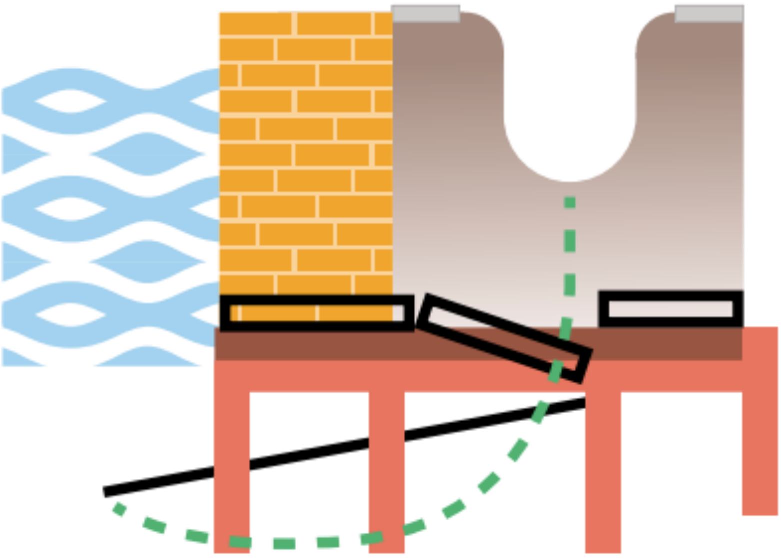
Development of a decision-making framework for assessing lifespan extension measures of quay walls

Master thesis



Mohamed Awad
Construction Management & Engineering

Internal supervisors:
Dr. Andreas Hartmann
Dr. Irina Stipanovic

External supervisor:
Eng. Maurice van Heesch

UNIVERSITY OF TWENTE.

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Preface

Hereby, I am glad to announce the submission of the final thesis version with the title "Development of a decision-making framework for assessing lifespan extension measures of quay walls". This graduation report is part of the MSc programme Construction Management & Engineering at the University of Twente.

In the past year, I enrolled for the course Infrastructure Asset Management and it has appealed to my interests, where I decided in the upcoming academic year to search for a thesis topic in that field. Due to the qualitative nature of the research, the research topic involved intensive collaboration with several consultancy firms. This led to collecting and gaining valuable knowledge about their proposed lifespan extension measures for quay walls, which was mostly not available on open access platforms. This research study aims to develop a framework that can be used as a guide for the municipality of Amsterdam at a preliminary stage to decide about suitable intervention measures for deteriorated quay walls.

I would like to express my sincere gratitude to the examination committee for their support and assistance during my thesis period. Special thanks go to Dr Andreas Hartmann and Dr Irina Stipanovic for putting their expertise and feedback moments during the past six months. Moreover, I sincerely appreciate Engineer Maurice van Heesch at Wagemaker consultant firm for hosting, supervising, and connecting me to individuals whom I interviewed to complete this research study. I extend my thanks to the following interviewed contact persons for their input and time: Wilbert van Leeuwen (BAM), Nick den Adel (Iv-Infra), Yvo Veenis & Caroline van Steenoven (Groundwater Technology), Ernst Oosterveld & Arno Makkink (Tauw), Guido Visch & Stefan de Jong (Boskalis), and Mellany Doldersum (Municipality of Amsterdam).

Last but not least, I am grateful to my parents, siblings, and friends for their continuous encouragement and support towards achieving the optimum of my potential skills during this challenging period.

Mohamed Awad

Enschede, 3 July 2023

Executive summary

The inner-city quay walls of Amsterdam are approaching their end lifespan. In the past years, several media channels reported the failure modes occurring at quay wall locations. According to recent inspection reports, approximately 200 km of quay walls are discovered to be in an insufficient technical condition, which either requires an immediate renewal or a lifespan extension measure. Additionally, there were events where urgent measures and immediate actions had to be commenced to temporarily stabilise unsafe quay walls, such as the installation of sheet piles. It is a complex task for asset managers to deal with a densely populated area such as Amsterdam while preventing hindrance. A systematic planning process of applying intervention measures is required, since it is not possible to apply the measures simultaneously at all deteriorated locations. In this research, the focus lies on the retaining walls founded on wooden piles. The aim of this research is to develop a decision-making framework to decide on the most suitable intervention measure. The framework involves the option of selecting a renewal or lifespan extension measure. Therefore, the aim is to develop a framework that analyses the different types of impact caused by the intervention measures. Besides that, the failure mechanism should be checked to choose a potential intervention measure. The main research question formulated for this research is stated as follows:

“ How can the lifetime extension measure be assessed for the inner-city quay walls?”

The research method is composed of four parts to reach an interpretation of an assessment criteria in the decision-making framework. Firstly, a literature review is conducted to (1) categorise general criteria for the intervention decision of infrastructure assets, (2) identify the typical components of retaining walls in Amsterdam, (3) understand the failure mechanisms, and (4) retrieve the requirements of the municipality. The second part is to collect required data by conducting an interview with the six construction firms and the municipality. Each construction firm has proposed an innovative lifespan extension measure to solve the failure mode of quay walls. The interview focuses on questions related to topics such as the execution steps of the measure, structural capacity, social impact, environmental impact, and economic impact. The third part of the methodology is to develop the decision-making framework after all interviews are finalised. The framework for quay walls is linked to the general categorisation of criteria for infrastructure assets and the outcome of the interview. The framework includes seven consequent steps which need to be elaborated for each scenario study, namely, structural capacity, safety risk matrix, economic assessment, technical feasibility, impact on the surrounding and social impact, environmental sustainability, and concluding remarks. The fourth part is to guide the reader to the final outcome through showing the applicability of the established framework by means of fictive scenario studies. Three different scenarios are introduced based on a given technical information, which resulted in a variable outcome for each scenario.

The results of scenario study 1 has availed the necessity of applying a renewal option despite the lower costs of applying lifespan extension measure in comparison to renewal. The space limitation applied on the quay wall location appears to be an attention point. The required space for the potential lifespan extension measure is greater than the available space between the quay wall and residential houses. Therefore, the technical feasibility is

not fulfilled by the lifespan extension measure. Scenario 2 suggests the application of lifespan extension measures. Two lifespan extension measures were proposed. However, both lifespan extensions measure scores differently in areas related to environmental, social, and economic impact. Scenario 3 recommends the application of renewal due to the severe deterioration of all quay wall components and the end of lifespan in the very short term. This placed the quay wall in the red zone of the safety risk matrix, where the renewal option is the only possibility to apply.

There are certain uncertainties in this research. Research recommendations could enhance the content and applicability of the framework. Firstly, the verification of the structural capacity of the lifespan extension measure during the pilot phase is recommended. This is done by checking the predicted structural model generated in the conceptual phase with the actual structural effectiveness during the pilot phase. Secondly, the critical conditions of quay wall components have an inconsistent definition between the firms. It is currently unclear when an existing component of the quay wall falls under critical condition. This is an important input to conclude whether the lifespan extension measure is feasible in the sense of allowing drilling through masonry wall and excavation behind the wall without damaging the entire structure. Lastly, a better overview of the emission categories related to the environmental impact should be specified by the municipality of Amsterdam. Emission categories could include global warming potential, acidification, and ozone depletion. Quantitative scores of distinct toxic emission categories for the proposed lifespan extension measures could be a follow-up step of this research

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1. Introduction

1.1 Background and Problem context

Infrastructure is a vital part of life needed for the operation and welfare of society. A high infrastructure quality is an essential phenomenon to encourage productivity and competitiveness in a national economy. A successful infrastructure management creates a decent reputational image about a certain country. Infrastructure asset managers are confronted with multiple decisions throughout the entire lifecycle of an asset. The task of an asset manager is to optimise the asset value and benefits through a specific lifetime, while monitoring the performance and cost of infrastructure (Urra & Pyle, 2020).

The provision of assets requires a balance between the stakeholders requirements and lifecycle costs. Meeting the requirements and expectations of various stakeholders while translating them into a measurable performance is conceived as the biggest challenge in infrastructure asset management. Other challenges include: (1) the ability to accommodate infrastructure services with the trend of population growth, (2) lack of infrastructure and design information yielding to uncertainties, (3) political decisions to cut back technological investments, and (4) planning strategies not offering a long-term vision (Too & Tay, 2008). The challenges of specifically managing inner-city assets to select a suitable intervention measure is related to themes such as zoning laws, restrictions on logistics, traffic disruptions, space limitation, environmental impact, and costs (Davis, 2021). The optimisation of a specific asset has to assess all relevant aspects without underestimating the significance of one aspect with respect to the other.

In this research, the type of investigated asset will be the inner-city quay wall of Amsterdam. Amsterdam is a compact city with a relatively high residential density and various interconnected spatial functions. The zone classification of Amsterdam is mixed use which blends multiple functions such as commercial, cultural, and entertainment into one integrated space. Therefore, the challenge is accompanied by the allocation of rehabilitation activities in quay walls while ensuring the liveability and accessibility of Amsterdam. The scale of renovation of the historic quay wall in the city centre of Amsterdam is quite huge, with around 200 km of running length (Gemeente Amsterdam, 2021). The large scope of the investigated area in combination with the historical structures to be maintained require a more long-term perspective. To be more specific, a strategic level of thinking is suggested to counteract the challenges and implement the most suitable measures. A strategic level of thinking is a positive behaviour that stimulates proactive rather than reactive decision-making processes, since the potential hazards and opportunities of tackling the quay walls are achieved in a timely manner (Tepe, 2022). Strategic level promotes feedback loops where intervention mistakes can be learned from the past. Strategic thinking also avoids instant emergency events of failure modes as much as possible by constantly tracking the structural conditions of quay walls (Deloitte, 2015).

The municipality of Amsterdam has started an extensive research under the programme “bridges and quay walls” based on three pillars to deal with different challenges related to the inner-city quay walls. The three pillars are predictive maintenance, lifespan extension, and renewal (Gemeente Amsterdam, 2019). Moreover, the programme “bridges and quay walls” also undertakes the activity of monitoring the structural conditions in order to reinforce or renew the existing quay walls. The initial monitoring process of quay walls gives an indication about the changing performance level along the course of time depending on the structural strength and exerted loads on the quay walls. Three different colours are displayed: green, orange, and red as shown in Figure 1. The different colours in Figure 1 are regularly monitored to avoid the so-called “point of collapse” which is reached when the exerted loads exceed the current bearing capacity of the quay wall. In that case, urgent measures are critical to be applied on quay walls immediately (Gemeente Amsterdam, 2019).

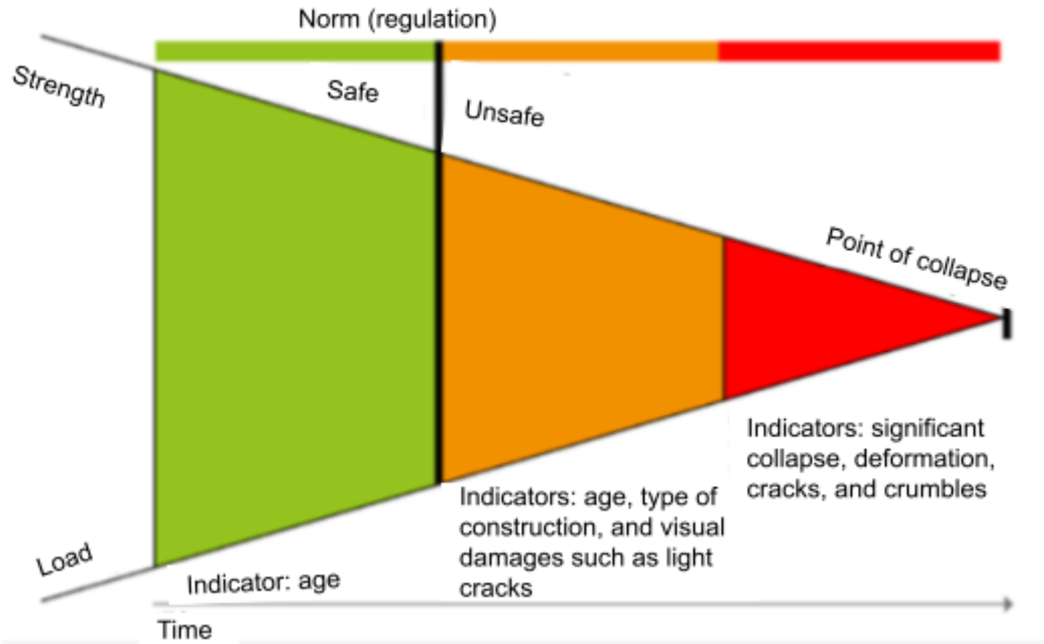


Figure 1: Threshold indicators of safety margins (Gemeente Amsterdam, 2019)

The current database from the municipality of Amsterdam stipulates that the performance and serviceability level of the inner-city quay walls have become worse. The deterioration of quay walls is a result of the backlog in undertaking maintenance activities. There are multiple reasons for the degradation of quay wall components. Firstly, the inner-city quay walls were built more than 100 years ago, so ageing of infrastructure is relevant. Secondly, the environmental impact induced an influence on the quay wall components. For instance, with time, climate change has caused water level fluctuations, which rotten materials like the wooden pile foundations in some areas. Thirdly, the change in user behaviour has contributed to low quality and deterioration signs. The structures are nowadays prone to a heavier traffic load due to increased vehicle users. Additionally, the quay walls are not structurally designed to withstand the huge loads at occasions of festival celebrations as testified in the past (Voortman, 2021).

1.2 Problem description

The decision process to obtain the right method of intervention measure for each quay wall situation is a process full of dilemmas. Each potential lifespan extension measure has advantages and disadvantages to be evaluated. The decision problem faced by the municipality of Amsterdam is the assessment of the lifespan extension measure based on multi-criteria to apply a suitable intervention measure. This particularly includes the social, economic, and environmental impact of the lifespan extension measures. The interests of different stakeholders may collide at a certain moment due to the impact of construction activities. Stakeholders with interest and power to influence the decision could include the nearby inhabitants, users of road vehicles, tour boat tourists, and environmental activists. The multiple assessment criteria need to be adequately balanced to decide on the optimal intervention measure of quay walls while reducing the resistance and inconvenience caused to stakeholders.

1.3 Research objectives

The main goal of this report is to provide an assessment framework to support the decision of applying renewal or lifespan extension measures on quay walls. The study examines the most frequently occurring failure mechanisms and local context of the surrounding quay walls. Currently, there are distinct lifespan extension measures proposed to the municipality, which offer solutions to failure mechanisms. However, not all lifespan extension measures are suitable to be implemented at all locations due to differences in contextual embeddedness, failure mechanisms, and technical limitations. There is no doubt that all proposed measures fulfil the minimal requirements and boundary conditions which are laid down by the municipality. This research will analyse the differences in structural capacity, technical feasibility, and impact on the surrounding between distinct lifespan extension measures. After analysing the data, consistent multiple criteria can be drafted and elaborated in a schematic diagram to improve the decision-making process. Scenario studies will be incorporated in this research to clarify the workability of the framework. The final framework will provide guides through an earlier and suitable intervention measure for quay walls while saving management time.

1.4 Research scope

This research will gain a comprehensive understanding of different intervention measures on the inner-city quay walls. Quay walls situated outside the urban area (city centre) such as industrial terrains are not covered within the scope. Historic quay walls with the typology of retaining walls on piles are specifically examined since they are majorly represented and detected with severe failure mechanisms in Amsterdam compared to L-walls. The decision-making framework is composed of two parts to reach an outcome. The decision to use lifespan extension measures instead of renewal or do nothing, and the decision to implement a specific lifespan extension measure. Urgent measures of restricting forces in order to decrease the deterioration rate of quay walls is beyond the research scope.

1.5 Research question

The main question that needs to be answered to achieve the objectives is stated as follows:

How can the lifetime extension measure be assessed for the inner-city quay walls?

Several sub-questions are derived from the main question which includes the following:

1- What are the most frequently occurring failure mechanisms in quay walls?
2- What are the relevant assessment criteria for the general selection between renewal and potential lifespan extension measures for quay walls?
3- What are the identified criteria to make a specific selection between proposed lifespan extension measures for quay walls?
4- What are the characteristics of the proposed lifespan extension measures?
5- What are the results of the imaginary scenarios regarding the best intervention measure?

1.6 Research strategy

This research strategy can be divided into 4 core parts, and an elaboration on each part is described in Figure 2.

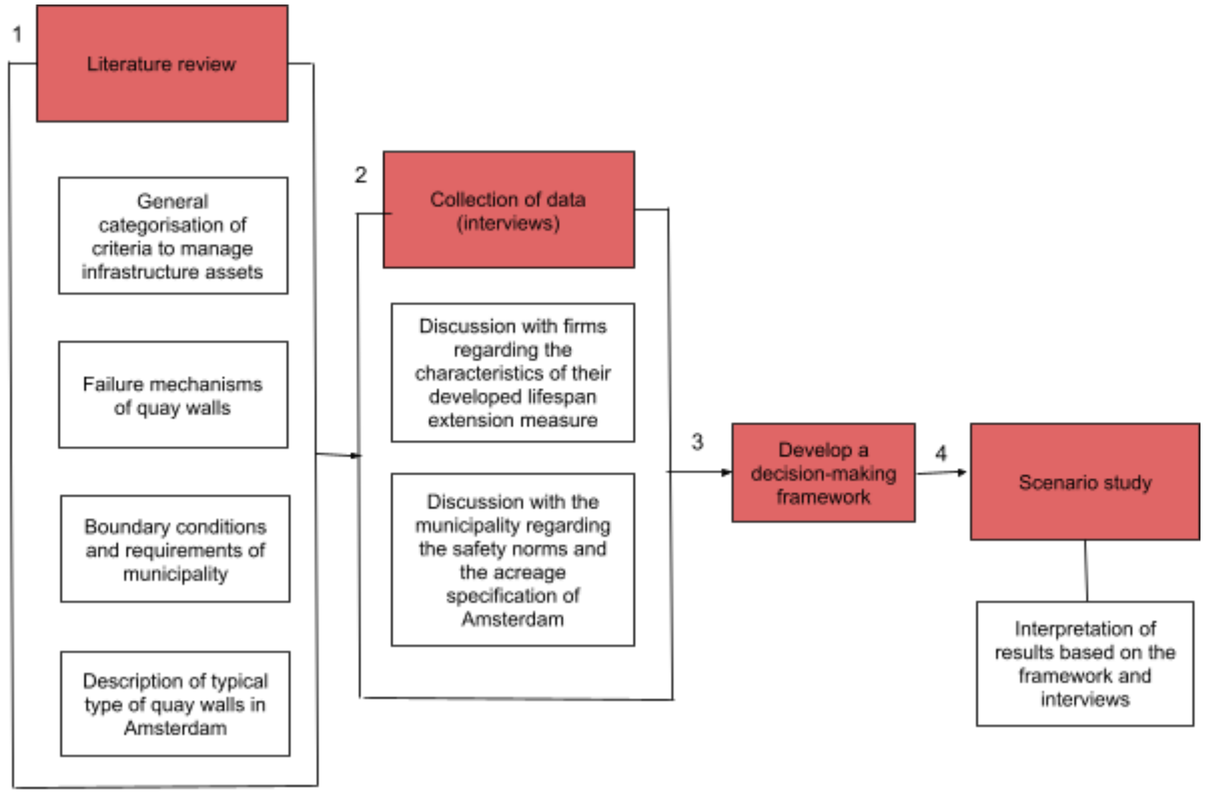


Figure 2: Overview of the research approach

1. Literature review
Firstly, a general literature is collected regarding the assessment criteria that are typically used for the intervention decision of infrastructure assets. Secondly, an overview of the requirements and boundary conditions of the municipality of Amsterdam are reviewed and drafted. Thirdly, literature review is used to understand the different types of failure mechanisms that are occurring in the inner-city quay walls of Amsterdam based on the retaining wall type of quay walls. The different components of the retaining wall are described before approaching the failure mechanisms.

2. Collection of data through interviews

This research paper is of qualitative nature. It is common to arrange an interview, survey, or questionnaire as part of the research methodology (Qu & Dumay, 2011). Seven interviews are arranged with the municipality and consultancy firms to collect information related to their developed lifespan extension measures. The function of the interviewees vary from project manager to 3D designer and structural/geotechnical advisory role of infrastructure projects.

The semi-structured interview questions are formulated and divided into distinct parts to compare different answers within the firms. Most of the interviews are recorded to recover any lost valuable information. The interview with the construction firm will identify the characteristics and performance of their developed lifespan extension measures. Moreover, the interview conducted with the municipality contributes to gain an insight on the safety regulations of quay walls and specify conditions which makes the lifespan extension measure to be considered effective to inventorize. Additionally, practical information related to the average costs and minimum years of lifespan extension for a renewal intervention are noted during the interview. The technical information of safety margins will be used in the scenario studies.

3. Develop a decision-making framework

The decision-making criteria are established for the framework by brainstorming. Generating ideas using a brainstorming technique can be carried out by free writing, clustering, or journaling (Paulus & Kenworthy, 2019). The most suitable technique in this phase is clustering. The aim of the brainstorming session is to figure out a match between two things: (1) the general assessment criteria on infrastructure assets and (2) the outcome of the interviews with the firms. The general assessment criteria from the literature will be linked to the specific assessment of the quay wall and further expanded into sub-criteria if it is relevant to the research.

4. The applicability of the framework using fictive scenarios

Three fictive scenarios are released to understand the applicability of the decision-making framework. In order to build a complete picture, each scenario is meant to undergo a different loop and outcome in the decision-making framework. The answers (yes/no) to certain questions will lead to a different loop and step-process in the framework. In other words, the result of one scenario study can be determined halfway through the framework by choosing a renewal option. Another scenario requires a more extensive study till the end of framework, as the lifespan extension measure turned out to be a favourable option.

1.7 Reader's guide

The layout of the report is illustrated in this section. The answers to the research questions can be found in the corresponding chapters, as presented in Table 1.

Table 1: Overview of the research layout

Chapter	Title	Research question
3	Literature review on the problem of existing quay walls	What are the most frequently occurring failure mechanisms in quay walls?
4	Lifespan extension measures of quay walls	What are the characteristics of the proposed lifespan extension measures?
5	The decision-making framework for quay walls	What are the relevant assessment criteria for the general selection between renewal and potential lifespan extension measures for quay walls? What are the identified criteria to make a specific selection between proposed lifespan extension measures for quay walls?
6	Scenarios	What are the results of imaginary scenarios regarding the best intervention measure?

This research is composed of eight chapters. Chapter 2 will elaborate on the available literature regarding the general assessment criteria that are crucial for the intervention decision of infrastructure assets. Chapter 3 continues with a literature review by describing the types and typical components of quay walls that are constructed in the Netherlands. Additionally, the requirements of the municipality of Amsterdam and potential failure mechanisms are listed while explaining the causes behind their occurrence in quay walls. Chapter 4 contains the interviews conducted and provides a detailed description regarding the execution method, structural strength, impact on the surrounding, and lifespan years and cost approximations for distinct lifespan extension measures. Chapter 5 is devoted to establishing the decision-making framework related to the specific decision for the quay walls of Amsterdam. Chapter 6 demonstrates the results of multiple scenarios based on the decision-making framework. Chapter 7 will briefly discuss the obtained results. Chapter 8 contains the conclusion and recommendations.

2. Literature review on the general categorisation of intervention criteria in infrastructure assets

The typical intervention decisions of the inner-city assets are related to aspects such as safety, legal restrictions, utility access, space limitations, disruptions, costs, environmental impact, and logistics (Davis, 2021). Main studies convey a common practice in terms of observing a balance between the environmental life cycle assessment (ELCA), social life cycle assessment (SLCA), and life cycle costs (LCC) in construction projects where relevant. For instance, a case study on the implementation of different design solution variants on road embankments is conducted based on the social, economic, and environmental impact (Ito et al., 2015). The specified decision aspects can be integrated using a multi-criteria decision analysis (MCDA) to develop an assessment model (Zhu et al., 2021). The various decision aspects of the intervention criteria will be individually discussed in detail below.

2.1 Safety aspect

The safety aspect is twofold according to the multiple researchers' interpretation. Firstly, safety could be the prevention of accidents and injuries of pedestrians near the construction site during the execution phase. This is highly occurring in large crowded cities as by-passers can barely manoeuvre. The action plan to prevent incidents refer to the recommendations of precautionary measures, such as the placement of fences and clear signage to avoid entrance to the site (Oresky, 2023).

Another alternative expression to safety is related to the structural capacity by mapping the risk and consequences of an asset failure. A past thesis report has investigated the reliability of an asset to withstand the current and future forces according to safety norms of the Eurocodes (Terwel, 2014). The concluding fact of safety is to check the structural conditions of all components in a certain infrastructure using monitoring instruments. Afterwards, detailed structural calculations should be carried out by using relevant formulas for bridge components such as the bearings, girder, deck, superstructure, substructure, and bridge anchoring (Zwicky, 2005). The results of the calculations are verified against the set safety norms to analyse whether a surplus or deficit in safety exists in a certain component. The classification of results contains classes such as “good", “sufficient”, and “insufficient” depending on the percentage of safety surplus or deficit. In case the load exceeds the maximum capacity, then the structure is not safe and the failure mechanism should be identified. Typical failure mechanisms of bridges include web crushing of concrete, bending moment of girders, and cracking of beam sections. In case of a “sufficient” classification, then an extensive assessment is needed and sometimes minor maintenance is necessary. If the structure is “good”, further monitoring is carried out for a longer course of time period (Zwicky, 2005).

2.2 Legal restrictions

Legal restrictions should consider the limited working hours on the weekdays and weekends to avoid noise disturbance besides the permitted weight of machines on the road (Sheng et al., 2022). Regulations regarding the maximum acceptable exposure to noise level are usually expressed in decibels. Additionally, the maximum permitted weight during construction is expressed in tons or KN/m2. The violation of regulations such as exceeding the limitation of machinery loads on the road or the acceptable noise level will result in liability claims and lack of trust between the client and contractor. The contractor should strictly adhere to the contract clauses drawn by the client to avoid disputes. Different types of contracts are available in the construction industry such as the design-build contract, cost-plus contract, and lump-sum contract to reimburse any liability claims.

2.3 Utility access

Several agreements with external parties regarding their own facilities have to be arranged. For instance, coordination with utility providers regarding their underground utilities has to take place in the preparation phase. This could include re-routing sewage lines and power systems, relocating garbage containers, and moving lamp posts. Additionally, the positioning of an existing object has to be known for the contractor to decide whether the intervention measure is feasible to apply. In case, the movement of objects is not possible or clashes are likely to take place without an alternative solution, then the intervention measure can not be proceeded. This criterion is significantly important to accurately predict the total execution duration of intervention measure and phase up the planning timeline (Haggar, 2021).

2.4 Space limitation and disruptions

The extent of traffic disruptions depends on the frequency of logistical means of transporting building materials to the construction site. The dimensions of machinery equipment on the roadway can reveal the degree of hindrance on the traffic vehicles. In urban areas, accurate measurements of the required site spaces need to be known such as the sidewalk closures, delivery and loading zones, equipment parking, material staging, and crane location. With little or no room, an alternative method of execution should be considered, such as working from the waterways. Moreover, it is quite often the case that dust particles are emitted to the nearby tenants during the construction activities. This matter has to be adequately communicated with the tenants before construction activities start to avoid conflicts (Claassens, 2020).

2.5 Costs

The initial costs per running metre of intervention measures can be divided into direct and indirect costs. There are multiple variables that influence the initial costs (Copper8, 2017).

- The direct costs are composed of the costs of delivery and installation of construction elements. The costs include the material, labour wages, equipment, and subcontracting instances.
- The indirect costs include the risk and profit margins as well the material price index showing the future price development of materials in the budgeting phase. This is often a fixed percentage adapted over the direct costs.
- The administration and management costs of employees.
- The residual value of materials and elements after the technical lifespan, where suppliers are willing to capitalise the materials in quay walls. This is expressed in the

calculation of net present value. The higher the components' detachability, the higher the value is gained from the materials.

Previous case study generated the whole life cycle cost assessment of different rehabilitation measures in bridges. The measures include the decision between the application of a moveable bridge with electrical and mechanical decks or just a fixed bridge. The social benefits of the passage of vessels underneath the bridge is compared with the construction costs (Al-Wazeer et al., 2005). This case study indicates that the whole life cycle cost analysis is not only associated with the initial costs as aligned above, since social benefits were translated to costs. A particular intervention measure should assess the combination of initial costs, maintenance and repair costs, failure costs, and user delay costs (Carse et al., 2002). In some cases, the initial cost is assessed and compared with the years of lifespan extension of an intervention measure. For instance, if there is no maintenance carried out during the lifetime of the applied intervention measure, then it will be excluded from the cost assessment. Uncertainties in failure costs can also lead to excluding it from the assessment. Finally, the user delay costs can be excluded if it is expressed in the social impact.

2.6 Environmental impact

The environmental impact should evaluate the distinct air, soil, and water pollution caused by the intervention measure in construction projects (Environmental Pollution Centers, n.d.). A previous project incorporates the comparison of quay wall typologies according to their composition of materials such as steel, concrete, wood, and fibre reinforced polymer to estimate the carbon dioxide (CO_2) emissions (Maas, 2011). The inventory analysis of the ELCA of this project is divided into two parts. The first part involves the estimation of CO_2 emissions according to the lifecycle phases resulting from the production of materials, transport, construction, use, and demolition. The production of materials is meant by the fabrication of materials by either using raw, recycled, or reused materials. The impact of material transportation is estimated by multiplying the total driving kilometres of trucks by the average emissions per km. The second part of the inventory analysis investigates other emission categories. The emission categories were: global warming potential, ozone depletion potential, human toxicity potential, acidification potential, eutrophication potential, biotic and abiotic depletion potential, and energy depletion potential.

The obtained quantitative results show that wood obtained the least CO_2 emission, while the fibre reinforced polymer had the most emissions in the production phase. Steel and concrete received an equivalent CO_2 emission in the construction phase, which is lower than wood and fibre reinforced polymer. An equal amount of CO_2 emissions was detected during the transport phase for the four materials. The fibre reinforced polymer scores in all emission categories were observed to be the highest with respect to wood, steel, and concrete. Wood contains lower and higher emissions in terms of global warming potential and photochemical oxidation, respectively, compared to concrete and steel. The presence of toxicity in fresh water is only evident in wood materials. Additionally, the presence of human toxicity is only present in steel and fibre reinforced polymers (Maas, 2011).

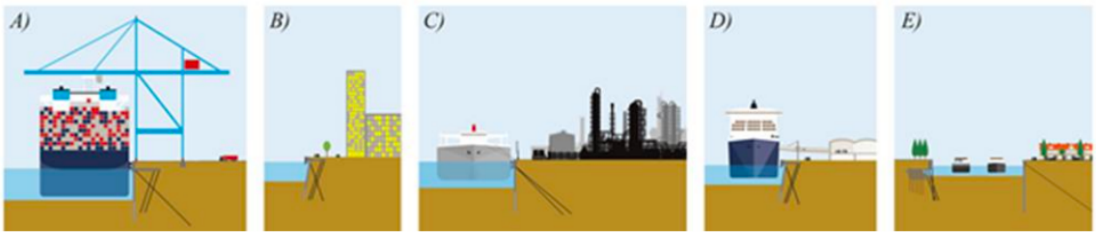
3. Literature review on the problem of existing quay walls

3.1 Background information

Amsterdam is known by the ‘belt of canals’ due to the fascinating top view to which the city is bounded with a network of canals. The inner-city quay walls have a historical and aesthetic value that forms an iconic character for the city of Amsterdam. As a result, the inner-city quay walls serve as a tourist spot that attracts millions of visitors annually. The quay walls serve as a primary function to separate the canal from landscape. During the golden age, the Netherlands experienced an economic boost through loading full stocked ships on the canal to transport goods from warehouses to the harbour. The city had a shortage in living units while an expansion project was planned. This led to land reclamation of 3 main canals, in which residential houses were built around them. In the 20th century, a huge demand for parking spaces narrowed the riverbed of Amstel. Therefore, the original functionality of canals is lost and got substituted by car traffic and tour boats. According to statistics, 50 percent of the water areas in Amsterdam are dumped as a result of urbanisation (Amsterdam Info, n.d.).

3.2 Types of quay walls

Quay walls consist of different types such as sheet piles, cantilevered walls, gravity walls, and caisson. The types of quay walls are mainly determined by engineers depending on the geographic conditions (location) and service requirements which the quay walls intend to facilitate. The location can vary from urban to commercial and industrial, where soil conditions and water depth could be one of the key geographical conditions. The service condition takes into account the durability and lifespan, besides, the loading capacity and dimensions of ships sailing through the canal (Allen & Moore, 2016). Figure 3 demonstrates different types of quay walls depending on the location and purpose of use.



Impression of different types of quay walls:
A) commercial quay wall, B) urban quay wall, C) quay wall that is part of a dangerous plant,
D) quay wall that facilitates cruise ships, E) quay walls that facilitate main commercial waterways.

Figure 3: Different types of quay walls (De Gijt & Broeken, 2013)

- **Commercial quay walls:** In the Netherlands, the most often used design in ports and harbours are diaphragm walls. A sheet pile made of mainly concrete or steel is installed as part of the structural design of diaphragm walls. The sheet pile is assembled by either driving or pushing into the ground by a pile hammer.

- **Urban quay walls:** Gravity walls are present in historical areas, which primarily relies on its own weight to withstand earth and water pressure. Gravity walls were intended to be the oldest and most basic characteristic design between the 1500s until 1830s. After the 1830s, the retaining wall on piles is the most dominant type that took place. This type of quay wall is featured by the existence of masonry stones found on wooden piles. The piles are drilled into wooden floors and intersected by a beam. After developments in the 19th century, reinforced concrete on relieved platforms in combination with steel anchors and L-walls took part in the new construction design of quay walls. Figure 4 below depicts the evolution trends in the construction process among centuries.

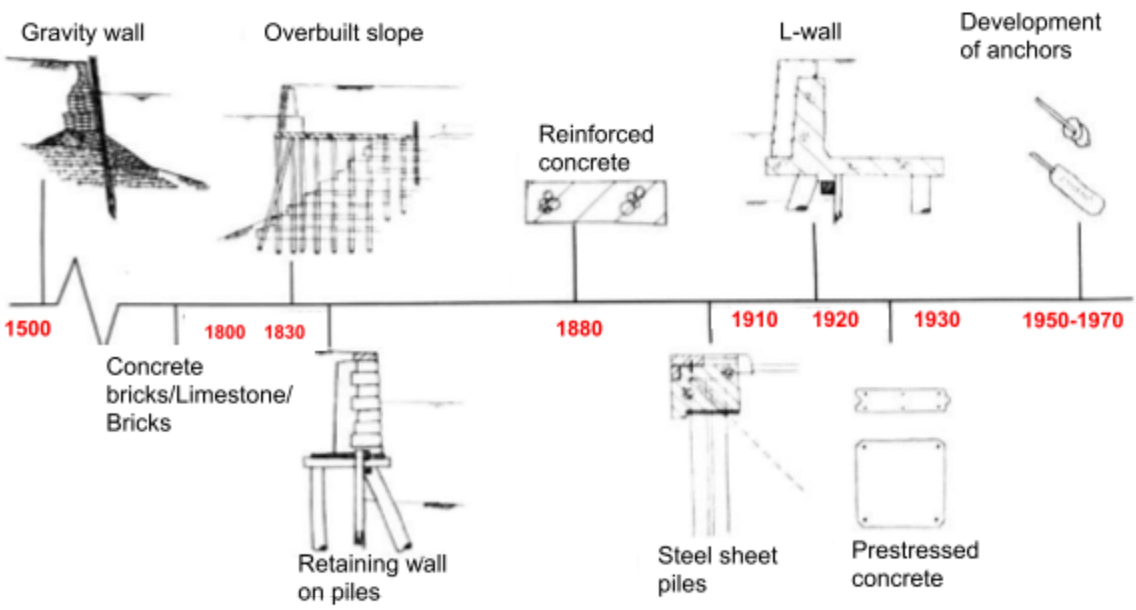


Figure 4: Development of quay wall design in urban cities (Roubos et al., 2014)

- **Quay walls that facilitate cruise ships:** This is a combined wall system composed of pipe piles, sheet piles, and connectors. Both pile types are welded and interlocked to the concrete wall by a beam connector. The beam promotes the overall stability of the structure by supporting the lateral forces and preventing deformation. The sheet piles offer great resistance to water and soil pressure caused by cruise ships manoeuvring by transferring the vertical loads into intermediary pipe piles.

- **Quay wall that is part of dangerous plant:** This design encompasses a selection of any above specified quay walls, depending on the location and the type of toxic substances. Customised building materials need to bear minimum safety requirements such as corrosion for a certain lifespan to avoid early interventions. The reliability index of the structural limit state is large, since the risk danger to life is high.

3.3 Typical type of quay wall in Amsterdam

This research focuses on the quay walls with the type of retaining walls on piles. The retaining wall is composed of different components. A description of the components related to the retaining wall is described below as follows (Haverkamp, 2021):

1. Retaining wall: This is a vertical separation between the waterways and the landside. The retaining wall is made of masonry stones with mortar joints to provide a cohesive layer of aesthetically looking bricks. The quay wall is connected with a deck slab to stabilise the upper part of the wall. Additionally, a bollard is attached to the deck slab to provide a mooring line for the boats.

2. Foundation piles: the element takes charge of transforming the forces from the superstructure into the subsoil. The piles can be distinguished between vertical and slanted piles. The piles are structurally distributed along the length of the quay wall. For large loads, multiple pile rows are constructed to bear the forces acting downwards. The strength capacity of the pile depends on the depth of the tipping pile and the soil rigidity.

3. Wooden floor: an element distributed at a longitudinal direction to transfer forces induced from the superstructure and above soil through the capping beam. The superstructure includes the self-weight of the masonry wall in addition to the traffic loads.

4. Capping beam: an element located below the wooden floor to connect the pile foundation with the floor elements.

5. Soil retaining screen: An element placed at the front of the first pile row or behind the rear pile row. The purpose of the soil retaining screen is to avoid the erosion process as a result of the difference between the level of groundwater and surface water. A higher frequency of inflow and outflow of water quantities into the quay wall results in a higher likelihood of erosion to take place in the vicinity. At particular locations, the soil retaining screen is constructed at a later stage to limit the erosion.

An overview of the positioning of elements within the quay wall can be shown in Figure 5.

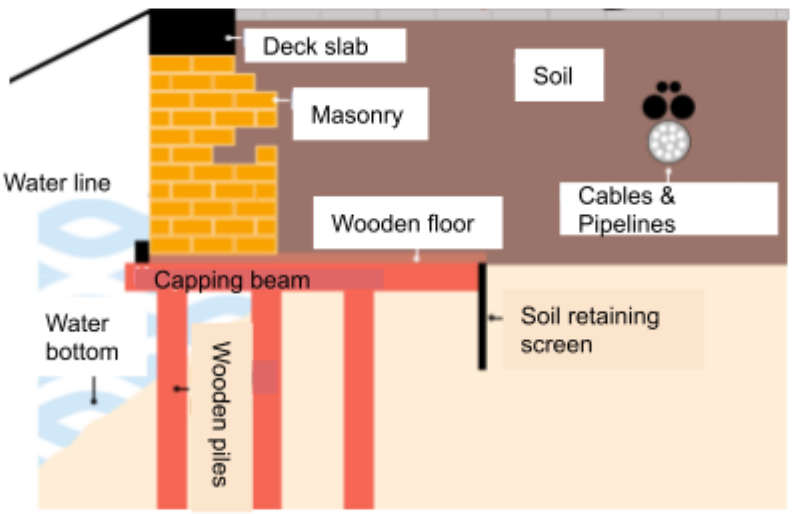


Figure 5: Overview of quay wall components (Gemeente Amsterdam & CROW, n.d.)

3.4 Failure mechanisms

Typical failure mechanisms of quay walls are related to geotechnical, structural, and hydraulic issues. The structural failure deals with the capacity and integrity of the structure to bear current loads without observing damages in a certain component of quay walls. The geotechnical aspects reflect the reaction forces related to soil mechanics. The hydraulic failure addresses the air and water contamination in the quay wall structure. Furthermore, the most frequently observed failure mechanisms of inner-city quay walls are presented in the guideline content published by the municipality of Amsterdam. The three most frequently occurring failure mechanisms detected in the inner-city quay walls are related in a broad spectrum to soil leaching, damages in foundation, and deterioration of masonry wall (Gemeente Amsterdam, 2021). Several inspection reports are published online to understand and explain the failure mechanisms relevant to real collapse events, such as the Grimburgwal in Amsterdam (Korff et al., 2022). Scientific source (Suckling, 2021) and manual guide (Gemeente Amsterdam & CROW, n.d.) provide a useful discussion related to the magnitude and direction of non-equilibrium forces that play a role in failure modes. The ten types of failure mechanisms occurring in Amsterdam as shown in Figure 6 will be explained below.

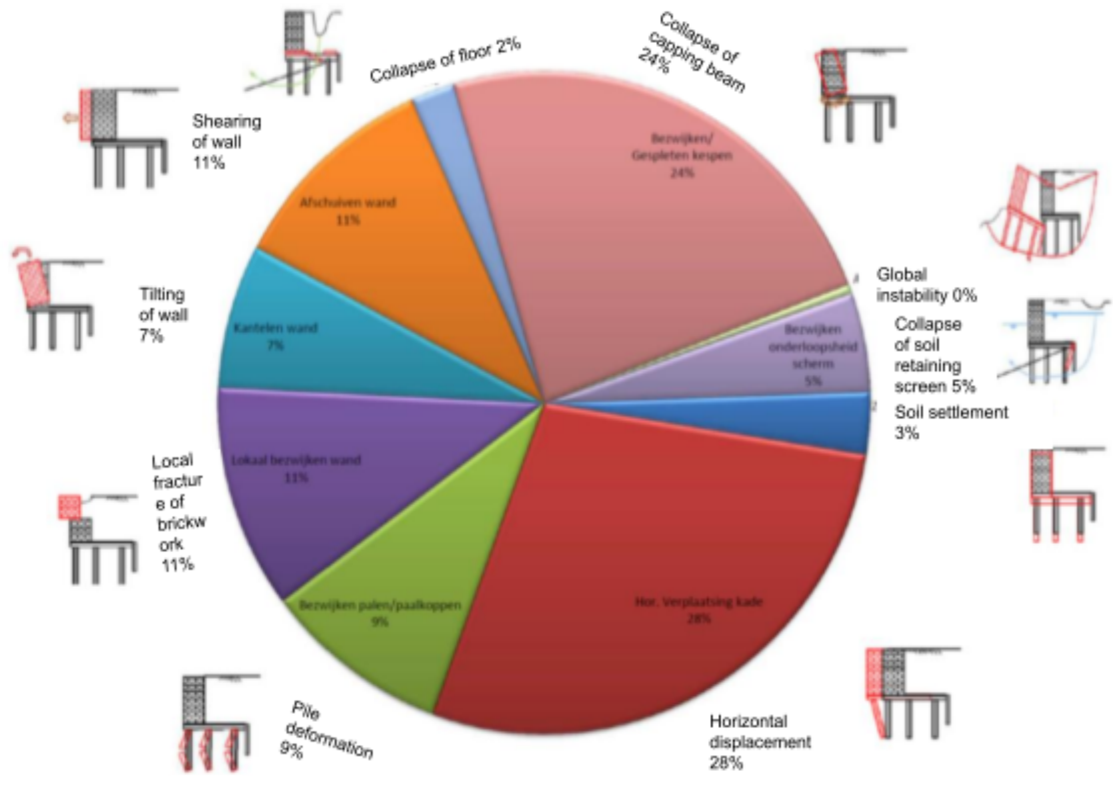


Figure 6: Chart depicting the proportion of failure mechanisms (Gemeente Amsterdam, 2021)

1. Collapse of soil retaining screen: A leakage causes differences in inflow and outflow of water quantities. This creates a hydraulic heave as a result of differences in groundwater level between the quay wall and landside. In many cases, water pressure causes salty water to accumulate at the surface of quay walls, which ruins the soil layer to which the foundation piles are found. In some locations, no soil retaining screens are visualised in quay walls.

2. Collapse of capping beam: The capping beam is a crucial connection between the relieving floor and wooden pile foundation. If a certain failure occurs in the wooden floor or piles, then the binding rigidity is no longer ensured. The masonry walls are slightly tilted as the piles are not structurally solid to withstand the loads.

3. Deformation of (head) piles: A natural decay process caused by microbes such as bacteria and fungi is found on the wooden pile foundation, which leaves away rot and degrades the strength through an oxidation process. Another important cause is the frequent dredging and ship propeller taking place nearby the piles. As a result of soil being washed away, piles are no longer perpendicularly positioned with respect to the relieving floor. This is due to a negative skin friction occurring when the piles are situated in soft soils, yielding to downward movement and increase in shaft loads on the piles. It is often the front pile row that is more vulnerable to damage, since the rear pile row is less prone to energetic water motions.

4. Shearing of masonry wall: A sliding motion occurs due to soil pressure acting behind the wall. In practice, the horizontal soil pressure is distinguished between active and passive forces, depending on the magnitude and direction. As active forces exceed the passive ones, a non-equilibrium scenario causes destabilisation of the structure. The contrast in force capacity is caused by faulty design estimations, as the surface area/depth of the masonry wall is small compared to the weight of soil behind the retaining wall. The traffic load and vibration are main sources of increasing the soil weight.

5. Local fracture in brickwork: The masonry walls are exposed to regular tour boat collisions. The current tensile load acting on the masonry walls exceeds the designed elasticity modulus of the building material. Therefore, there is a high chance of humidity accumulation as a result of crack and tear formation in the masonry wall. The aesthetic quality of the retaining wall is ruined as loose stones are constantly toppling. Additionally, the mortar jointing between the brickwork is not deep enough due to the use of inaccurate traditional methods. The nearby tree roots can expand and extract local water from the soil, which lowers the groundwater level, resulting in constant pushing of foundation towards the canal side and thus forming cracks.

6. Tilting of masonry wall: The damages in the foundation elements have an important influence on the tilting of masonry wall. The axial displacement in the front pile row in addition to the cracks in masonry walls yields to the tilting effect. The vertical reinforcement bars are detached from the foundation footing as a result of lack of stability in the capping beam.

7. Horizontal displacement: Excessive bending of piles occurs due to the local deepening of the canal just in front of the quay walls. Therefore, the row of piles tends to deform and geometrically deviate at different levels. The masonry wall shifts to the end side, which encounters an uneven distribution of forces among the front and rear pile rows, resulting in instability. Another important reason is the overdue maintenance of road pavement which takes place in the vicinity. After time, a sinkhole significantly appears at the paved road, which washes soil away through the wooden floor to the piles. In response, the cohesion of soil where the pile foundation is settled on begins to weaken. This failure is often related to soil subsidence as the void proportion in the soil composition does no longer sustain the foundation.

8. Soil settlement: The constant and excessive surcharge load acting on the surface of quay walls due to moving vehicles, heavy trees, and deep excavations along the road are exceeding the soil bearing capacity around the tipping piles. This causes subsidence of the total structure, which typically occurs in poorly compacted soils.

9. Collapse of relieving floor: The floor no longer withstands the downward vertical pressure of soil acting behind the quay walls in combination with the self-weight of masonry walls. Also, sinkholes behind the quay wall play an important role in washing away the pressurised soil towards the wood floor, which creates a gap in the floor.

10. Exceedance of global stability: The complete rotation of the structure due to non-equilibrium horizontal and vertical forces acting above and below the relieving floor. It is a very unlikely scenario for the inner-city quay walls, where all components are witnessed to be damaged. This includes the decrease in wall thickness and pile diameter due to degradation alongside the increase in height of masonry wall are all contributing factors that cause global instability. The soil retaining screen is also completely broken, thus losing its functionality.

3.5 Requirements and boundary conditions

The municipality has the ambition to rehabilitate the quay ways on a larger scale without harming the environment and using robust measures. The traditional method of replacement by dewatering, excavation, and using vibratory equipment is time-consuming. It imposes a burden on the environment such as traffic congestion and shortcoming on underground utilities. The safety of inhabitants is the priority aspect in the municipal policy, but environmental impact concerns of innovative measures should address the biodiversity, water quality, and aesthetical appearance of the city. Therefore, the municipality has requested from parties to develop innovative measures to attenuate the failure mode of quay walls. A feasibility and quotation report are expected from participant firms to be delivered in phase 1 of the nomination procedures. Following up, an independent commission team will assess the report content and give advice to the municipality. Several boundary conditions must be fulfilled in order to admit the lifespan extension measures in the inventory tool of the municipality and the research framework. The ten requirements are specified below as follows (Gemeente Amsterdam, 2021):

1. The proposed measure is feasible and cost-efficient for practical realisation.
2. The proposed measure should extend the functionality of quay walls for a minimum lifespan of 20 years.
3. The measure is vibration-free and proven during (dis)assembly not causing significant damage to the surrounding area.
4. The measure requires little to no maintenance in the period of exploitation.
5. The probability of surface water drainage in the canals is minimal.
6. The measure must adhere and conserve the aesthetic value, whether that's considered a permanent or temporary placement of components.

7. The measure does not damage the cables, pipelines, planted trees, and street furniture deployed around the quay walls during the execution phase.
8. The removal and installation of construction should preferably take place via the waterways to prevent traffic congestion.
9. No influence is imposed on the vessel dimensions (NAP depth, height, and width) sailing through the canal.
10. The traffic safety during construction activities is promoted.

A complete overview of requirements stemming from the project inquiry of the municipality of Amsterdam can be shown in detail in Appendix A. For each category, the list of requirements are divided into separate columns of demands and wishes. The category is related to the above-mentioned boundary conditions and elaborated in a more extensive way. The demands specified for each category needs to be minimally fulfilled to get acceptance for the implementation (including pilot projects) of the lifespan extension measures. The wishes are considered as bonus aspects to realise in the solution.

4. Lifespan extension measures of quay walls

In section 4.1, a short overview is given about the urgent actions to attenuate the failure mechanisms. Afterwards, sections 4.2 - 4.7, successively provide an in-depth discussion regarding the six innovative lifespan extension measures, which are currently proposed to the municipality of Amsterdam. To gain further insights into these measures, the project participants from the six firms are met and interviewed following a semi-structured list of questions. Based on this, the lifespan extension measures are categorised by collecting the following data: the execution method, structural strength, and the impact of lifespan extension measures. The entire list of interview questions can be found in Appendix B. The main key points of this chapter are categorised in Appendix C and D.

4.1 Urgency measures

Several precautionary measures have been taken into consideration in the past years to reduce the loads, such as restricting the access of heavy vehicles and removing trees with heavy roots. The root system of trees consists of a load bearing and nourishing part. The former part consists of thicker roots to ensure the stability of trees. Trees can also in return stabilise the ground. The latter part are finer roots to ensure that trees are provided with necessary substances to grow. Also, the loads exerted by trees on the quay are distinguished by four types. Those are the self-weight of the tree, expansion of root system, wind load on the tree that is transferred to the subsoil, and scour holes after collapse of trees (Roubos et al., 2014). In other cases, stability beams are placed at lateral position between the quay walls which completely blocks the ships mooring in the canal. Another solution to this issue is the installation of sheet piles parallel to the deteriorated quay wall. Both solutions tend to significantly transfer the horizontal loads, but they do not fulfil the mooring and hydrological specifications set by the municipality. The two temporary solutions can be seen in Figure 7.

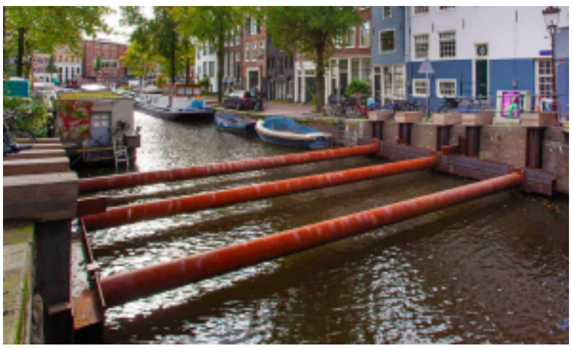



Figure 7: Stability beams and Sheet piles (Gemeente Amsterdam, 2019)

4.2 Grout injection pile system

4.2.1 Introduction

The Grout injection pile system is known as the Grout Compact Paal (GCP) in Dutch. This GCP technique has often been experimented by BAM Infra in the past and proven to yield effective results in multiple construction projects. The GCP technique involves the penetration of a steel pile through the masonry wall towards a specific depth in the soil layer.

Materials such as steel piles, grout, and mortar are the main elements used to make GCP an effective and realised solution to reduce the tensile forces applied on the quay. Grout is applied on the soil layers, while a better quality mortar is pasted along the sides of the masonry wall to stabilise the steel pile. This innovative measure has been applied to the 'Bullebak project' with the aim of preserving the brickwork during the replacement of an existing movable bridge in the heart of Amsterdam. The 'bullebak project' involves the renewal of a monumental bridge by partially using the GCP technique due to the non-compliance of the current bridge bearing capacity with an increasing traffic load. The bridge serves an important connection route for cyclists and public transportation. Nevertheless, the Bullebak project is practically considered to be a more complex project than quay walls. This is because the bridge is bounded by vulnerable quay walls; while intensive coordination is required between mechanical experts and civil contractors to concisely handle many construction interfaces. In contrast, this technique requires more planning efforts in inner-city quay walls, such as the placement of a noise barrier to ensure low nuisance due to its proximity to residential houses.

4.2.2 Execution procedures

The grout injection pile solution is implemented by specific steps, these will be outlined in this section. First and foremost, the deck slab of the quay wall has to be temporarily removed to allow vertical drilling of holes in the masonry wall according to the selected pile diameter. Secondly, the tubular steel pile is penetrated through the masonry wall and wooden floor. The grout injection pile system is provided with a screw head at the bottom, which enables rotation and driving of the tipping pile from ground level into the second layer of sand. Subsequently, the screw head is equipped with an opening to fill the soil layer with grout for lubrication purposes. The lubrication will reduce the soil resistance during the pile installation and easily allow mixing of grout with soil. The speed of drilling constantly decreases as soon as the injection piles reach a greater depth with a high soil bearing capacity. Finally, the spacing between the wall and steel pile is filled with mortar. The hollow spaces between the wooden floor and masonry wall are sealed to prevent mortar leakage into soil. The lifespan extension measure is visualised below, in Figure 8.

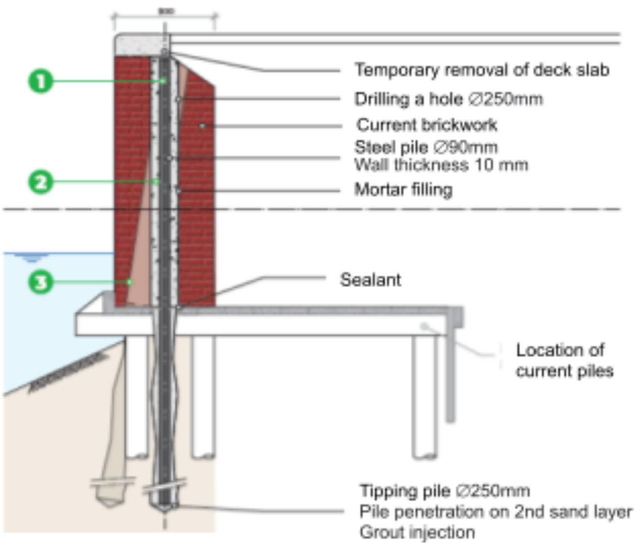


Figure 8: The GCP principle (BAM, personal communication, 2023)

4.2.3 Structural strength

This method aims to bear tensile forces that are induced on the deteriorated masonry walls by diverting the vertical loads towards the tubular pile. The vertical forces acting on the quay is a combination of traffic load and the self-weight of the wall. The mixing of the grout with sand has a positive influence on the strength and stiffness of the pile. The effectiveness of the grout injection pile system is highly reliable on the current shear strength of the brickwork of the quay wall, and the binding rigidity between the steel pile, mortar, and masonry wall. Both factors play a direct role in determining the required pile spacing in the GCP system. A higher shear strength will result in a larger pile spacing. The GCP solution will only address the failure mechanism related to wall shearing. The expected shear bearing capacity amounts to 23 KN/m^2. The structural calculation takes into account the least favourable scenario.

The original vision of BAM was to resolve other failure mechanisms by integrating the design with supplementary measures to withstand the horizontal forces. BAM's ambition to consider one of the two options to withstand the horizontal forces, as an integral design to the GCP system was not feasible; hence, it was excluded from the proposal. Both options did not comply with the requirements of the municipality. The first option refers to the folding anchors, which incorporates excavation to take place on the backside of quay walls, to steeply drill the folding anchor. As a result, the anchor is positioned alongside the wooden floor. Moreover, the bottom face of the folding anchor ends up resting on the tidal flats, which substantially raises the risk of creep failure in the anchor. Applying a longer anchor length to allow for deeper driving into the first layer of sand is technically not possible because this clashes under the existing buildings. Besides, a steeper application of anchors at different angles, to reach the second layer of sand, is undesirable as it penetrates through the wooden floor.

The second option is the reinforcement of soil by tensile elements such as geogrids. This option requires excavation up to the water level to avoid drainage. Additionally, excavation of wide sections of the carriageway (almost half the carriageway) has a negative influence. This leads to traffic congestion and severe restrictions on the possibility of cables and pipelines to be laid down or maintained. Consequently, the horizontal forces acting on the brickwork and wooden floor are observed to decrease and increase, respectively.

4.2.4 Impact on the surroundings and social impact

A minor burden will be imposed on the environment by implementing the GCP technique. The assembly of piles by means of a rotating screw points out that this technique is vibration-free. The machine foundation deployed around the quay walls has a small dimension with light weight (2500 kg) on the infrastructure. This is a supporting fact to meet the space occupation and workload during the execution phase as specified in the programme of requirement by the municipality. The GCP method can be flexibly executed via the waterways or landside, depending on the location. The predicted execution duration is one week per 10 m of section area, excluding the mobilisation of equipment. The most preferred and common way is to utilise the waterways for material transportation and work execution. The choice of waterways will allow small tugs to drag the floating pontoon into another location. Due to the workload limit on the landside, the advantage of working from waterways is that more powerful equipment can be laid down on pontoons to speed up the construction process. However, landside should be utilised in case houseboats are present in the vicinity of quay walls to avoid moving the houseboats. The impact of the latter scenario is that the parking lots will be closed off, since a 2.5 m distance behind the quay wall is considered a sufficient space for machinery to be positioned. Nonetheless, the road will not be blocked; thus, the traffic flow is not obstructed during the construction activities. Additionally, the presence of trees does not form a barrier with response to height restrictions for machinery operation. Cables and pipelines will only be encountered during the GCP execution if they prolong under the canals, which needs a bridging construction to avoid damages.

4.2.5 Environmental and economic impact

The water quality is retained by taking preventative measures before the piles are injected into the soil. After quay wall inspections, it is often the case that the current soil volume lies lower than the technically designed soil level of quay walls. This is caused by the drifting of soil as a result of boat propellers. This is a downside since hollow spaces are observed between the wooden floor and current soil level. In regard to the execution of this process, sand backfill to the original design level is required prior to construction activities. This prevents grout spillage and pollution of canal water when the pile is released upwards.

The total cost of GCP is €15,000 per running metre, and the determined lifespan of the GCP solution is 50 years. The lifespan extension of other components is unknown, as it depends on the current conditions of quay walls. The GCP components cannot be removed and retained after its end of lifespan. It is expected that the quay wall has a remaining lifespan of less than 50 years. In that case, the GCP component can be disassembled and reused in the current form to be incorporated for a new quay wall construction. There is no maintenance required for the lifespan extension measure; however, it is recommended to perform inspections in order to identify problems at an early stage. The biggest uncertainty is the conditions of brickwork in existing quay walls. The GCP solution cannot be applied in quay walls which contain excessive cracks in the brickwork. The presence of cracks has a negative impact on the bearing capacity of vertical forces subjected on the masonry wall.

4.3 Bioinspired Soil Improvement (BISI)

4.3.1 Introduction

The characteristics of the bioinspired soil improvement (BISI) method is identified through testing geotechnical samples in a facilitated research lab owned by Groundwater Technology. This method represents an ideal ‘building with nature’ solution to enhance the cohesiveness of soil layers subjected with a weak bearing capacity in quay walls. The BISI solution makes use of residual products from the food industry to activate the biological process in soil layers. In this sense, consumption of new raw materials is minimised as waste materials and microbes in subsoil are fully utilised to develop the BISI solution. This method offers a wide field of application, such as mitigating liquefaction caused by earthquakes and counteracting piping underneath the dikes. An example of a pilot project concerning the strengthening of soil, using BISI, was performed in the air force base of Eindhoven.

4.3.2 Execution procedures

BISI requires few preparation steps for the execution activities to take place behind the quay wall. Firstly, tiles are removed from the street to allow for ground drilling. This is followed by the installation of an infiltration well, which is later connected to a porous plastic pipe to allow pumping of biobased material. The pipe is brought into a depth of almost 2.7 m below ground level, where the wooden floor is allocated. Afterwards, the substance is applied in a dissolved form without the need of pressurised injection or excavation to avoid jeopardising the soil stability. The geotechnical soil property in the quay wall is enhanced through a natural, biological, and sustainable cycle. The dissolved substance with the presence of bacteria results in an interaction process with existing ions and molecules in the subsoil. Lastly, a calcite crystal is released in the soil layer after the biological reaction is completed. Calcite crystal is a carbonate mineral and the most stable polymorph of calcium carbonate ($CaCo_3$). The formation of calcite crystals binds the grains together to empower the soil resistance against current loads. Figure 9 illustrates the BISI solution in quay walls.

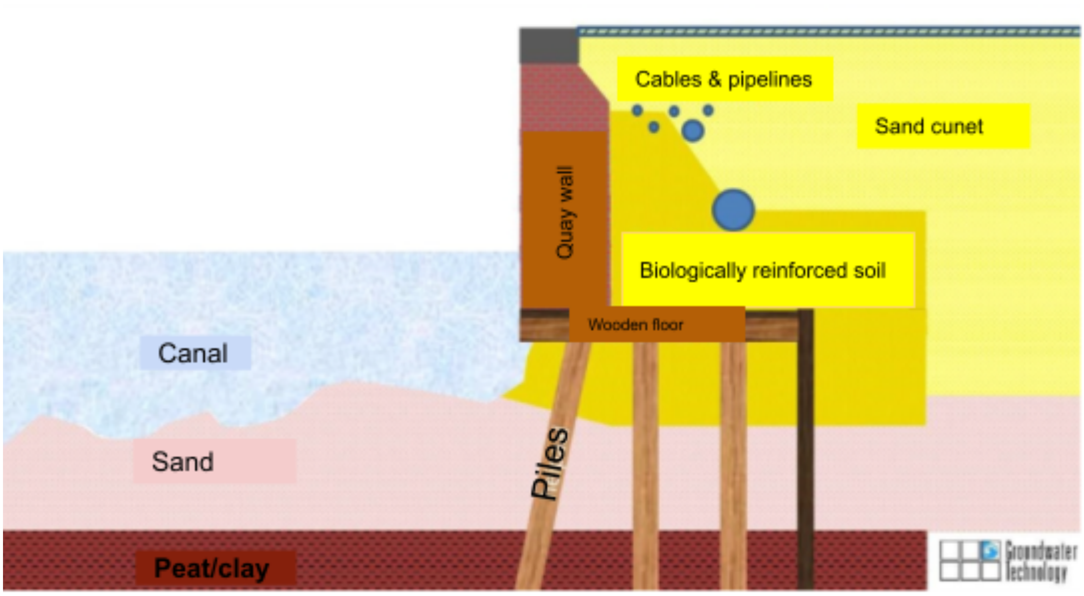


Figure 9: BISI procedure (Groundwater Technology, 2022)

4.3.3 Structural strength

BISI is developed to solve all underlying failure mechanisms that occur in quay walls to a certain extent. In principle, any failure mode caused by a weak soil resistance can be immediately addressed through this lifespan extension measure. Structural defects related to a particular component cannot be directly recovered through the implementation of the BISI solution. This includes among other things the cracks in masonry walls, cracks in wooden floor and capping beam, and rotting of wooden pile foundations. However, this method can contribute to solving the aforementioned failures by avoiding soil being washed away through the cracks. It can also minimise the consequences of floor cracks by establishing a light layer of cementation above the floor to distribute the dynamic load of traffic and promote stability. Moreover, it could reduce the catastrophic impact of sinkholes in the pavement by increasing the soil coherence.

Regardless of the effectiveness of this lifespan extension measures, the municipality of Amsterdam has requested from Groundwater Technology to only focus on resolving failure mechanisms related to the tilting, shearing, and horizontal displacement of masonry walls. The pilot project will be awarded at a later stage to observe and evaluate the efficacy of BISI on quay wall situations based on the three previously mentioned failure mechanisms. The strength increase of soil bearing capacity depends on other factors besides the ratio of calcite mineral formation. During the interview, a model representation shows that different soil types and conditions have a major influence on the proportionality of soil strength increase. This means that a linear increase of soil strength with respect to the ratio of calcite crystal is not always an assumption to take into account. For example, a 4% of calcite crystal could rapidly result in a 2.5 MPa while 8% yields to a soil strength of 0.5 MPa to withstand the horizontal forces. Under normal circumstances and without BISI treatment, the quay wall is observed to have a 52 mm of horizontal displacement. The horizontal displacement can be reduced to 40 mm after applying the lifespan extension measure exactly above the wooden floor, which falls within the acceptable boundary limit. A 70% reduction of horizontal displacement is practically achievable if work activities are expanded further to the carriageway.

4.3.4 Impact on the surroundings and social impact

The execution phase does not require massive equipment to start the rehabilitation activities of quay walls. The transportation of materials and machinery from the point of origin will be through waterways, where the stocks are loaded on the pontoon. The application of biobased substances in a dissolved form does not emit noise disturbance on the surrounding. The reparation of quay walls is planned from the landside, since it is a complex task to construct an infiltration well with pipe prolongation from the canal. It is sufficient to close parking lots to allow working from the landside. The precondition of the latter statement is that the BISI solution aims to decrease the horizontal displacement to 40 mm. A larger spread of calcite crystal to attain greater soil resistance under the road pavement is feasible. Nevertheless, this results in a higher traffic congestion due to the necessity of space occupation. The duration for implementing BISI is two days per 10 m of section area. Special attention is paid to the cables and pipelines before installation of infiltration wells, but the movement of underground utilities is not necessary. The lifespan extension measure can be applied next to or underneath planted roots without harming the valuable trees.

4.3.5 Environmental and economic impact

BISI is a durable and sustainable technique with no impact on the soil and water quality. The total realisation cost of this lifespan extension measure ranges between €7,500 and €10,000 per running metre. The lifespan of the BISI solution is unlimited, as it does not depend on the availability of bacteria in the long term. The calcium carbonate mineral will be left behind, which remains functional even if the bacteria vanish. The initial existence of bacteria is just to produce the mineral. The lifespan extension measure does not require maintenance, while it is unknown whether an intermediate inspection is necessary. According to the interviewee, the BISI solution is ideal to apply for quay walls in fair conditions with a remaining lifetime of 10 years. In this case, the lifetime can be extended to 40 years. This calcite crystal will deteriorate entirely in events where digging on large areas behind the quay is inevitable, for instance, when solving another occurring failure mechanism.

A challenge of this method is the difficulty in immediately examining what has changed in the soil characteristic during the execution phase. In addition, the heterogeneous form of soil plays a significant role in the factor of soil cohesion. A heterogeneous soil results in a relatively low permeability and minor effect on the soil strength when biobased material is gradually penetrating through the infiltration well. The uniformity coefficient cannot be assumed at each soil layer to be equivalent; because uniformity is a numerical value that expresses the variety in particle sizes in mixed natural soil. Lastly, the largest uncertainty is whether the biobased material does contribute to the dampening of the vibration of traffic.

4.4 Foundation reinforcement solution

4.4.1 Introduction

The Foundation reinforcement solution is called Fundovatie in Dutch. The Fundovatie system consists of tubular screw piles, grout anchor, anchor bolt chair, jack element, and other structural attachments. The tubular piles withstand the self-weight of the masonry walls. The anchoring element consists of a rod embedded with a grout body at the end to absorb the tensile forces arising from the quay wall. The anchor receives the tensile strength from the shear stress between the grout and surrounding soil. Different components are prestressed by an auger to evenly position the Fundovatie method with respect to the existing quay walls. Figure 10 shows the final 3D design of the Fundovatie system developed by Iv-Infra.

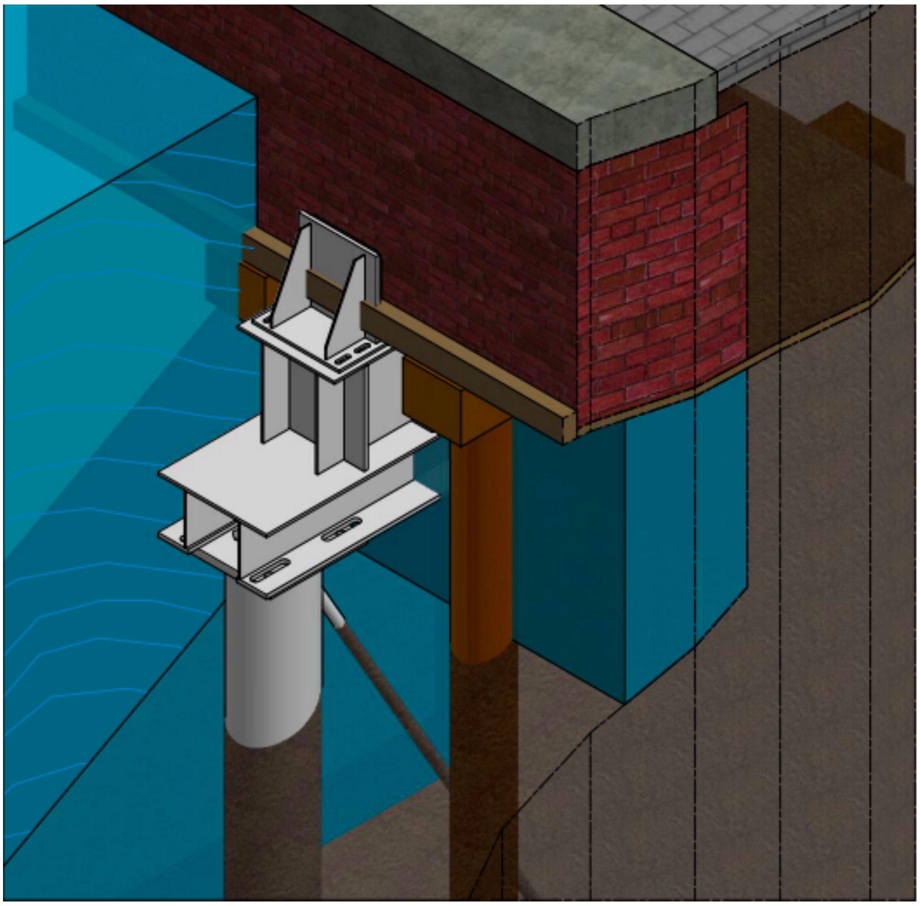


Figure 10: The 3D design of Fundovatie system (Iv-Infra, personal communication, 2023)

4.4.2 Execution procedures

In Figure 11 the execution steps of the Fundovatie method are outlined. Firstly, the tubular pile is assembled in front of the quay wall. The pile is screwed into the soil by a drilling rig and without interfering with the masonry wall. Secondly, a grout anchor is laid over the top opening of the pile. A diver will ensure that the anchor is positioned behind the pile. Subsequently, the anchor is installed into the depth of the second layer of sand by an anchor drilling machine. Thirdly, an anchor chair will be bolted and fixed above the steel pile through the four holes by a diver. Fourthly, an attachment element is placed above the anchor chair by a crane and diver guidance. The jack element (black square in Figure 11) will be pressured in order to have the attachment element uniformly intersected between the wooden floor and capping beam. In this step, the quay wall is stabilised only in the vertical direction. Finally, the previous step is repeated, where the jack element is prestressed in the horizontal direction before loads are released from the quay wall. The last two steps are necessary to eliminate the space between the Fundovatie and the existing quay wall.

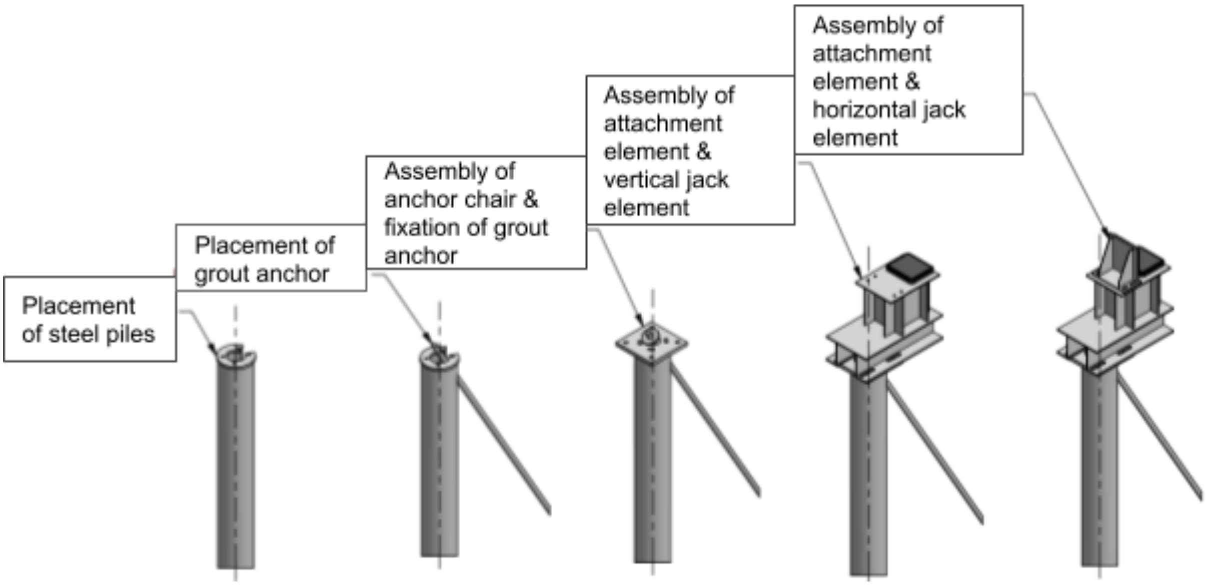


Figure 11: The execution steps of Fundovatie system (Iv-Infra, personal communication, 2023)

4.4.3 Structural strength

The lifespan extension measure is designed to reinforce and relieve the foundation exerted in both, the horizontal and vertical direction. The tubular piles primarily solve the two failure mechanisms related to the pile deformation and soil settlement, which is limited to the front row of piles. The anchor tends to support the horizontal loads, namely solving the issue related to horizontal displacement. The last execution step in Figure 11 prevents the shearing of the masonry wall. The structural strength to withstand vertical loads amounts to 600 KN. The exact magnitude can fluctuate depending on the local cone penetration test of soil that is conducted for each quay wall location. The test method involves pushing an instrumented cone with tip facing down into the ground at a controlled rate to identify the soil bearing capacity of distinct layers. In areas with troublesome soil, the choice can be made for a different pile profile and a wider foundation footing to increase the bearing capacity. The reduction in the functionality of this solution is mainly a result of crumbling or cracking of brickwork. If this happens, the distribution of loads cannot be transformed through the wall into the front row of piles with a spacing of 2 to 3 m in the Fundovatie method.

4.4.4 Impact on the surroundings and social impact

The installation of the Fundovatie system does not result in soil displacement. The type of pile foundation used is tubular screw pile which is featured with low noise and vibration-free assembly. The pontoon situated on the canal is equipped with cranes and drilling rigs which causes a significant noise disturbance for the inhabitants. However, the execution of the chosen system is quickly completed. All equipment and materials are transported over water to the designated quay wall. This also applies to the realisation of execution activities. This resulted in closing the parking lots on the landside. A space of 3 to 4 m long is sufficient behind the quay. The execution time of Fundovatie takes around 1.5 to 2 months per 10 m length of quay wall. The most critical factor in the planning is the curing of grout anchors. The high curing period of grout anchors is typically relevant in very small stretches of quay walls. Houseboats are not required to be moved elsewhere during the construction process of Fundovatie. The Fundovatie system does not hinder the mooring of ships through the canal as no change is encountered to the waterway cross-profile dimensions. The necessary working height is limited for the operation of drilling rigs, which makes it possible to preserve trees, but, in exceptional conditions, the pruning of tree branches is required. The underground utilities are not shifted elsewhere, as the pile system can be flexibly orientated to another location. Special attention must be paid to any dredging works in the vicinity of the Fundovatie system. Concrete block mats are laid down around the Fundovatie system as a safety buffer to avoid damage when dredging is planned.

4.4.5 Environmental and economic impact

In rare cases, the water quality can be subjected to minor pollution as a result of grout leakage after injecting the soil layer with grout to assemble the anchors. According to the interviewee, sand backfill is not observed to add a particular value in this solution to minimise the pollution.

The Fundovatie is designed for a lifespan of 50 years. In principle, the lifespan of Fundovatie highly depends on the degradation rate and remaining lifespan of quay walls. For instance, if the brickwork topples or cracks, then the lifespan is reduced to a greater extent. The lifespan of the quay wall should be extended for at least 20 years. The total cost of this lifespan extension measure is €10,000 per running metre. No maintenance is needed to be performed for the Fundovatie technique. The periodic inspection is necessary to measure the development in wall displacement and track the integration of Fundovatie solution with the existing quay. The removal of the pile system for reuse purposes after the end of lifespan is currently not possible. At a later stage, research will be conducted to discover other circularity options for retaining the pile system. Nonetheless, the anchor and connection element at the pile head can be disassembled by a diver to be reused for a new Fundovatie application.

The largest uncertainty is the circularity aspect of recovering the pile component after the end of lifetime is a critical point to consider. Additionally, the perceived variations in the condition of quay walls at distinct locations since the effectiveness of this method depends on the strength of brickwork. The deterioration of brickwork has an influence on the structural decision regarding the distance between piles. A lower masonry strength results in a shorter spacing between piles. This leads to the installation of more piles and higher investment costs to reinforce the quay wall. The lifespan extension measure might no longer be efficient to apply if the pile spacing is less than 1 m.

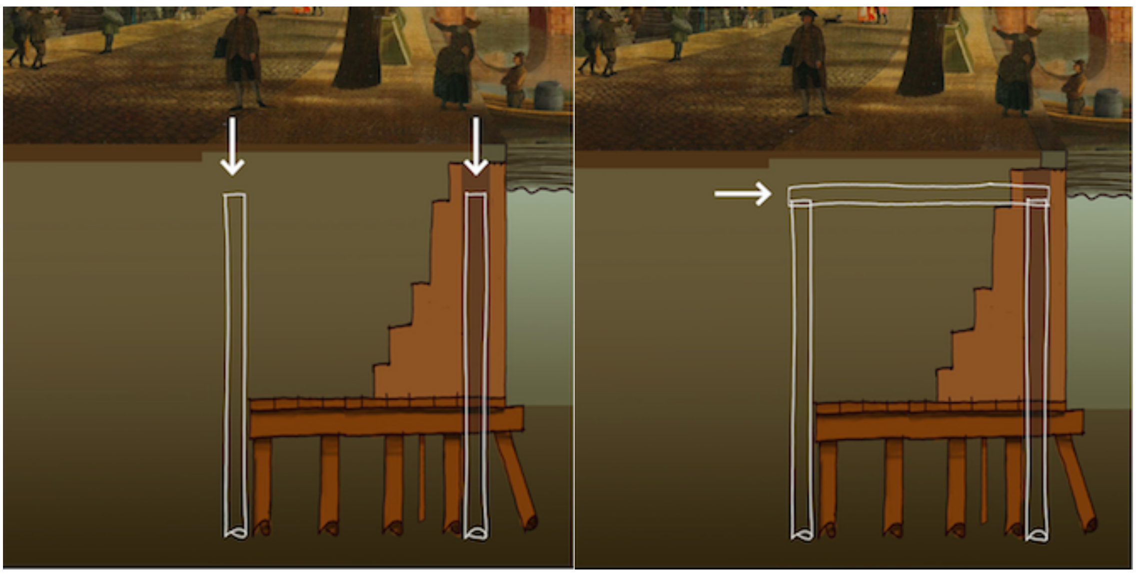
4.5 Modular quay wall

4.5.1 Introduction

The modular quay wall is designed by Wagemaker as an integral concept to provide structural reinforcement to the existing quay. The modular method consists of four new building components, namely, the tubular screw piles, coupling beams, floor elements, and soil retaining screen. The modular construction completely takes over all types of loads exerted on the main structural elements of the current quay walls. In other words, the functionality of the old quay is replaced by the new construction with minimal impact to the surrounding area.

4.5.2 Execution procedures

Firstly, the excavation of 1 m depth takes place behind the quay wall to install the steel piles. The front row of piles are drilled through the masonry wall and screwed into the soil layer between the existing wooden piles. The rear row of piles are assembled behind the current relieving floor. Secondly, a coupling beam is inserted in a perpendicular direction to the quay to connect two piles together. The connection between both the beam and piles is hinged. The front and rear row of piles are coupled by welding a rounded tube on each pile. The optimal spacing between the front and rear piles amounts to 2 m. Thirdly, the soil retaining screen made of steel plates is pushed behind the rear pile row to approximately 6 m below the ground level. Fourthly, the floor element made of prefabricated concrete plate is established above the coupled beam. The terrain is cleared up and repavement of the road is done after construction activities are finished. Figure 12 shows the complete described steps of this modular solution.



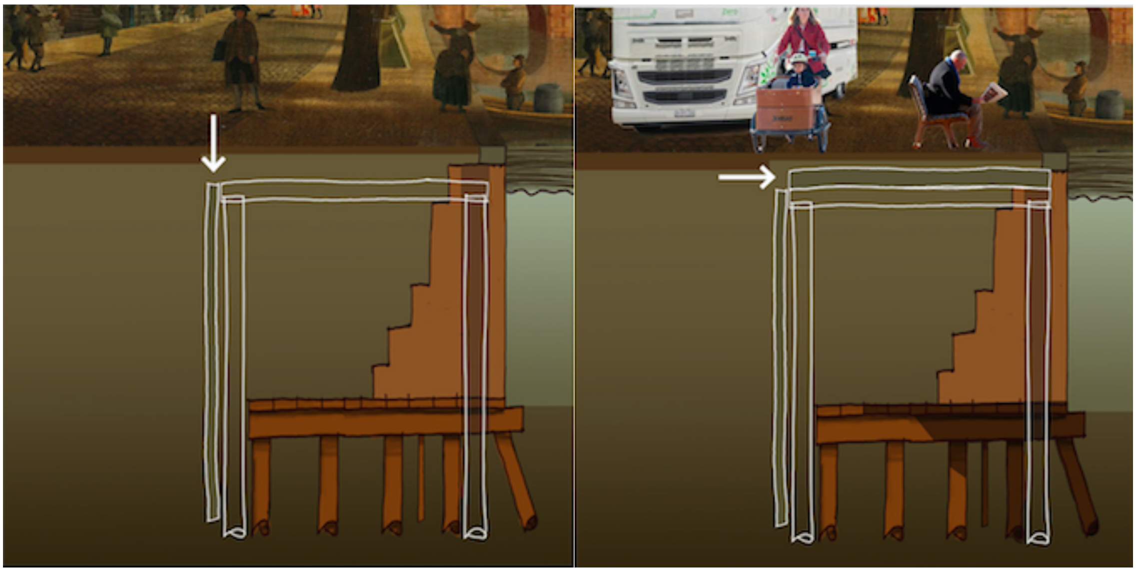


Figure 12: Visualisation of the execution steps (Wagemaker, personal communication, 2023)

4.5.3 Structural strength

All failure mechanisms are perceived to be resolved by adapting the modular design on quay walls. This includes failure related to the foundation, wall, and geotechnical soil. The front wall is the only part from the existing quay construction that is included in the new design concept. In the old situation, the horizontal force is applied to the masonry walls and carried by the substrate through the wooden pile foundation. In the new case, the floor element is considered an essential building part to eliminate the direct loads of the parking lot on the deteriorated masonry wall by transferring the forces into the new construction. Similarly, the soil retaining screen reduces the top loads sourced from the carriageway to the masonry wall. Therefore, only the remaining horizontal soil load and the self-weight of the masonry wall is transferred by the wall to the front row piles. The idea of installing the soil retaining screen behind the rear pile row instead of on the front of the wall is beneficial in terms of space utilisation. The space between the current wall and retaining screen can be facilitated for underground garbage containers or bicycle parking racks. From the future perspective, the dismantling of the old quay is an option which can be easily performed as the spatial area is secured by the soil retaining screen.

4.5.4 Impact on the surroundings and social impact

The type of pile foundation used is tubular screw pile which is featured with low noise and vibration-free assembly. Screwing piles appears to be the most suitable method to assemble piles as other contractors proposed as well. The design concept of the lifespan extension measure indicates that small equipment will be used as much as possible for segmented assembly of piles and to avoid traffic hindrance. Lightweight equipment can be, in particular cases, necessary to meet the municipal requirement of a workload of 2.5 KN/m^2 on the infrastructure. The modular construction can be flexibly executed via the waterways or landside, depending on the situation. The landside is the most preferred way to implement the new modular quay wall in case of nearby houseboats or lightweight equipment. If no restrictions apply, the most favourable scenario is to initially work from the waterway until the piles and floor elements are laid down. After this phase, heavier equipment can be placed on the new floor element to continue with other sections of the quay walls in the same sequence. The floor elements can be easily designed to withstand a load greater than 2.5 KN/m^2. The material transportation is determined to take place via waterways and be stored on the pontoon. The impact of executing activities from waterways is that parking lots will be closed off. A space of 5 m behind the quay is considered sufficient for the mobilisation of drilling rigs. Less space might be required if the modular quay wall is completely executed from the waterways. The execution activity from the waterways is recommended in situations where narrow quay walls are present to avoid blocking the carriageway. The expected execution duration is one week per 10 m of section area. The most critical phase in the construction process is the drilling of masonry wall in combination with the installation of piles.

During execution, there are certain restrictions for the trees and underground utilities, where alternative solutions need to be adapted to prevent the damages of both objects. The intersection of floor elements with the tree roots can form a barrier while no complementary measures are taken. The options that are proposed depend on the available space around the trees for each quay wall location. The measure includes the application of a horizontal frame instead of the rigid floor element. The other possibility is making a recessed floor element to cover the tree roots. Further, it is uncertain whether the soil retaining screen can be assembled without harming the tree roots. The first solution is to place the soil retaining screen in the front side of the wall directly into the canal. The technical slope is arranged in a way it does not hinder the sailing boats during execution nor disrupt the waterway cross-profile dimensions. The second possibility is to exclude the soil retaining screen from the modular design and incorporate other innovative measures such as the Buoycrete to resolve failure mechanisms related to soil leaching.

A similar issue is confronted with the underground utilities in terms of intersections. In particular situations, the cables and pipelines are laid down with an interface that falls within the dimensions of pile spacing. There are several possible options to avoid clashes of both objects. The relocation of cables and pipelines to be placed behind the installed soil retaining screen is a suitable idea. This is the most optimal action, since future maintenance activities of underground utilities can easily be conducted without temporarily removing any new elements of the modular construction. The second option is to assemble the floor at a deeper level while the underground utilities are established in the overlying soil layer. The third option is to significantly raise the floor element to the ground level and not interfere with the current location of cables and pipelines. The last option requires the temporary removal of the floor element during maintenance operation.

4.5.5 Environmental and economic impact

The total cost of the lifespan extension measure is between €15,000 and €20,000 per running metre. The lifespan of the modular construction is determined to be 100 years. The lifespan of the existing masonry wall can be extended for 30 years after renovation is completed. There are no maintenance activities required for the new elements of the modular quay wall. However, the steel piles will most likely corrode in the course of time; regardless, it is incorporated in the structural calculation by choosing a larger pile diameter to increase the strength and avoid intervention during the lifespan. Still, the masonry wall should be renovated before the drilling of the front pile row takes place. For instance, damages in the brickwork such as cracks must be repaired to guarantee the cohesion of the masonry wall. After execution is finished, periodic inspections are scheduled to monitor the exact condition of the brickwork. The solution has a demountable system to easily retain the materials used after the end of lifetime. The steel piles can be screwed out and withdrawn from the soil layer. It is expected that a part of a cross-section in a steel pile will be subjected to degradation, which reduces the probability of reusing the element in another modular construction. Nevertheless, the recovery and recycle process of the material is possible to be used for a new purpose if the functionality and strength capacity is lacking. The concrete element can be directly reused as well. The greatest uncertainty is dealing with a modular construction that functions independently of the masonry wall, while taking into account that the old quay wall will be completely demolished after 30 years of renovation. The requirements of the municipality, namely the horizontal deformation, must remain in force also with the absence of interaction with the old quay wall.

4.6 Lightweight concrete

4.6.1 Introduction

The light-weight concrete solution is known as Buoycrete in Dutch. Buoycrete is a reinvented concrete carried out by Boskalis and tested in their own facilitated hydrolab to define its strength capabilities of the material. Buoycrete is a non-dissolvable concrete mixture that is applied between the row of existing wooden piles to stabilise the foundation and prevent soil from leaching in quay walls. The mixture is composed of a cement-bound material with a substituted aggregate. The aggregate substitutes the necessity for sand and gravel and produces a lighter concrete mixture of equivalent density to water (1000 kg/m^3). This makes the mixture featured with a neutral buoyancy in water, which will not sink or rise. Neutral buoyancy allows any object submerged in water to be stabilised by balancing the downward gravitational force with the upward buoyant force. The buoycrete mixture is flexibly produced in shape and does not require drainage. The execution allows for quick reparation and does not add extra weight on the quay walls by mobilising heavy equipment. The use of traditional hard formwork during maintenance is also not required. The mixture is invented for its good adhesion and superior rigidity to reinforce the quay walls for a long lifespan.

4.6.2 Execution procedures

Firstly, a pontoon gets loaded with containers and diving equipment to start preparation. A diver, with a pressurised water jet cleaning nozzle, goes underwater to remove local sand and garbage nearby the pile foundation. After levelling up the soil, the diver inspects by means of a sensor device the required volume of buoycrete that needs to be filled between the piles. Afterwards, a hopper is brought and loaded on a pontoon that carries the dry mortar, two silos, and buoycrete mixture with a pump system. The hopper is a container with the capability of discharging the buoycrete mixture at the bottom to be established between the piles. Subsequently, the diver distributes the quantity of buoycrete mixture across the quay wall. The procedure of mixing and pumping the buoycrete is the same as the traditional concrete. Figure 13 shows the placement of buoycrete between the pile foundation.

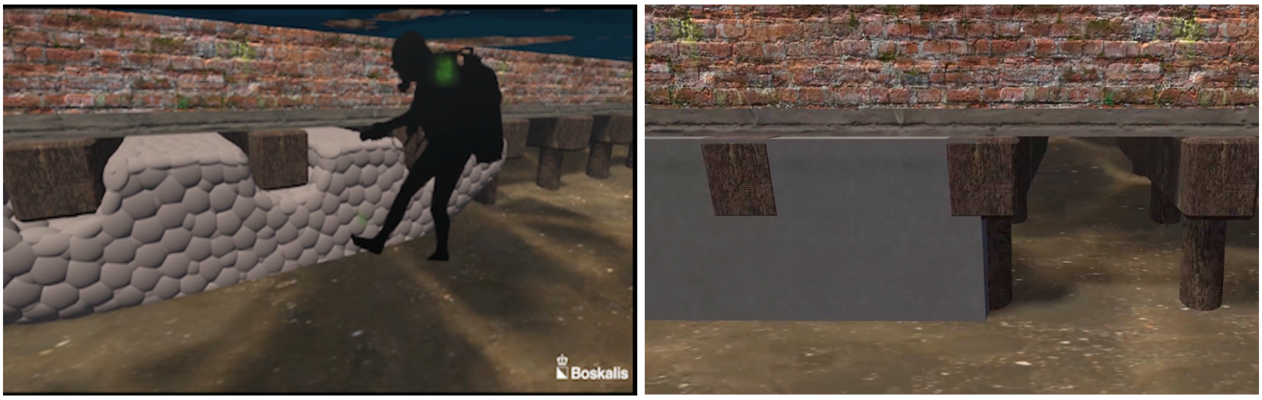


Figure 13: Buoycrete before and after it cures (Royal Boskalis, 2022)

4.6.3 Structural strength

The four failure mechanisms that are directly avoided by buoycrete are the deformation of piles, collapse of soil retaining screen, and collapse of floor and capping beam. The buoycrete contributes in an indirect way to reducing forces causing the horizontal displacement, shearing of masonry wall, and tilting of masonry wall. According to the latest calculation of a case study, the safety factor related to shearing of masonry walls is increased from 1.11 to 1.26 when a top load of 10 KN/m^2 is applied. Buoycrete is mainly awarded by the municipality of Amsterdam to solve the issue related to soil leaching. The formwork protrudes at least 0.5 m into the soil, which forms a new soil retaining screen. Buoycrete also resolves the collapse of foundation elements in quay walls by redistributing the horizontal and vertical loads on the piles. The rotting of wooden materials is also stopped by buoycrete. Due to neutral buoyancy, the buoycrete does not exert additional weight on the piles when immersed in water. The collapse of the floor and capping beam is prevented by filling the hollow space between the pile head with buoycrete in combination with the soil retaining screen. The combination ensures that soil will be stabilised. The uniaxial compressive strength (UCS) of buoycrete is greater than 35 MPa. The tensile strength is greater than 2 MPa as tested in the laboratory.

4.6.4 Impact on the surroundings and social impact

The impact of buoycrete is set at a minimal level, as heavy equipment is not present. The concrete mixer is not expected to produce noise disturbance for the inhabitant. The working activities will take place from the waterways as much as possible. The execution duration of buoycrete is two days per 10 m of section area, excluding the preparation activities. The assembly and preparation activities could be done simultaneously when a large stretch of quay wall needs to be repaired with buoycrete. In case of a small stretch, the filling of buoycrete proceeds after the preparation phase is done. A space of 3 m behind the quay is required where the parking lots are closed off. It is important to relieve the quay walls during execution for the diver's safety. The waterway is to a minor extent narrowed with the presence of pontoons. The logistic process of delivering materials to the location will also be transported through the waterways. All equipment is electrically operated, including the pontoon, where air pollution is eliminated. Houseboats should be temporarily moved elsewhere until the execution works are finished; this is necessary mainly for the inspection, cleaning, and soil levelling to take place in front of the quay wall. The process of mixing the buoycrete is done from the pontoon, while the mixture is cohesive and non-separable when pumped underwater. Thus, there is no impact on the soil and water quality. It is expected that litter under the capping beam needs to be cleaned. Additionally, buoycrete ensures that trees will not be chopped as the lifespan extension measures does not interfere with the soil above the capping beam. The same applies for cables and pipelines, it will not be displaced or damaged during the implementation phase.

4.6.5 Environmental and economic impact

The total cost of the lifespan extension measure is between €7,500 and €8,500 per running metre, which is equivalent to the sheet pile. The lifespan of the quay wall can be extended to a minimum duration of 30 years, based on the assumption that wooden piles have a remaining lifetime of 30 years as well. The lifespan extension of the complete system depends on the conditions of other relevant components in the quay wall. The masonry wall should be maintained before the buoycrete is poured between the piles. The buoycrete method is not suitable to apply if the masonry walls are extremely deteriorated and cannot be renovated. The durability aspect of buoycrete is not entirely predicted, as a follow-up ‘schiedam method’ will be applied afterwards by Boskalis to extend the lifespan for another 70 years. According to the interviewee, an expert has calculated the environmental impact, which pointed out that it is lower than the sheet pile due to the exclusion of steel material and the use of recycled materials to produce buoycrete. There is no maintenance and inspection required for buoycrete. However, the inspection regarding the state of the masonry wall needs to be frequently conducted. There are several underwater inspections available that show the consequence of soil leaching. Most visuals indicate that leaching occurs through the entire length and not at specific local spots along the quay wall. Leaching mainly occurs due to the effect of dredging by means of boat propellers on the soil where maintenance is not performed for a long period. The effectiveness of buoycrete significantly increases when the first and second row of piles are connected in a longitudinal and cross direction. Most loads are exerted on the first and second row of piles as the weight of masonry wall is positioned above them, where buoycrete has the capacity to redistribute the loads. The largest uncertainty lies specifically in the conditions of pile foundation at distinct quay wall locations.

4.7 Anchors with internal concrete wall

4.7.1 Introduction

The anchors with internal concrete wall solution is developed by consultancy firm Tauw. The firm has developed many possible design variants for selection depending on the maximum loads, quality of masonry wall, intensity of road and shipping traffic, and available space per situation. The extended principle will only be taken into account in this description as it fulfils the minimum years of lifespan set by the municipality of Amsterdam. This consists of components such as steel tubular piles, grout anchors, and reinforced concrete wall. The concrete block ensures extra strength to withstand the top load on the quay wall. The method can be technically realised in concrete L-wall construction type of the 1950s, besides the historic gravity walls. This solution has been successfully applied and proven its effectiveness for deteriorated quay walls and bridges located over 5 cities. It is predicted that this solution is feasible to apply for at least 20% of the inner-city quay wall in Amsterdam.

4.7.2 Execution procedures

Firstly, vertical drilling of holes in masonry walls to install the new tubular piles at the depth of the soil bearing layer. Unlike other solutions, the steel piles are driven instead of screwed into the soil layer. The hollow space between the masonry wall and steel piles is filled with mortar. The tubular piles take over the bearing capacity of wooden piles. Secondly, the installation of grout anchors takes place from the waterways to be drilled diagonally downwards into the sand layer underneath each tubular pile. The horizontal loads imposed on the quay walls are relieved once the tubular pile is connected with the grout anchor. Thirdly, the reinforced concrete wall is placed by excavating behind the quay wall. The cables and pipelines are moved while trees are protected by applying preventive measures. Chemical anchors are glued over the entire height of the masonry wall to bond reinforcement bars. The formwork is inserted, and reinforcement bars are braided around the anchors to allow for concrete pouring. After the concrete cures, the formwork is removed, and the quay wall is filled back with soil. The fourth step is the reparation of brickwork and mortar joints in the quay wall where necessary. A hydraulic lime mortar is used as much as possible for the joints to provide a suitable substrate for the existing flora and fauna. Figure 14 shows the design principle of Tauw.

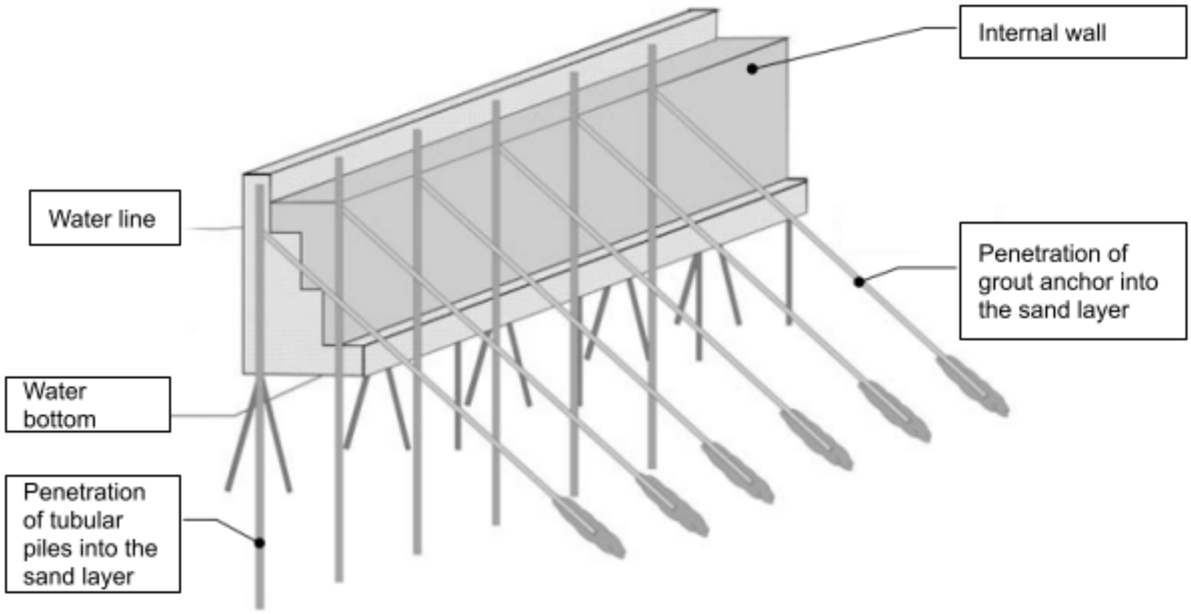


Figure 14: Tauw design principle (Tauw, personal communication, 2023)

4.7.3 Structural strength

The tubular piles aim to withstand the vertical forces, while the anchors ensure that horizontal forces are transferred to the substrate. The distance between the tubular piles is almost 4 m. All failure mechanisms are prevented by this lifespan extension measure except for the global instability and leaching of soil since the retaining screen is not part of the designed solution. The tubular piles and reinforced concrete wall will function together to avoid the local fracture in brickwork. The combination of this lifespan extension measure with complementary solutions such as sheet pile or buoycrete results in resolving the soil leaching. In most situations, Tauw did not experience any bad conditions in the retaining screen. However, in Amsterdam it is most likely necessary to replace the screen. The conditions of wooden floor and sheet piles at the back side can be verified during the pouring phase of concrete. There are some bottlenecks for the application of concrete walls. The concrete wall behind the quay wall should be substituted by steel beams in cases where monumental trees must be retained. In the past, an agreement was reached in one of the projects, with the municipality of Deventer, to apply steel beams to retain the monumental lime trees. Though, this reduces the overloading capacity of the quay wall. The municipality of Amsterdam expects from participant firms to take into account a top load of 20 tons. The steel beams were never calculated in past projects on such overloading capacity, which is not expected to be a realistic approach for such huge loads. The presence of cracks in the brickwork creates a restriction to the application of this lifespan extension measure. The bond between the masonry and wooden floor should be sufficient in order to safely pour the reinforced concrete wall. In the past, the wooden floor collapsed during the concrete pouring due to weak binding rigidity. This caused soil to leach through the floor cavities, with months of delays to finish the remaining execution activities.

4.7.4 Impact on the surroundings and social impact

A limited noise disturbance is expected during the construction process. All building materials are transported via the waterway to the quay wall, including the excavated soil to the processing location. The execution of the lifespan extension measure mainly takes place from the waterways. The assembly of steel piles can be done via the waterways and landside. A small crane drilling machine is settled on a connectable pontoon to install the steel piles from the waterways, which is the most preferred option. The grout anchors are assembled using an anchor drilling rig placed on the pontoon. The pouring of concrete in the formwork should be implemented from the landside. This step occupies a width of 5 m from the edge of the quay wall, which will partially block the carriageway. It is also necessary to move the cables and pipelines behind the quay wall before pouring the concrete. There is no interference in cables and pipelines situated in front of the quay wall. There are restrictions in trees during the installation of steel piles. Shorter steel piles are driven in areas where the distance between trees is small. As mentioned before, the concrete wall results in the removal of trees. Steel beams are used as purlins instead of concrete walls to connect the grout anchors and tubular piles while maintaining the surrounding trees.

4.7.5 Environmental and economic impact

During the reparation of the brickwork, the flora and fauna is protected by using a watertight steel platform on the canal to lift the mason, besides the use of hydraulic lime mortar as jointing. The glass ampoules filled with chemical substances are placed by drilling a hole behind the quay wall to glue the anchors. The chemical substance gets accumulated within the hole after the glass breaks down to start the process, where leakage is prevented into the canal. Additionally, the hollow space between the steel piles and wooden floor is sealed when grout is filled above to prevent leakage into the soil.

The total cost of this lifespan extension measure is €5,400 per running metre. The lifespan of the existing quay wall can be extended to a minimum 30 years. The lifespan of the measure can be designed for almost 70 years. The measure does not require certain maintenance nor inspection after being realised at location. Still, the corrosion of steel should be taken into account towards the intended lifespan extension by designing an excess thickness in steel piles to maintain the bearing capacity. All components can be removed and reused after their end of lifespan, except for the grout anchors. In this design, the concrete wall serves as an internal quay wall to connect the grout anchors and steel piles into an entire monolithic construction. The internal quay wall creates a vertical arcing effect within the steel piles to avoid the collapse of the quay wall towards the canal and to absorb the bearing capacity of traffic load.

5. The decision-making framework for quay walls

Following up the interviews, chapter 5 is devoted to illustrate the decision-making framework for quay walls. The decision-making framework is divided into steps that need to be followed to reach a suitable intervention decision. Steps 1 to 3 will present the assessment related to the selection between a predictive maintenance, lifespan extension measure, and renewal in the framework. Steps 4 to 7 will be continued in case the preference goes to the selection of a single or combined lifespan extension measures rather than a renewal option for the deteriorated quay walls. The decision-making framework can be visualised in Appendix E and F. Appendix E covers close-ended questions starting from step 1 until step 4. Appendix F is adhered with a more contextual overview of the different types of impact of the application of lifespan extension measures, which were discussed in the previous chapter.

5.1 Justification of the order of steps in the decision-making framework

The decision-making framework consists of seven steps in the following order: structural capacity, safety risk matrix, economic assessment, technical feasibility, impact on the surroundings and social impact, environmental sustainability, and concluding remarks. The reason behind the suggested order can be justified as follows:

- Firstly, the safety aspect is considered an important criterion for the structural capacity and risk matrix. Besides the renewal option, different lifespan extension measures fulfil different expectations regarding the solved failure mechanism. The inherited failure mechanisms differ for each quay wall situation. It would be pointless to conduct an economic assessment of all available lifespan extension measures before actually filtering and selecting the potential measures that contribute to stabilising the quay wall and improving the safety aspect.

- Secondly, the technical feasibility of step 4 can only be discussed once the decision goes to the lifespan extension measures. The traditional renewal option can be applied in all scenarios of quay walls, regardless of the severity of quay wall components. Additionally, a renewal is a single-applied option and independent of complementary measures. This means there is no overlap of planning activities between two measures, as could be present in lifespan extension measures. Hence, this criterion is relevant at a later stage of the framework. The technical feasibility is a crucial step to undertake, as the decision could encounter a turning point to consider once again a renewal option. The renewal option can be finally considered in case all potential lifespan extension measures lack technical feasibility, which does not adequately fulfil the questions in the framework.

- Thirdly, the impact on the surroundings and social impact is perceived to weigh higher than environmental sustainability. Moreover, the environmental sustainability weighs higher than the economic aspect (concluding remarks). This information was retrieved during the interview with the municipality of Amsterdam. However, the exact percentages of the weighting factor are unknown at this stage.

5.2 Description of steps in the decision-making framework

Step 1 Structural capacity: The rehabilitation measure cannot be accepted if it does not meet the current and future traffic load within the designated lifetime. Firstly, Appendix C corresponding to the previous chapter will be checked to select the available potential measures to solve the failure mechanisms. If none of the lifespan extension measures are available for the existing failure mechanisms, then a renewal will directly take place. Secondly, two aspects should be known, the maximum achievable structural capacity of the lifespan extension measure besides the required reduction of horizontal and vertical forces for each quay wall situation. If one of the two aspects are unknown, then a safety risk matrix needs to be conducted to evaluate the quay wall conditions. Hence, step 2 should be worked out. An economic assessment is carried out in case both aspects are known and the fact that the structural capacity of lifespan extension measures meets the required reduction of forces. Therefore, a safety risk matrix is not required where step 2 can be neglected.

Step 2 Conduct a safety risk matrix (if needed): A safety risk assessment could be carried out in situations where data related to the structural capacity is missing. Thus, the safety matrix is an alternative technique to analyse the given monitoring data about the condition of quay walls, which paves the way to conclude whether the most suitable strategy to apply is lifespan extension measure or renewal. The risk matrix will evaluate whether the lifespan extension measure can reduce the risk in the quay wall based on the classified colour in the matrix (red, yellow, and green). This is done by evaluating the risk of failure based on two criteria (Raydugin, 2012):

1- Likelihood: The level of probability that the failure will occur.

2- Impact: The severity level of the failure on people, assets, and environment.

The collection of the likelihood-impact information leads to the prediction of the outcome in the risk matrix. The average result of failure severity and probability level of failure in the masonry wall, foundation, and soil retaining screen of the quay wall will guide through drawing up a conclusion. The conclusion states whether the quay wall falls under the green, yellow, or red category of safety indicator. Table 2 illustrates an example of a safety risk matrix, where the likelihood and impact score of each aspect is multiplied. The green box implies that predictive maintenance is a suitable option. The yellow box expresses the option of applying either a lifespan extension measure or a renewal, depending on the results of economic assessment for both interventions. The red box represents the necessity to implement a renewal for the quay wall.

Table 2: Example of a risk matrix (Raydugin, 2012)

IMPACT ON PROJECT OBJECTIVES							PROBABILITY				
	Cost, $M	Schedule, Mos	Product Quality	Safety	Environm.	Reputation	< 0.1% Very Low (1)	0.1% - 10% Low (2)	10% - 50% Medium (3)	50% - 90% High (4)	>90% Very High (5)
Very High (5)	>50	>6	System requirements are not achieved	Single or multiple fatalities	Massive Effect	International media coverage. Irreparable stakeholder impact	5	10	15	20	25
High (4)	20 -- 50	3 -- 6	Substantial effect on performance objectives	Serious personal injury resulting in permanent disability	Major Effect	National media coverage. Substantial stakeholder impact	4	8	12	16	20
Medium (3)	5 -- 20	1 -- 3	All design and operating margins eliminated	Injury to personnel not resulting in permanent disability	Localized Effect	Regional media coverage. Moderate stakeholder impact	3	6	9	12	15
Low (2)	0.5 -- 5	0.5 - 1	Minor decrease in system performance	Medical treatment of personnel. Lost time incident	Minor Effect	Local media attention. Minor stakeholder impact	2	4	6	8	10
Very Low (1)	< 0.5	< 0.5	Slight degradation of element performance	Minor impact on personnel. First aid only. No lost time	Slight Effect	Slight media attention. Little stakeholder impact	1	2	3	4	5

Step 3 Perform an economic assessment: An economic assessment is calculated to compare the costs between the specific lifespan extension measures and renewal option. The economic assessment is usually calculated by multiplying the initial realisation cost per running metre of the lifespan extension measure or renewal with the length of deteriorated quay wall stretch. Afterwards, the total costs are divided by the years of lifetime extension of the entire quay wall. It is important to note that the entire quay wall is typically extended for a lifespan of 100 years, with an average cost of €30,000 per running metre when a renewal option is applied. The actual realisation costs and lifetime extension years for each lifespan extension measure is already indicated in the previous chapter. The aim of step 3 is to apply a renewal strategy if it leads to a less financial burden than implementing a lifespan extension measure.

In case the result of the framework yields to apply the lifespan extension measures, the input in Appendix D should be retrieved to assess the upcoming steps. The steps in the framework are stated underneath as follows:

Step 4 Technical feasibility: A particular solution could include a single or multiple lifespan extension measures. In case of multiple lifespan extension measures, the execution activities should be checked against any overlap set by one measure on the other. The requirement of excavation behind the quay wall and drilling of masonry wall is a crucial indicator to assess the technical feasibility. In the framework, special attention is paid to the critical conditions of the current quay wall components. Suppose a scenario study indicates a critical condition in brickwork, then a selected lifespan extension measure whose workability depends on the masonry wall can not be applied. An exemption could be made for combined lifespan extension measures if at least the workability of one of the measures does not depend on the masonry wall. Finally, the space between the edge of the quay wall and residential houses is an important factor to consider. A renewal option should be applied in events where all gathered lifespan extension measures are observed to impose a technical constraint on its applicability.

Step 5 Impact on the surroundings and social impact: Firstly, the impact of execution activities on the surrounding object is addressed. The surrounding object could include the interface between the components of lifespan extension measure, trees, and cables and pipelines. Additionally, the trees and pipelines can also be damaged when the equipment is mobilised nearby them on the landside. Special attention is taken into account regarding the height and dimensions of machinery. The weight of the machinery can impose a restriction on placing it on the landside due to load limitations set by the municipality. Furthermore, the logistical process of transporting materials to the quay wall should be assessed for each lifespan extension measure. The choice of utilising the waterways and landside is interpreted in order to analyse the impact of execution activities on the surrounding objects. The place of execution for particular lifespan extension measures can be affected due to the high season and the availability of houseboats near the quay wall. The high season can be an indicator that the waterway is crowded with tour boats, which does not allow the placement of pontoons and temporary narrowing of cross-profile of waterways. The movement of houseboats can also be considered a huge operation, as it consumes significant time when working from waterways.

Secondly, the execution activities can lead to a social impact. The execution activities on the landside may cause a high traffic congestion to vehicle users by blocking roads, diverting routes, and applying speed limits. The execution can partially or completely block the road behind the quay walls. The partial congestion includes closing the parking lots to the vehicle users. The complete congestion can include closing the parking lots, carriage way, and sidewalk. Moreover, the execution time of lifespan extension measures per 10 m quay wall length is indicated to reveal the degree of hindrance on the society. The execution activities can cause significant noise disturbance due to different methods of assembly encountered by the lifespan extension measure. For instance, the installation of steel piles can be implemented by either driving, pushing, or drilling into the subsoil.

Step 6 Environmental sustainability: Step 6 depicts the environmental impact of the lifespan extension measure. The focus lies on the type of produced materials and the recycling opportunity of materials and components after the end of lifespan. The utilisation of new virgin materials to produce the components of lifespan extension measure is described in the ‘environmental pollution’. A linear waste or circular processing of materials and components after the end of lifespan is indicated in the ‘circularity part’. The circularity aspect is based on the future speculations on the reuse or recycling opportunities after the application of a specific lifespan extension measure in the quay wall.

Environmental pollution: The construction industry contributes to the sector with the most waste stream of materials, with around 2 billion tonnes worldwide on an annual basis and 25% of the total waste production (El-Haggar, 2007). In practice, the environmental impact of manufacturing different materials to realise the lifespan extension measure can be expressed in direct values related to global warming potential, acidification, and CO_2 footprint. Many environmental indicators can be accumulated to release a so-called environmental life cycle assessment. By knowing the dimensions and lifespan of materials, typical parameters of environmental impact of material types could be gained and compared from literature sources. For instance, the global warming potential of concrete and brick is 156 kg/m^3 and 342 kg/m^3, respectively. This means bricks have twice the impact on this factor. Aluminium contains the highest carbon footprint with 18000 kg/m^3. The embodied energy is an important indicator to the environmental aspect, which is expressed in MJ/kg (Van Dam & Van Den Oever, 2012). The quantitative data is not generated for each lifespan extension measures since this research is rather qualitative. A rough analysis will be made based on the type of inherited materials and the percentage of raw and recycled materials that composes the innovative solution.

<u>Circularity principles:</u> an evolving concept developed in recent decades to enable construction materials and components to be restored and regenerated after their lifecycle period. This process prevents components from losing their incremental value and hence being disposed of into landfills. As demand trends of resources are rising, action has been undertaken to make sufficient use of labour input, energy consumption, and scarcity of materials. Currently, there is no specific measurement to accurately evaluate whether a particular lifespan extension measure yields an acceptable level of circularity. The most common criteria of determining the circularity index of lifespan extension measures are to examine the processing chain loop of materials after the end of desired lifespan. In order to achieve the goals of a circular economy, several design principles are proposed according to VandenBroucke (2016):

- Design for disassembly of components: The main idea is to use reversible connections that allow reusing of components after the end of lifecycle time, while preventing welding and gluing as part of the construction system. The best reversible connections applicable are bolts, screws, and magnets.

- Design for adaptability and flexibility: The modularity of the designed solution increases when the components are manageable to be dismantled. The process speeds up as the workforce can easily reach most locations by using standardised tools. A higher pace in manageability will be achieved by limiting the number of connections, as less time is needed to switch between tools and the assembly process. Moreover, small-sized elements give a high degree of architectural freedom for flexible design. The use of dry connections like screws is more preferable than mortar to speed up the process of manageability.

- Design for durability: This aspect reflects on the longevity of components. Durable elements tend to be reused and transported to other sites without being damaged. Materials with higher environmental and financial impacts require a higher demand to reuse the component than low impact materials. The amount of retained and reused materials with respect to waste materials is an indicator of level of circularity. An example of a durable component is bricks.

Step 7 Concluding remarks: In this step, the cheapest lifespan extension measure among different options is indicated. The costs are already calculated in step 3, which will be referred to give a short remark.

6. Scenarios

In this chapter, three fictive scenarios are established to show the application of the framework and its possible outcomes. The selection of the three scenarios is justified to cover all loops in the decision-making framework to build a complete picture of its applicability. Moreover, the scenarios are highly realistic according to my analysis of distinct interviews. For instance, the frequency of statements reported from interviewees regarding the criticality of masonry walls is a leading point to include it in the scenario. In other words, the uncertainties are taken into account as much as possible. Moreover, the municipality of Amsterdam has reported typical combinations of the occurrence of different types of failure mechanisms in a quay wall situation. Each scenario contains sufficient data which is related to the detected failure mechanism, remaining lifespan of quay wall components, the critical conditions of brickwork and pile foundation, the availability of houseboats, and technical dimensions. The technical dimensions are useful to identify any constraints in the vicinity of the quay wall. Relevant information for each scenario is underlined in Table 3.

Table 3: Failure mechanism and local context of quay wall

	Scenario 1	Scenario 2	Scenario 3
Length of quay wall	100 m	120 m	90 m
The detected type of failure mechanisms	Shearing of masonry wall and soil settlement	Tilting of masonry wall, damage in the capping beam, and deformation of pile foundation	Exceedance of global stability
Remaining lifespan of foundation, masonry wall, and soil retaining screen	30 years for all components	50 years for all components	5 years for all components
Is the brickwork in critical condition?	No	Yes	Yes
Is the pile foundation in critical condition?	No	No	Yes
Are houseboats available?	Yes	Yes	No
What is the distance between the edge of the quay wall and residential houses?	4 m	6.5 m	5.5 m

What is the distance between the monumental trees?	10 m	10 m	10 m
What is the depth of the cables and pipelines?	0.8 below ground level	0.8 m below ground level	0.8 m below ground level

6.1 Scenario 1

The available options to can address the failure mechanisms related to shearing of masonry walls and soil settlement in quay wall include four solutions (See Appendix C):

Option 1: Fundovatie method

Option 2: Modular quay wall

Option 3: Tauw measure

Option 4: Renewal of quay wall

Step 1 Structural capacity: The structural strength of the Fundovatie, Modular quay wall, and Tauw measure is retrieved during the interview. It is expected that the three methods could withstand the horizontal shearing forces induced on the masonry walls and vertical soil settlement. According to the interview with the municipality, the safety norm for the sliding of masonry wall and annual settlement rate of piles should remain within 5 mm and 2.5 mm, respectively, to consider the lifespan extension measure an effective option. In this scenario study, the quay wall is inspected with an 8 mm sliding and 5 mm annual settlement rate. The reduction from 8 mm to 5 mm of shearing of masonry wall accounts to 38% decrease in sliding motion. The reduction of 5 mm to 2.5 mm accounts to 50% reduction of annual soil settlement rate. Iv-Infra, Wagemaker, and Tauw firm certainly fulfil the required minimum reduction of vertical and horizontal forces (75%) as stated in Appendix A. Step 2 is not performed since the structural values are already known and proven to be sufficient.

Step 3 Perform an economic assessment: The realisation cost of option 1 and 3 depends highly on the remaining lifespan of the masonry wall.

Option 1: €10,000/m * 100 m= €1,000,000, €1,000,000/30 years= **€33,333/year.**

Option 2: €17,500/m * 100 m= €1,750,000, €1,750,000/100 years= **€17,500/year.**

Option 3: €5,400/m * 100 m= €540,000, €540,000/30 years= **€18,000/year.**

Option 4: €30,000/m * 100 m= €3,000,000, €3,000,000/100 years= **€30,000/year.**

Option 2 is €12,500/year cheaper than option 4. Option 3 is €12,000/year cheaper than option 4. The Modular quay wall and Tauw measure have a lower financial burden than the renewal, thus options 2 and 3 are selected. Hence, step 4 to 7 is proceeded to assess both lifespan extension measures.

Step 4 Technical Feasibility: Scenario 1 of the quay wall does not indicate any critical conditions in the masonry wall and pile foundation. It is worth noting that option 2 and 3 requires drilling through the masonry wall and excavation behind the quay wall. However, option 2 and 3 are both not considered suitable measures for this scenario as they require a 5 m distance behind the quay wall. This technical constraint makes it impossible for the equipment to mobilise in the vicinity of the quay wall. Therefore, option 2 and 3 are not taken into account for further assessment. It is concluded that renewal is the only feasible option to apply in this scenario.

6.2 Scenario 2

The available lifespan extension measures to solve the failure mechanisms in quay wall include four different options:

Option 1: Modular quay wall

Option 2: Bioinspired soil improvement (BISI) and Tauw measure

Option 3: Buoycrete and Bioinspired soil improvement (BISI)

Option 4: Renewal of quay wall

Step 1 Structural capacity: The structural capacity of the lifespan extension measure meets the required reduction of forces. The remaining lifespan of distinct quay wall components indicates the possible application of the lifespan extension measures. Hence, step 3 of the economic assessment will be carried out.

Step 3 Perform an economic assessment: Option 1 does not depend on the remaining lifespan of quay wall components. The designed lifespan of the modular quay wall is taken into account towards the calculation. The cost per running metre takes into account the renovation of the masonry wall after 30 years. Options 2 and 3 depend on the remaining lifespan of quay wall components. The average realisation cost per running metre of both options are summed up in the calculation.

Option 1: €17,500/m * 120 m= €2,100,000, €2,100,000/100 years= **€21,000/year.**

Option 2: (€5,400/m + €8,750/m) * 120 m= €1,698,000, €1,698,000/50 years= **€33,960/year**

Option 3: (€8,000/m + €8,750/m) * 120 m= €2,010,000, €2,010,000/50 years= **€40,200/year.**

Option 4: €30,000/m * 120 m= €4,200,000, €4,200,000/100 years= **€42,000/year.**

Options 1, 2, and 3 appear to have a lower cost than renewal. Therefore, steps 4-7 will determine which of the three options is more suitable to implement in this scenario.

Step 4 Technical feasibility: Option 1 includes a single measure without the interference of execution activities caused by other lifespan extension measures. Option 2 is a combined measure. The Tauw measure is originally developed to fulfil the given failure mechanisms as shown in Appendix C. The combination of Tauw measure with the Biobased soil improvement in this scenario study is necessary due to the critical condition in the brickwork.

The workability of Tauw measure is highly dependent on the brickwork. Thus, the Tauw measure can be technically executed after the implementation of BISI. The application of BISI states beforehand that a complementary solution should not involve execution works behind the quay wall. The Tauw measure requires execution behind the quay wall to install the steel piles. Hence, option 2 is not feasible to apply due to the aforementioned reason. Option 3 is a combined measure. The BISI should be applied before the Buoycrete measure due to two main reasons. Firstly, the divers cannot fill buoycrete between the pile foundation if the brickwork is in bad conditions. Secondly, the simultaneous application of both measures is not possible. The parking lots should be closed for a successful application of buoycrete. Furthermore, the BISI measure is only executed via the landside. Option 3 is feasible with pre-conditions regarding the execution sequence of the measures on the quay wall. A space of 6.5 m is sufficient for options 1 and 3 to be realised. Option 1 and 3 will be further evaluated.

Step 5 Impact on the surroundings and social impact: Houseboats are available in the vicinity of quay walls. This means that execution of modular quay wall will mainly take place via landside to avoid movement of houseboats. The distance between the quay wall and residential houses is sufficient to implement the solution via landside. The duration of execution for the entire stretch of quay wall is 12 weeks. The modular quay wall can be scaled down by removing the soil retaining screen, since soil leaching is not observed. This exclusion of the soil retaining screen reduces the risk of damage to trees. A horizontal frame can be assembled instead of the rigid floor element to cover the tree roots. The head of steel piles is positioned at 1 m below the ground level. The concrete floor is placed above the coupling beam. A 0.2 m gap between the steel piles and cables and pipelines is not sufficient to assemble the concrete floor without clashes. The intersection of the concrete floor with cables and pipelines is likely to occur taking into consideration the thickness of the coupling beam and concrete floor that extend from a 1 m below ground level and upwards. Therefore, the cables and pipelines should be shifted temporarily to assemble the concrete floor. After installation of the concrete floor, the cables and pipelines can be placed on the overlying soil layer.

In option 3, the execution of buoycrete will result in the movement of houseboats for the second phase of the execution (3.5 weeks). The application of buoycrete and BISI will take place via the waterways and landside, respectively. The total execution duration of option 3 is around 7 weeks, equally distributed among both lifespan extension measures. The lifespan extension measures in option 3 does not influence the trees and cables and pipelines. The occupation of a 3 m distance behind the quay wall is significantly lower than the modular quay wall (5 m). The utilisation of heavy equipment to realise the modular quay wall might yield to a slightly higher noise disturbance than option 3. The traffic accessibility and liveability of option 3 scores better than option 1. The disadvantage of choosing option 3 is the impact of the huge operation of relocating the houseboats on the inhabitants. The affected stakeholders of the last statement are limited in comparison to the users on the landside (bike facilities, parking lots, and carriage way). The execution duration of option 3 is lower than option 1 on the landside. Therefore, the impact assessment reveals that option 3 has a lower impact on the surrounding area with respect to option 1.

Step 6 Environmental sustainability: The environmental pollution of option 1 is higher than option 3 due to the use of new virgin materials. Direct expression values such as carbon footprint and embodied energy will score higher in modular quay walls than both lifespan extension measures in option 3 due to the use of concrete and steel elements. In option 3, the material composition of buoycrete is partially made of recycled concrete and substituted aggregates. The BISI measure is composed of a completely sustainable by-product from the food industry.

Regarding the circularity principle, all elements are expected to be reused in option 1 after the end of lifespan, except for minor cross-sectional piles with corrosion defects. There is a reversible and dry connection between the adjacent coupling beam and steel piles, namely a hinged connection. This creates an adaptable and flexible design, as the modular quay wall is a demountable system. Few connections are also present between distinct components in option 1 which promotes the manageability process of dismantling the components after end of lifecycle. The designed lifespan of the modular quay wall (100 years) is equivalent to the functional lifespan extension of the entire quay wall. Therefore, the embedded resources are efficiently processed in the design of the components to achieve the maximum serviceability of quay walls. The circular loop of reusing the components is defined as 'cradle-to-cradle' for option 1 as the incremental value of the components are preserved. The circularity aspect of option 3 after the end of lifespan is unknown. No answers were given on the circularity question during the interview with both representative firms. According to my point of view, the recycling of materials is the most realistic loop for the buoycrete and BISI solution. The reuse of the components in other quay walls is not likely to happen, as the extraction manageability of materials is only possible with damaged leftovers. For example, there are no immediate connectivity tools to access and remove the calcite crystals. Crushing the crystals below ground level is the only possible method to gain accessibility. This indicates that the recycling process has a lower quality grade than reusing principles in the circularity score. Finally, the lifetime extension of the quay wall is lower than the designed lifespan of buoycrete and BISI solution. To conclude, option 1 has a higher circularity performance than option 3.

Step 7 Concluding remarks: Option 1 is €19,200/year cheaper than option 3 as retrieved from the calculations in step 3.

6.3 Scenario 3

The available options to eliminate the failure mechanism in the quay wall include two solutions:

Option 1: Modular quay wall

Option 2: Renewal of quay wall

Step 1 Structural capacity: The exact structural capacity of option 1 to reduce the vertical and horizontal loads related to the exceedance of global stability is unknown. Therefore, step 2 of the safety risk matrix is extensively investigated to analyse the quay wall defects.

Step 2 Safety risk matrix: All elements of the quay wall are observed to lack stability. Those elements include the wooden floor, pile foundation, capping beam, brickwork, mortar jointing, and soil retaining screen. The remaining lifespan of the aforementioned components has almost reached an end, while maintenance of the quay wall was not undertaken in the past to recover the defects on time. The health monitoring through inspection has not been frequently observed by the municipality as well. The degree of deterioration has approached a late stage where the treatment through lifespan extension measures will unlikely reduce the risk completely. The modular quay wall is highly independent upon the old construction, except for the slight transformation of vertical load through the old masonry wall.

This scenario study is typically categorised in the red zone of safety aspect, taking into account the remaining lifespan of the quay wall components. This means an immediate action is necessary to consider. It is obvious that the probability of failure ranges from high to very high. The proximity of damage to the area is huge and for a large distance for this failure mechanism. The cost of reparation if global instability happens is also high, where the quantitative estimation depends on the length of the deteriorated quay wall stretch. The system is no longer functional to retain water, nor does it withstand traffic flow if the quay wall is featured with excessive rotation. There is certainly a major to massive effect caused by flooding to the nearby building. The impact of flooding is also dependent on the distance between the edge of the quay wall and the residential houses, in this case, a catastrophic event. Additionally, the shortcoming in underground utilities is likely to occur where gas and electricity provision to households are halted. The sailing of ships through the canal could not take place for a long period of time. The lack of water regulation to allow sailing of ships is expected to incur considerable economic costs and liability claims to the municipality. The fatality rate of the incident could result from permanent disability to dozens of deaths, depending on the place and timing of the incident (rush hours).

Fortunately, global instability is a type of failure mechanism which barely happened in the past in the inner-city quay walls of Amsterdam. The detection of this failure mechanism leads to the conclusion that a renewal is the most favourable action to undertake due to the remaining lifespan of 5 years and the red zone categorization. Additionally, the certainty of risk reduction is an important concern in this scenario study. The remaining lifespan of 5 years is not an ideal period to experiment the effectiveness of modular quay wall during the pilot project. The pilot phase usually takes 2 years of probation period as acknowledged from the interview with the municipality. It is more suitable not to wait for the lifespan extension measure to be approved as nothing is guaranteed while the risk of failure occurrence is expected to increase in the course of time.

7. Discussion

The aim of this research is to develop a decision-making framework to guide through a suitable intervention measure for deteriorated quay walls. This chapter will elaborate on the obtained results of the scenarios, discuss uncertainties in input data, state limitations of lifespan extension measures, and conclude it with the implication of the study.

Results of the scenarios

The outcome of the scenario studies is established after developing the decision-making framework. The lack of real contextual information regarding the quay walls of Amsterdam resulted in imaginary scenario studies. The results of the three scenario studies are observed to be correlated with the structural capacity, safety risk matrix, economic assessment, technical feasibility, impact on the surroundings and social impact, and environmental sustainability.

In scenario 1, the technical feasibility is observed to be a restriction to implement the lifespan extension measures due to the insufficient spacing between the quay walls and residential houses. A backwards loop suggested the application of a renewal option, despite the lower calculated costs of the application of the lifespan extension measure. In scenario 2, the application of lifespan extension measures turned out to be the most favourable solution. Option 3 scored better than option 1 regarding the impact on the surrounding, social impact, and environmental pollution. Option 1 scored better than option 3 in terms of circularity and total costs. In scenario 3, a renewal is suggested to resolve the deteriorated quay wall. One of the six lifespan extension measures is revealed to solve the exceedance of global stability in quay walls due to its complexity. This depicts that global instability has the least number of addressed lifespan extension measures in contrast to other failure mechanisms. The data suggests a correlation between the colour zone allocation of the safety risk matrix and two aspects, namely the remaining lifespan of components and the number of quay wall components which are inspected under critical conditions.

Uncertainties in input data

There are multiple uncertainties regarding the input data in the assessment of lifespan extension measures. The frequency of occurrence of each type of failure mechanisms are known for the quay walls in Amsterdam. This is an important input to choose an initial intervention measure and enhance the safety of the structure. However, three main uncertainties are revealed during this research:

1. The required percentage of reduction of forces is variable with respect to the categorised ‘minimum requirements’ and ‘wishes’ as shown in Appendix A. The construction firms did not indicate what exact percentages were met during the interviews, to accurately conclude whether their intervention measures could withstand a specific quay wall situation. For a load percentage reduction of 75% or lower, it is certain that all interviewed firms fulfil the minimum requirements. Nonetheless, a higher percentage than stated yields to uncertainties to provide a conclusion regarding the safety aspect.

2. The workability of most measures depend on the structural conditions of one or more existing quay wall components. For instance, it is uncertain to what extent the cracks in brickwork of a certain quay wall can influence the centre-to-centre spacing between steel

piles. A shorter spacing than the optimum spacing can yield to a higher realisation costs and influence the economic feasibility as more materials are required to stabilise the quay wall. A similar explanation can be related to the geotechnical solution, such as the biobased soil improvement. The variable homogeneous and heterogeneous feature of the soil composition in each quay wall can cause a difference in the geotechnical strength improvement, when the biobased material is poured through the infiltration well. It is uncertain whether the biobased solution can be still favourable in a heterogenous soil mixture.

3. There are uncertainties regarding the circularity aspect of the components in the lifespan extension measure. For instance, some firms are still developing new and circular steel piles that could be demounted after their end of lifespan. The exact type of steel piles could differ in the future than indicated in chapter 4. This aspect could influence the outcome for the environmental sustainability step in the framework. Additionally, it is a hard judgement to compare two lifespan extension measures with qualitative data, especially when similar types of materials and components are implemented in the solution. This is due to the qualitative nature of data that is inserted in the decision-making framework. Quantitative data regarding the dimensions and used percentage of each material should be known. In that case, the amount of CO_2 emissions of each lifespan extension measure can be compared with the traditional sheet piles to allow for a more objective conclusion.

Limitations of the three lifespan extension measures
The three lifespan extension measures awarded by the municipality of Amsterdam for the pilot phase are Fundovatie, Buoycrete, and Bioinspired soil improvement. The limitations of the three measures can be observed in Appendix C. The three solutions do not address the failure mechanism of global instability nor the local fracture of brickwork. Additionally, the soil settlement is resolved by the Fundovatie method. However, the prevention of soil settlement is limited to the front row piles of the existing quay wall. In case a severe water motion takes place in the rear row piles, then the Fundovatie measure can not attenuate the soil settlement acting on the rear pile foundation. Therefore, the structural integrity could be gradually harmed due to the constant loss of load bearing capacity. In that sense, it is useful to continue searching for new innovative ideas applicable on quay walls. The focus should be laid down on the three aforementioned failure mechanisms: local fracture of brickwork, global instability, and soil settlement.

Implications of the study
This research has contributed to adapt a systematic approach to decide on intervention measures. The interdependencies and order of steps in the decision-making framework formed a solid decision flow structure, which the municipality of Amsterdam can take into consideration. The framework is relevant as it saves management time and complexity by directly understanding the impact of each lifespan extension measure and their solved failure mechanisms while mapping them with a potential lifespan extension measure. This research revealed that the safety aspect acts as an important fundament, which should always be a starting point of evaluation.

Previous literature review suggested a categorisation of intervention criteria in the decision of infrastructure assets. Davis (2021) indicated the decision criteria based on the key challenges faced through applying intervention measures in highways. Ito et. al (2015) have discussed the decision of applying different design variants in road embankment based on main assessment criteria such as the LCC, ELCA, and SLCA. However, the prioritisation and order of steps were missing to adequately examine the decision-making framework for quay walls. The extensive specification of relevant sub-criteria for quay wall structures was outlined in this paper. In this research, the actual steps in the framework are drawn up to be in a realistic order to reduce the tension between stakeholders when intervention decisions are applied. Additionally, the assessment criteria address the requirements and wishes of the municipality of Amsterdam, although missing information is evident in particular areas. This includes the absence of a numerical weighting factor to assess the different types of impact of measures on the quay wall.

To conclude, the decision-making framework is not limited to the interviewed lifespan extension measures. The decision-making framework is a good starting point to release an outcome, even if other developed lifespan extension measures are proposed to the municipality in the future. The accuracy of results generated from the framework can be enhanced in case uncertainties are reduced.

8. Conclusion and Recommendations

8.1 Conclusion

The inner-city quay walls are in poor condition based on inspection data published by the municipality of Amsterdam. The inspection report is released to gain a list of overview and proportions of failure mechanisms that are inherited in the city of Amsterdam. The municipality is interested to perceive a decision-making framework to manage the deteriorated quay walls. The framework describes the complete steps that should be gone through to obtain the right choice of intervention for each quay wall situation. The framework is schematized in order to save time and prepare a detailed restoration plan. This is a particularly useful tool to assess a wide range of quay wall stretches. The city council has contracted distinct firms to develop innovative measures to reduce the impact on the environment. The innovative measures are meant to substitute the traditional renewal option as much as possible, which will be inventoried after being proved to be effective during the pilot phase of the tendering procedures. Effective measures must comply with the safety norms and technical standards that fit the expectations of the municipality's requirements and legislations.

The most frequently occurring failure mechanisms are horizontal displacement, connection of capping beam, and shearing of masonry wall. The damaged components in a quay wall situation may include: the masonry wall, brickwork, pile foundation, capping beam, relieving floor, and soil retaining screen. The reduction of driving forces or reinforcing the quay wall is expressed as urgency measures. Those include installing sheet piles, lifting parking lots, and removing trees. Urgency measures are excluded from the scope of the research as it does not contribute to a meaningful and long-term vision. The reinforcement of quay walls is either done by applying lifespan extension measures or renewal. The criteria of both intervention strategies are evaluated in the decision-making framework. The lifespan extension measures are extensively explained in this research, which include the following:

- Method 1: Grout injection pile system
- Method 2: Bioinspired soil improvement (BISI)
- Method 3: Foundation reinforcement solution
- Method 4: Modular quay wall
- Method 5: Lightweight concrete
- Method 6: Anchors with internal concrete wall

A summary of the characteristics of the above lifespan extension measures are viewed in Appendix C and D. Part one of the developed framework for the selection between renewal and lifespan extension measures includes the following main criteria: structural capacity, safety risk matrix, and economic assessment. Part two of the developed framework for the selection between specific lifespan extension measures include: technical feasibility, impact on the surroundings and social impact, environmental sustainability, and concluding remarks. A continuous loop with steps of closed and open-ended questions are represented in the assessment framework to reach a final outcome. Subsequently, three fictive scenarios are reflected upon to show the applicability of the framework.

8.2 Recommendations

The research can be further expanded to gain a better understanding of the lifespan extension measures. The following suggestions for more study are proposed:

- The effectiveness of the applicability of lifespan extension measures are discussed in light of purely theoretical context. The representative firms have utilised the Plaxis software to model the structural strength of their lifespan extension measure. Further research could take place to validate the theoretical concept with a practical approach. The exact percentages of reduction of vertical and horizontal forces should be known for each lifespan extension measure. The specified uncertainties such as the minimum years of extended lifespan, structural strength, and workability of measure can be minimised. This could be done by recording the conditions of an already inspected and measured quay wall before an intervention takes place. The workability of the lifespan extension measure can be observed among distinct time periods after the assembly of measure. The validation process of the Plaxis models could come in force after technical details are reported during the pilot project.

- The terminology 'critical condition' of quay wall components has an inconsistent definition between the firms. This is sometimes measured according to the required spacing between the piles. In some measures, it is unclear what design dimensions should be considered to conclude whether a quay wall falls under critical conditions. This is an important factor to make the technical feasibility of the decision-making framework more insightful. The pilot phase is expected to give answers to the critical conditions and the scalability of the lifespan extension measure in Amsterdam.

- The minimum requirement and wishes contains limited information about the sustainability and circularity for lifespan extension measures. A complete overview of the desired parameters of investigation for both concepts is not mentioned by the municipality. For example, the sustainability factor could include parameters such as acidification, ozone depletion, global warming potential, eutrophication, and CO_2 footprint. As soon as the exact parameters are known, a follow-up quantitative study could be arranged for each lifespan extension measure to deliver an environmental life cycle assessment through the utilisation of DuboCalc.

- Heavy construction equipment is sometimes required to be deployed on the landside to start the execution process of the quay wall. The minimum distance between trees should be conceived for each lifespan extension measure by the construction firms to predict whether the measure is feasible without causing damage to trees.

- Particular lifespan extension measures are revealed to be flexible in their method of execution (waterways or landside). Remarkably, the realisation costs per running metre for both execution methods are discovered to be equal for the quay wall. However, in realistic terms, the realisation cost is not fixed within a particular lifespan measure as the movement of houseboats is an expensive operation to undertake. The construction firms which suggested during the interview the necessity of movement of houseboats should add those costs towards the given realisation costs for further assessment.

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Appendices

Appendix A: List of requirements and wishes from the municipality

Category	Minimum requirements	Wishes
Technical execution		
Deformation	The lifespan extension measures should not exert any deformation on the existing quay walls, unless the observed deformation is proven through calculations not causing any damages, cracks, or failure modes on the quay walls.	
	The horizontal deformation of extension measures may not exceed 50 mm of the serviceability limit state (SLS) on quay walls.	
	The annual settlement rate as a result of vertical deformation caused by lifespan extension measures may not exceed 2.5 mm.	
Failure mechanisms	The prevention of any three of the most frequently occurring failure mechanisms in inner-city quay walls, namely: horizontal displacement, shear and local fracture, and collapse of capping beam.	
Capacity of bearing load	Minimum bearing capacity of 15 KN/m^2 and 5 KN/m^2 on roadway and parking lots respectively.	20 KN/m^2 on the roadway and 10 KN/m^2 on parking lots.
Residual strength of wooden pile foundation	If the lifespan extension measure addresses failure modes related to horizontal forces, then 75% of the total horizontal forces acting on the quay wall should be beared.	The innovative lifespan extension measure has a bearing capacity for 100% of the total horizontal forces.
	If the lifespan extension measure addresses the vertical forces acting on the 1st and 2nd row of pile foundation, then 75% of the total vertical forces acting on the piles should be beared.	The innovative lifespan extension measure has a bearing capacity for 100% of the total vertical forces.
	The lateral forces, moment diagram, and deformation diagram should be schematized in an insightful way.	
Practical considerations of execution procedures	If work is executed on quayside, then working load may not exceed 2.5 KN/m^2 limited to a maximum distance of 3.5 m behind the quay, including the parking lots.	
	If work is done from waterways, then the maximum allowed width of the pontoon is 9 m with a precondition to perform a stability calculation prior to execution.	
	The lifespan extension measure does not hinder the nautical mooring of both, the touring boats and houseboats.	
Hydrology	The solution should not cause any fluctuations on the groundwater level.	The adaptation of water permeable

		solution as much as possible.
	The stability of the soil retaining screen of the quay wall must be ensured.	
	The rain water should flow from the facade of quay walls, if relevant.	
Geotechnical	Soil pollution should be prevented as much as possible. In this case, no sand, foam, or concrete is mixed with the bottom sludge. The landfill and waste treatment costs should be included beforehand in the budgeting in case mixing occurs.	
Preservation of surrounding infrastructure		
Construction	The surrounding context/objects are retained during the pilot phase. For example, no changes are made to road layout or underground garbage containers.	
Cables and pipelines	Cables and pipelines must remain accessible for maintenance activities. There is a possibility of temporarily shifting the position of cables and pipelines during execution.	
Trees	Valuable and monumental trees should be preserved.	
Cultural (historical) value	Preservation of cultural (historical) value of quay walls.	
Hindrance		
Logistics	This is integrated in the specification of 'practical consideration' of technical execution. For example, the truck loads and degree of hindrance are included in the workload.	
Noise disturbance	Mentioned in the Dutch building decree. Maximum 60 dB of noise level between 7:00 and 19:00. A separate permission is required from the municipality in case of construction activities outside the regular working hours.	
Durability		
Circularity		The solution offers the possibility of reusing the installed pile foundation for renovation purposes of the quay wall after its end of lifetime (If new piles are applied in the solution).
CO_2 emissions		Proof that the lifespan extension measure does exhibit a lower CO_2 emission than a

		new replacement (standard sheet pile solution amounts to an emission of 900 kg CO_2/m).
Ecology	The application of different types of materials such as foam must guarantee the protection of species. The solution should not pose any threat to the habitat quality.	
		Green areas are desirable, as suggested in the published handbook 'Natuur inclusieve kademuren en bruggen'. Core planting ideas are presented in the handbook, which could be adapted to the landscape.
Climate adaptation	Integrated in the sections of 'ecology' and 'hydrology'.	
Water management		
Water quality	The application of different types of materials such as foam and grout is expected not to leach during the execution process.	
The boat passage profile	The solution does not adjust the clearance depth. The clearance depth (distance between the bottom of the boat and canal bed) strictly complies with the sailing regulations.	
Estimated duration		
Realisation time		The realisation of solution within 3 months per stretch of quay wall.
Technical lifespan	Minimum 20 years.	30 years.
Costs		
Costs of temporary solution or extension of current quay wall	€7500 per running metre.	
Replacement costs including demolition of quay wall	€35000 per running metre.	
Scalability		
The application of solution	The extent to which the solution can be applied in the inner-city quay walls (location allocation) for the short and long term as long as it conforms to the agreed laid down budget of the innovation.	

Appendix B: Interview guideline

Deel 1: Introductie

Begin het interview met een voorstelronde. Daarna wordt er uitleg gegeven aan de geïnterviewde persoon met betrekking tot de doelstelling van het interview en mijn afstudeeropdracht. Bovenop wordt toestemming gevraagd in geval dat het interview wordt opgenomen. Dit is belangrijk om gemiste informatie straks tijdens de transcriptie te achterhalen.

Deel 2: Achtergrondvragen

1- Wat houdt de techniek eigenlijk in?

2- Hoe is het systeem bij elkaar in het ontwerp opgebouwd?

3- Welke principe zit achter het versterken van de kademuur?

4- Is dit een beproefde techniek? Zo ja, geef aan in welk project deze oplossing eerder wordt toegepast en vergelijk de uitvoering complexiteit?

Deel 3: Uitvoering en constructief sterkte

5- Kan je een volledig stappenplan over het uitvoeringsproces beschrijven?

6- Welke type bezwijkmechanisme wordt door deze maatregel opgelost? Horizontale of verticale krachten?

7- Wat bedraagt het draagvermogen van deze oplossing?

8- Op basis van welke factoren leent deze oplossing zijn werking toe?

Deel 4: Impact van levensduurverlengende maatregel

9- Kan je een overzicht geven over de impact van deze levensduurverlengende maatregel op de omgeving?

10- Wordt de uitvoering voornamelijk via de kade of waterwegen verricht? Welke heeft een grotere impact op de omgeving?

11- Vormt het gebruikt materieel een grote werkdruk op de nabijgelegen parkeervak/wegdelen waarbij schade is geconstateerd?

12- In welke mate wordt het verkeer belemmerd tijdens de bouwwerkzaamheden? Hoeveel ruimte heeft deze oplossing nodig achter de kademuur?

13- Wat is de geschatte uitvoeringstijd per 10 m vak kade?

14- Is de oplossing technisch haalbaar in alle locaties zonder bomen te kappen en kabels/leidingen van woningen af te sluiten?

15- Is er sprake van bodem/water vervuiling als gevolg van het aanbrengen van de levensduurverlengende maatregelen? Zo ja, welke voorzorgsmaatregel wordt getroffen om vervuiling te voorkomen?

Deel 5: Afrondende vragen

16- Wat is de verwachte levensduur van de oplossing?

17- Wat zijn de totale realisatiekosten per strekkende meter voor deze oplossing?

18- Wat voor onderhoud heeft deze oplossing op de lange termijn nodig?

19- Is het mogelijk om de componenten van de techniek te verwijderen en behouden na het einde van zijn levensduur voor eventueel hergebruik?

20- Wat zijn op dit moment de grote onzekerheden/uitdagingen?

Appendix C: The type of failure mechanisms solved for each lifespan extension measures

	Gracht compact paal	Biobased soil improvement	Fundovatie	Modular quay wall	Buoycrete	Tauw measure
Shearing of masonry wall	✓	✓	✓	✓		✓
Horizontal displacement		✓	✓	✓		✓
Tilting of masonry wall		✓		✓		✓
Local fracture of brickwork				✓		✓
Deformation of (head) piles			✓ *	✓	✓	✓
Collapse of soil retaining screen				✓	✓	
Collapse of relieving floor				✓	✓	✓ *
Exceedance of global stability				✓		
Collapse of capping beam				✓	✓	✓
Soil settlement			✓ *	✓		✓

* Fundovatie: The pile stabilisation is limited to the front pile row.

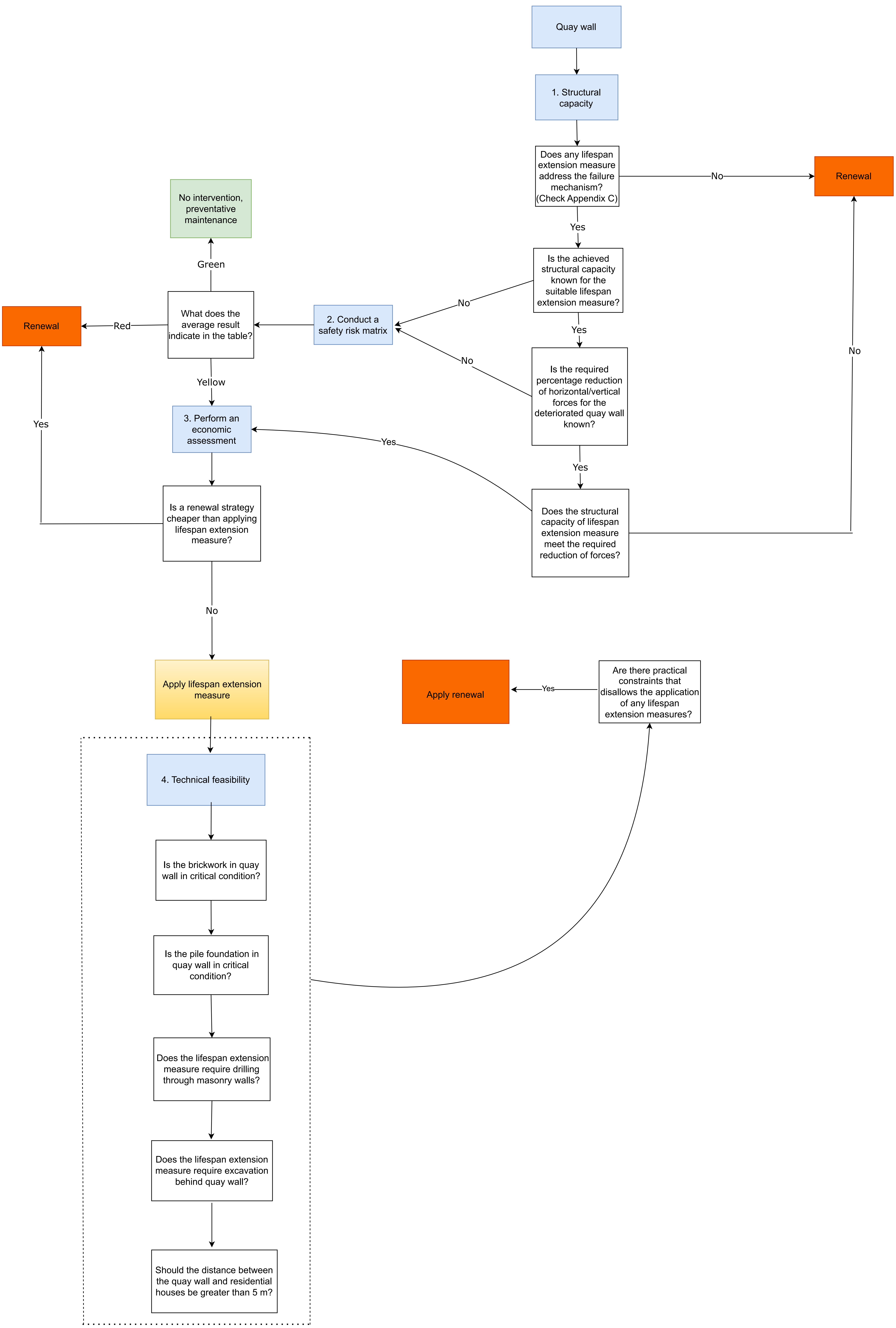
* Tauw: The collapse of the floor can not be prevented if the reason behind the failure is the underflow of soil through sinkholes.

Appendix D: Technical overview of the application of different lifespan extension measures

	Grout injection pile system	Biobased soil improvement	Foundation reinforcement solution	Modular quay wall	Lightweight concrete	Anchors with internal concrete wall
Does the method depend on the conditions of brickwork?	Yes	No	Yes	No	Yes	Yes
Does the method depend on the conditions of pile foundation?	No	No	No	No	Yes	No
Excavation required?	No	No	No	Yes	No	Yes
Drilling through masonry walls?	Yes	No	No	Yes	No	Yes
Required distance behind the quay wall	2.5 m, only required when working from landside	2.5 m	3.5 m	5 m	3 m	5 m
Place of execution	Flexible	Landside	Waterway	Flexible	Waterway	Waterway & Landside
Moving of houseboats required?	Yes, if working from waterway	No	No	Yes, if working from waterway	Yes	Unknown
Duration of execution per 10 m length quay	1 week	2 days	1.5 - 2 months	1 week	2 days	Unknown
Restrictions on nearby trees?	No, small sized equipment is utilised for quay wall locations.	No, applying biobased material around tree roots does not damage the tree growth/stability	No, pruning of trees is sometimes necessary due to height restrictions of machinery.	Yes, the soil retaining screen and concrete floor form a restriction. Preventative measures such as the placement of the horizontal frame and shifting/eliminating the soil retaining screen might be necessary.	No, buoycrete is poured underneath the capping beam.	Yes, with the concrete wall design variant. The substitution with a steel purlin is an option.

Restriction applied to cables and pipelines?	No, except if the cables and pipelines prolong under the canal. A bridging construction is required to avoid damages when drilling through masonry walls takes place.	No	No	Yes, the relocation of cables and pipelines behind the soil retaining screen or adjusting the depth of concrete floor are possible options to avoid clashes.	No	Yes, the cables and pipelines running behind the quay wall should be moved to allow for concrete pouring.
Does soil/water pollution occur during execution?	No, but preventative measures are necessary (soil backfill & sealant)	No, preventative measures are not taken	Leakage of grout into the canal occurs in rare cases. No preventative measures are taken.	No, preventative measures are not taken.	No, preventative measures are not taken.	No, preventative measures are not taken.
Components removed and reused after end of lifespan	Steel tubular piles can not be removed after lifespan	-	Grout anchors and attachment element	Concrete floor, coupling beam, steel tubular piles, and soil retaining screen	Not applicable, implementation of “schiedam’s method” after 30 years	Reuse of steel tubular piles. Internal concrete wall can be recycled
Number of failure mechanisms	1	3	4	10	4	8
Designed lifespan (years)	50	Unlimited	50	100	100	70
Lifespan extension of entire quay wall (years)	Unknown, depending on the conditions of brickwork	Minimum 30, depending on the structural characteristic of quay wall	Minimum 20, depending on the conditions of brickwork	100	Minimum 30, depending on the conditions of wooden piles	Minimum 30, depending on the conditions of brickwork
Costs per running metre	€15,000	€7,500-10,000	€10,000	€15,000-20,000	€7,500-8,500	€5,400

Appendix E: The decision-making framework



Appendix F: The subcriteria of different types of impact in lifespan extension measures (Steps 5-7)