$ = primary compression coefficient of the layer j according to Koppejan
$C'_{s:j}$ = secondary compression coefficient of the layer j according to Koppejan
d_j = the layer of the soil
$\sigma'_{v;z;0;d}$ = the value of the effective vertical soil pressure before loading in the middle of the soil layer
$\Delta\sigma'_{v;z;d}$ = the value of the increase of effective vertical soil pressure in the middle of the soil layer
T= time in days (for final settlements t = 10.000 applies)
T_o = unit for time, T_o = 1 day

Results (7)

In the case of Amsterdam, the assumption is made that geo bags will be applied for a period of maximum 2 years. The results are found in Table 36.

Table 36 Settlement geotexile bags after 2 years

Layer	Type	Bottom layer	ρw	Height	C'_p	C's	Primary settlement	Secondary settlement	Total settlement
		[m NAP]	[kN/m^3]	[m]	[-]	[-]	[m]	[m]	[m]
1	Clay & peat	6,7	16	4	15	60	0,26	0,19	0,45
2	Clay	11,7	17	5	15	160	0,09	0,03	0,12
3	Clayey sand	13,7	18	2	20	240	0,03	0,01	0,03
4	Clay & peat	15,3	18	1,6	25	320	0,01	0,00	0,02
5	Sand		20			-			
								Total settlement	0,6

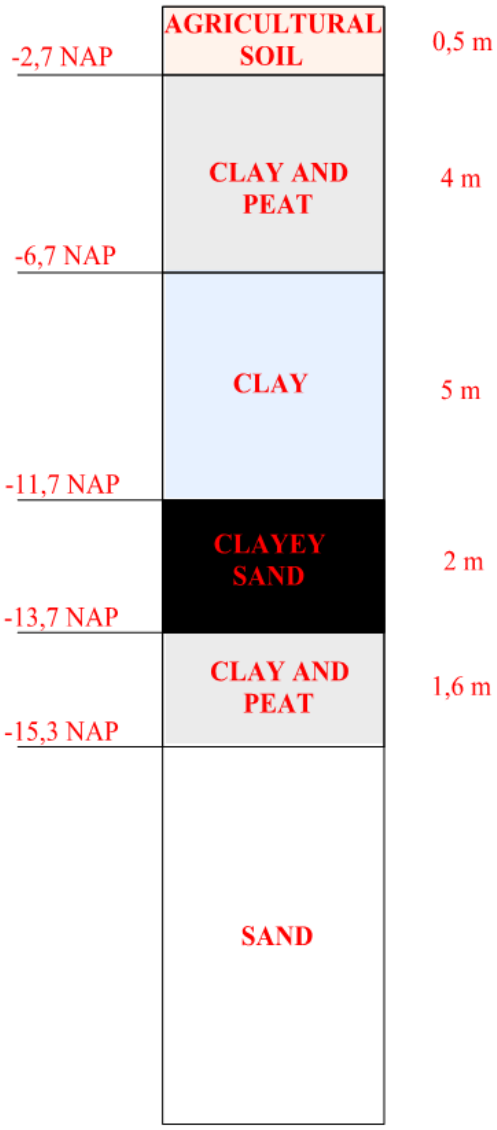


Figure 38 Soil profile Amsterdam canals (own illustration)

Concluding remarks:

- A geo bag with a width of more 7 meters need to be applied in order for the structure to be classified as safe.
- Over 0,6 metres of additional bags during a period of 2 years need to be placed in order to maintain the desired height.
- Based on these two conclusions, this additional intervention measure is not considered safe and feasible.

Appendix E – Case study Leliegracht

In this section additional information is given of the case Leliegracht. First the calculations regarding the damages are addresses. The second part gives an overview of the trade-off made at the respective decision-making moments discussed in section 8.5.3.

E1: Damage calculations

The damage calculations are categorized in seven impact areas. First an overview is given of the various impact area and its inputs. Next, the case study described in section8.5.1 is further elaborated on.

Input parameters
Table 37 gives an overview of the input parameters used to determine the cost of damages. The theoretical explanation behind the loss of life is described in section 4.3.1.2 through the theory of Jongejan et al. (2005). However, two input parameters were not introduced yet, namely the gross domestic product, leisure ratio and demographic constant. For the Netherlands the following values were found respectively: €4.7434, 0,2 and 20. These parameters are used to estimate the lower and upper bound for the loss of life presented in Table 37. The other impact areas were determined based on expert judgement and (public) sources. Infrastructure is excluded in this overview because in Amsterdam these costs are included in third impact area quay walls. 'Others' is also left blank because it depends on location specific objects.

Table 37 Input parameters damages quay wall

Estimation				
	Low	High	Unit	Source
Loss of Life	€ 1.185.841	€ 4.743.363	P/person	Jongejan (2005)
Dwellings	€ 10.000	€ 750.000	p/piece	Expert Judgement
Quay wall	€ 20.000	€ 74.000	p/m.	IB - Amsterdam
Means of transportation	€ 100	€ 300.000	p/piece	Expert Judgement
Trees	€ 1.000	€ 5.000	p/piece	Ruimtelijke plannen Amsterdam
Pipelines and cables	€ 438	€ 657	p/m^2	Decentrale regelgeving Overheid
Infrastructure				
Others				
Clean-up costs	€ 946	€ 90.373	3-8%	Expert judgement

Case Leliegracht
The analysis of the case Leliegracht revealed the following physical aspects:

Table 38 Case Leliegracht input variables

Input variable		
Loss of life	1	per person
Number of dwellings	0	p/stk
Length quay wall that fails	15	p/m1
Number of Parking spaces	5	p/stk

Input variable		
Pipelines and cable	110	p/m2
Infrastructure		
Trees	2	p/stk

The impact area 'loss of life' is the only variable element in this overview. The other impact areas are considered to be constant. This resulted in the following overview of damages (see Table 39) were the loss of life varies from 0 till 10 people. Again, boundaries are used to indicate the level of uncertainties.

Table 39 Overview damages as a function of the number of fatalities case Leliegracht

	Damages		
Fatalities	Lower bound	Estimated	Upper bound
0	€ 368.214	€ 1.597.549	€ 2.826.884
1	€ 1.554.055	€ 4.562.151	€ 7.570.246
2	€ 2.739.895	€ 7.526.752	€ 12.313.609
3	€ 3.925.736	€ 10.491.354	€ 17.056.972
4	€ 5.111.577	€ 13.455.956	€ 21.800.335
5	€ 6.297.418	€ 16.420.558	€ 26.543.698
6	€ 7.483.258	€ 19.385.159	€ 31.287.060
7	€ 8.669.099	€ 22.349.761	€ 36.030.423
8	€ 9.854.940	€ 25.314.363	€ 40.773.786
9	€ 11.040.780	€ 28.278.965	€ 45.517.149
10	€ 12.226.621	€ 31.243.566	€ 50.260.512

E2: Decision-making moments Leliegracht.

In this part each decision making moment is further elaborated on.

DM1:
The first decision is made based on the observed signals. These signals are coupled with possible intervention measures based on expert judgement and theoretical knowledge. This overview is presented in Figure 39. Only the failure mechanisms above the waterline were relevant in this case, due to lack of additional information. This resulted in the following list based on the signals: tears and horizontal displacement:

- Failure mechanism 1: Exceedance of the bearing capacity;
- Failure mechanism 2: Exceedance of the pile forces;
- Failure mechanism 3: rotation of the retaining wall;
- Failure mechanism 4: Horizontal displacement of the retaining wall;
- Failure mechanism 5: Exceedance of the overall stability;
- Failure mechanism 6: Structural failure of the retaining wall;
- Failure mechanism 8: Structural failure of the quay wall floor horizontal beam;
- Failure mechanism 9: Horizontal displacement of the entire quay wall structure

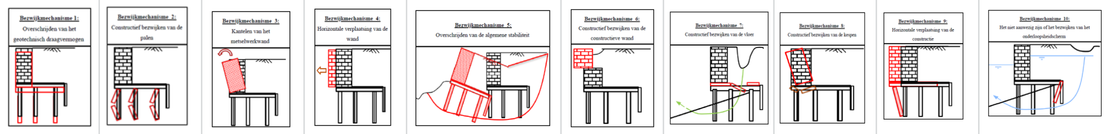
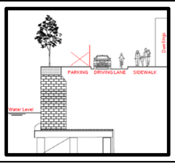
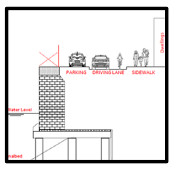
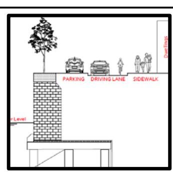
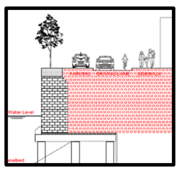
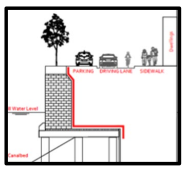
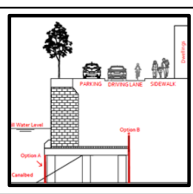
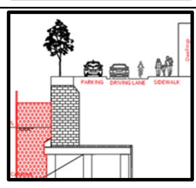
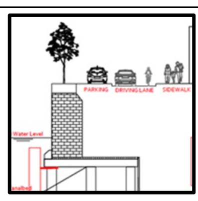
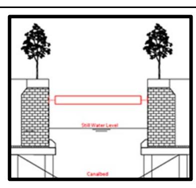
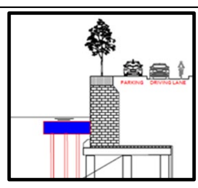
		Faalmechanismen									
Above the waterline		1	2	3	4	5	6	7	8	9	10
	Tears in the retaining wall	x	x	x	x	x	x		x	x	
	(Local) settlement of the structure	x	x			x					
	Bending of the retaining wall (horizontal displacement)		x	x	x	x	x		x	x	
	Deformation at ground level			x	x	x	x	x	x	x	x
	Sinkhole					x	x	x		x	x
	Loose/missing bricks			x			x		x		
Under the waterline											
	Damaged floor							x	x		
	Damaged/missing erosion screen										x
	Skewed piles		x			x				x	
	Deformation of the ground level					x		x			x
	Broken headbeam		x			x			x		
	Connection headbeam and pile fails		x			x			x		
	Infected/affected piles	x	x			x				x	
	Infected/missing crossbeam				x						
											
Intervention measures											
Removing parking spaces		■	■	■	■		■	■	■	■	
Removing trees		■	■	■	■		■	■	■	■	
Reducing the amount of heavy traffic		■	■	■	■		■	■	■	■	
Apply light fill material		■	■	■	■		■	■	■	■	
Geotextile											■
Application of an erosion screen					■					■	■
Vertical sheet pile with sand filling			■	■	■		■	■	■	■	■
Steel pile to support vertically and horizontally (large)		■	■		■				■	■	
Supporting beam between two sides of the canal				■	■		■		■		
Concrete floor with (inclined) piles to support the quay wall			■	■	■		■		■	■	

Figure 39 Relation between signals, failure mechanisms and intervention measures

The following list of intervention measures is derived from Figure 39:

1. Removing the parking spaces;
2. Reducing the amount of (heavy) traffic;
3. Apply light fill material;
4. Placing sheet pile with sand fill;
5. Supporting beam between two sides of the canal.

DM 2 and 3:
In this part the choice of intervention measure is based on the physical surroundings and the stakeholders. To measure the impact of the chosen intervention measure on accessibility and liveability certain assumptions and starting points are made. The most important note is that the impact after implementation of these intervention measures is used as starting point. Each impact area (decision-making criteria) and their respective assumptions and starting points are presented below.

Accessibility:
- Distinction is made between the accessibility on land and on the water side.
- Vehicle lost hours (see section 6.2.2 and 8.4.2) are used to measure the impact on land and on water.
- The shortest alternative route is assessed. The additional time in respect to the base case is used to monetize the impact.
- For cars an average value of 9 €/h is used. For vessels 7,5 €/h. These figures are determined by the 'Kennisinstituut voor Mobiliteitsbeleid' in the Netherlands (KiM) (kimnet.nl)
- For cars: Google maps is used to determine the travel time on land
- For vessel: The distance of the shortest route is measured in km. Secondly a vessel traveling max 6 km/h is used as starting point. According to Waternet this is the max speed that is allowed on the canals (waternet.nl)
- For the Leliegracht case the following results were found:

Table 40 Overview VLH Leliegracht

	Cars		Vessels	
VLH	9	€/h	7,5	€/h
Base case	1	min (less than)	1,3	min
Fastest alternative route	4	min	14,2	min
Addtional time ca.	3	min	12,9	min

Liveability:
- In section 8.4.3 liveability is operationalized, the following aspects are assessed:
    - Disruption of public space
    - View
    - Sound Pollution
    - Green spaces
- The following impact levels are used:
    - Low : Situation is reduced significantly in respect to the base case
    - No change: Base case

- High: Impact of the measure is significant higher

The results are presented in Table 41.

Table 41 Assessment accessibility and liveability Leliegracht

		ACCESIBILITY		LIVEABILITY			
		on-land (€)	on-water (€)	Disruption of public space	View (waterways and roads)	Sound pollution	Green spaces
1	Removing the parking spaces	0,45	n.a.	High	Low	Low	n.a.
2	Reducing the amount of (heavy) traffic	0,45	n.a.	High	Low	Low	n.a.
3	Apply light fill material	n.a.	n.a.	No change	No change	No change	n.a.
4	Placing sheet pile with sand fill	n.a.	1,61	High	High	No change	n.a.
5	Supporting beam between two sides of the canal	n.a.	1,61	High	High	No change	n.a.

From a practical point of view the following summary is made. Each number represents the intervention measure presented in Table 41.

1. Impact too high on businesses
2. Impact too high on businesses
3. Can help reduce the driving forces, however location pipelines and cables not available
4. Stabilizes the quay wall, however location pipelines and cables not known
5. Stabilizes the quay wall but impact on water high, impact on businesses is low. Plus: also stabilizes the other side.

Taking safety, the physical aspects and stakeholders in to consideration, it is found that intervention measure 5: 'Supporting beam between two sides of the canal' is best suited. However mitigation measures should be deployed to mitigate the impact on nautical traffic.

Concluding remarks:

- Loss of life is the largest contributor to the total damages and should therefore be avoided;
- There is a large range between the lower and upper bound of the damages, ranging from a factor of 4,1 till 7,7. This indicates a large uncertainty, which is understandable because it is nearly impossible to predict the actual number of fatalities.
- The theoretical approach does not necessary lead to the best intervention measure. Also the technical state under the waterline and the location of the pipelines and cables are crucial.

Appendix F – Interview Protocol

Interview protocol Municipalities

This document is used as guideline to interview assetmanagers and projectmanagers at the different municipalities. A semi-structure interview method is chosen in order to steer towards more important topics during the interview. The interview protocol and interview are in Dutch. This is to prevent loss of valuable information. For the transcripts, please contact the author.

Deel 1: Achtergrond informatie

I. Naam:
II. Organisatie:
III. Functie:

Start interview met introductie onderzoek. Daarna wordt er ingegaan op de functie en rol van de geïnterviewde(n).

Deel 2: Inhoudelijke vragen

A. Achtergrondinformatie kademuren in de stad

- Wat voor type kademuren hebben jullie in de binnenstad?
- Hebben verkrijgen jullie inzicht in de technische staat? (welke methodieken)

B. Faalmechanismen kademuren

- Zijn er kademuren bezweken?
- Hoe handelen jullie als zich acute gevallen voordoen?
- Hoe en welke bezwijkmechanismen komen het meeste voor?

C. Beheersmaatregelen

- Welke beheermaatregelen worden hier het meeste toegepast en waarom?
- Wordt er op basis van de waargenomen faalmechanimse een beheersmaatregel gekozen?

D. Besluitvorming

- Hoe vindt besluitvorming rond het implementeren van beheersmaatregelen in acute gevallen?
- Worden relevante bewoners en ondernemers meegenomen in de besluitvorming?

E. Impact van beheersmaatregelen

- Wordt de impact van beheersmaatregelen ook in acht genomen. In Amsterdam speelt bv veiligheid, leefbaarheid en bereikbaarheid een belangrijke rol.

- Zijn er ook andere criteria die een belangrijke rol spelen tot het komen van besluiten?

Deel 3: Afrondende vragen

- Zien jullie aanpassingen of verbeteringen mbt tot dit conceptueel model
- Zijn er vanuit jullie eigen ervaringen nog suggesties hoe Amsterdam het beste om kan gaan deze grote opgave (dan wel technisch, organisatorisch of procedureel)