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REINFORCED SOIL – THE QUAY WALL STRUCTURE FOR THE FUTURE?

Steel and concrete are the most common materials used in quay wall structures. The application of these materials contributes to a high emission of greenhouse gasses such as CO2 and the materials make up a large part of the construction costs. This graduate research examines whether alternative quay wall structures have the potential to be more cost effective and more sustainable compared to conventional structures for inland ports. An innovative quay wall of reinforced soil was designed and quay elements implemented to make a quay wall structure. A comparison was then made based on the criteria costs and sustainability between the innovative quay design and two conventional quays.

For their thesis, the authors conducted research on more sustainable and cost-effective quay wall structures for inland ports in the Netherlands. There is still a demand for new inland ports that can fulfil a function as a connecting link in the Dutch inland waterway network. Moreover, most of the current quay walls were constructed shortly after the Second World War. These outdated quays may have reached both the technical life span and safety limits due to increased loads over the years, and a large replacement programme must be executed in the next decades.

Expectations for the future must be considered prior to the design. By anticipating increasing loads, rising water levels and long-term trends will create a future-proof quay that is able to retain its functionality over a longer period. Due to the growing demand of today's consumer society, a trend is happening in the transshipment of containers. The rising number of transported containers results in a need for extra transshipment ports that require heavier port equipment and bigger storage loads.

As previously mentioned the most common materials applied in current quay walls are steel and concrete. The use of these materials results in both high emissions and high investment costs. However, the ongoing climate changes and rising material prices create a growing necessity for sustainable and more cost-effective quay wall structures. After promising results and having been successfully applied in different civil engineering disciplines, it is interesting to investigate the possibilities of reinforced soil structures within hydraulic engineering.

Quay elements

A reinforced soil structure is a well-known construction method with which height differences can be reached. Using a reinforced soil structure as a quay requires adjustments and implementations to withstand a combination of variable unfavourable loads caused by heavy port equipment, ships and water level fluctuations.

Conventional quay wall structures allow bollards to be anchored in a concrete substructure. Since there is no option for the bollard to be anchored in the structure itself, alternatives must be considered to be able to integrate a bollard into the body of the structure. Designing an L-shaped capping beam makes it possible to spread and transfer mooring forces in the reinforced soil structure with the least amount of concrete and the most favourable load transfer. A vessel classified in CEMT-Va/Vb has a line pull force of 250 kN, multiplied by a safety factor 1.5 gives a line pull force of 375 kN. The capping beam is able to spread this load over the track distance of the bollards, which is 15 metres. This results in a spread tensile load of 25 kN/m. Tensile forces due to mooring lines occur in either horizontal or vertical direction. The vertical load and moment are carried by the self-weight and the favour ground pressure on the feet of the beam. The horizontal tensile force is carried by a horizontal anchorage of geogrids consisting of a 5.6m long strip fixed in the concrete capping beam. When designing mooring facilities it is important that the bollard anchorage be a factor 1.5 stronger than the occurring line pull force. This results in a geogrid with a tensile strength of at least 37.5 kN/m.

Removable concrete panels as a facing of the structure improves the quays appearance and are a solution for the robustness of the structure. The concentrated load caused by a ship collision, which may occur, will be spread by the panel and prevents damage on the geotextile. Besides collision, the soil structure is protected against friction between a moored ship and the retaining wall, the polymer geogrids are protected against UV radiation and from the mounting of fendering systems on the retaining wall.

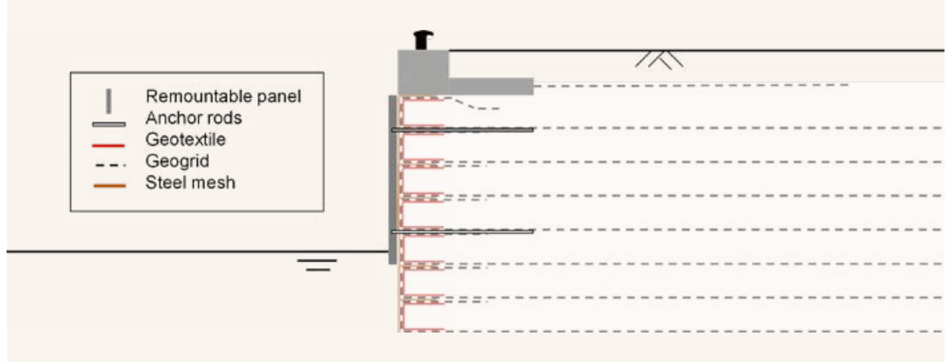

FIGURE 1

Quay wall elements reinforced soil structure.

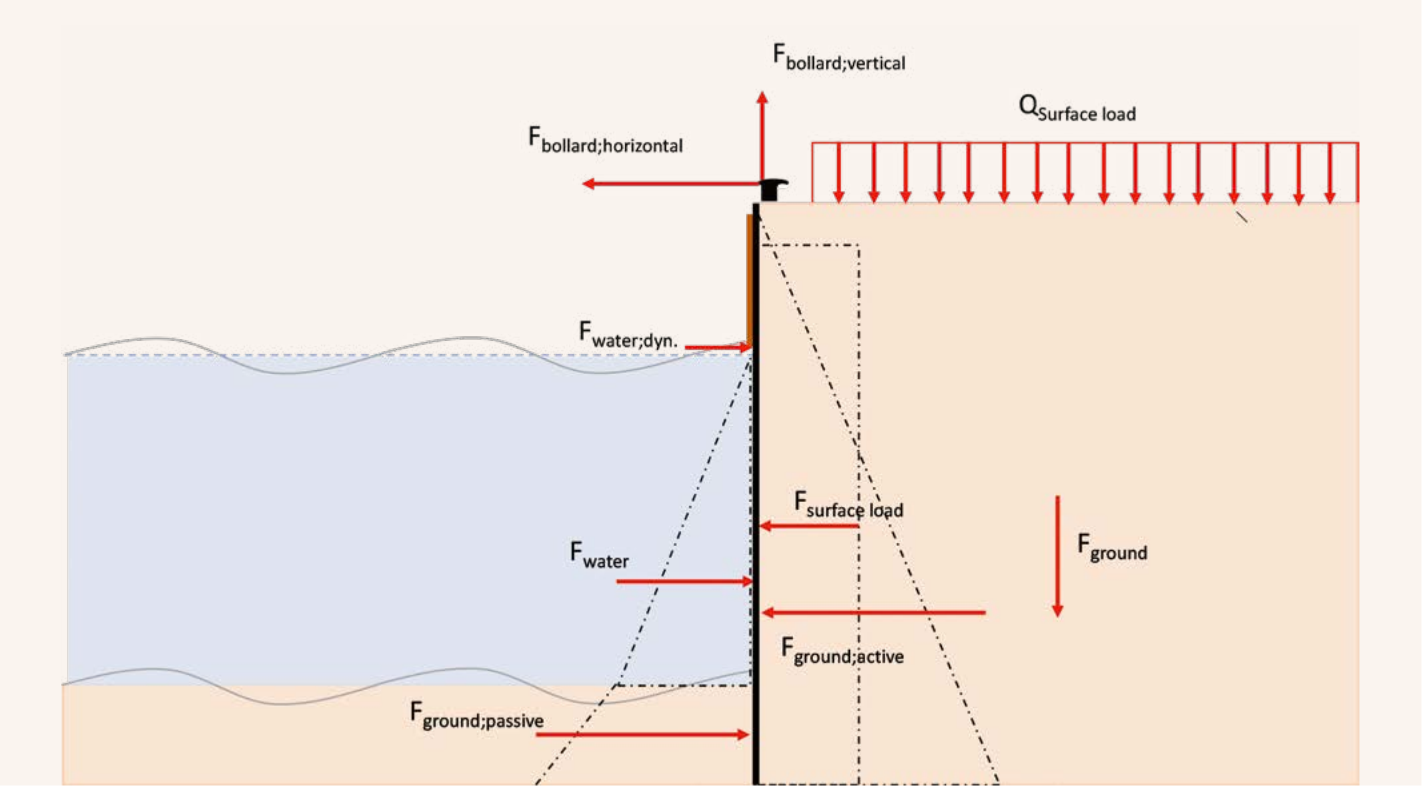

FIGURE 2

Loads on a quay wall structure.

Designs

For equal circumstances, all three quay wall structures are computed in the situation of the Flevokust haven, located near Lelystad, in the Netherlands. The main reason for choosing the Flevokust haven as case location is due to its representative characteristics for inland ports with deltaic soils. The soil consists of non-loadbearing soil types, there are limited water level fluctuations and this inland port is accessible to a representative number of vessels. In addition, this port is used as a container terminal that causes large surface loads, which is also representative for other inland ports due to a trend in the transshipment of containers.

The three different quay wall structures are designed with a total retaining height of 9.25 metres. In case of any settlement, an extra height can be added to maintain the total retaining height. The topside of the constructions must be on a level of 2.45 metres + N.A.P. With the current water level of 0.5 metres - N.A.P. there is 2.95 metres above the water surface. The remaining 6.3 metres of the total retaining height is below the water surface. This water depth provides the accessibility to vessels classified to CEMT-Va/Vb. The transshipment of containers requires heavy port equipment and storage of the containers resulting in high surface loads that effect the quay wall. Figure 2 includes all horizontal and vertical forces in the situation of the Flevokust haven.

Developments in the future that could affect the quays' safety or functionality were considered, resulting in the following being taken into account in the design of a future-proof quay. In Europe, regulation states that inland waterways must be able to receive vessels with a normative draft of 3 metres (CEMT VI). As the past has shown, ships are expected to increase in size; the next step in the modernisation of the inland waterway network is an upgrade to class CEMT-V. This has led to a design that is able to receive vessels with a normative draft of 3.5 metres (CEMT Va/Vb). A logical consequence is larger mooring forces, therefore instead of a line pull force of 200 kN for class VI, 250 kN for class V is taken into account.

Moreover, anticipating the transshipment of containers results in a quay that endures higher loads from both storage and heavy port equipment. Finally, approximately one metre will be added to the retaining height to protect the quay from weather conditions such as extremely high water causing wave overtopping for example.

Cantilever wall

The reinforced concrete cantilever wall represents one of two traditional quay wall structures that is used for the comparison with the innovative quay wall. The design is the basis for the bill of quantities with which the material costs can be estimated. General rules are used for the dimensions and proportions of the wall. The dimensions of the design are as shown in Figure 3.

After designing the construction, all forces on the wall are determined. This is necessary in order to calculate the moments of force including safety factors. Checking the design on geotechnical failure mechanisms according to the Dutch guideline for geotechnical designs, the KIVI-reader provides the following calculations: tilt stability, vertical loadbearing capacity (drained and undrained situation) and horizontal sliding of the structure.

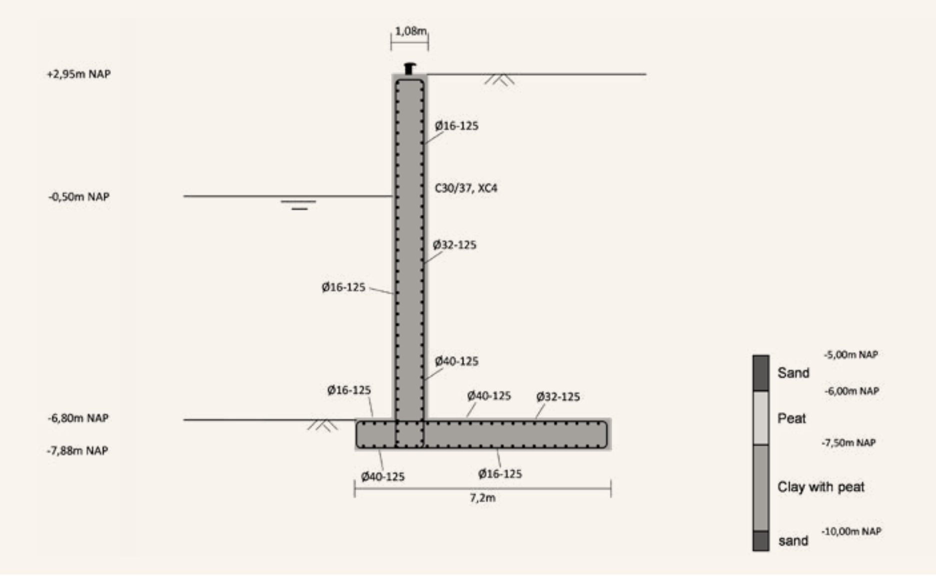

FIGURE 3

Cross-section concrete cantilever wall.

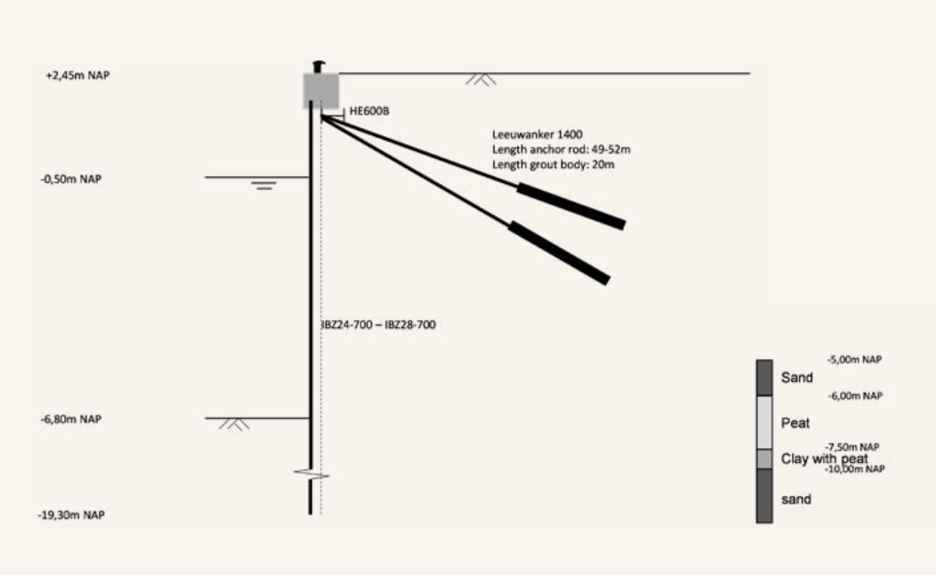

FIGURE 4

Cross-section sheet pile wall with anchor.

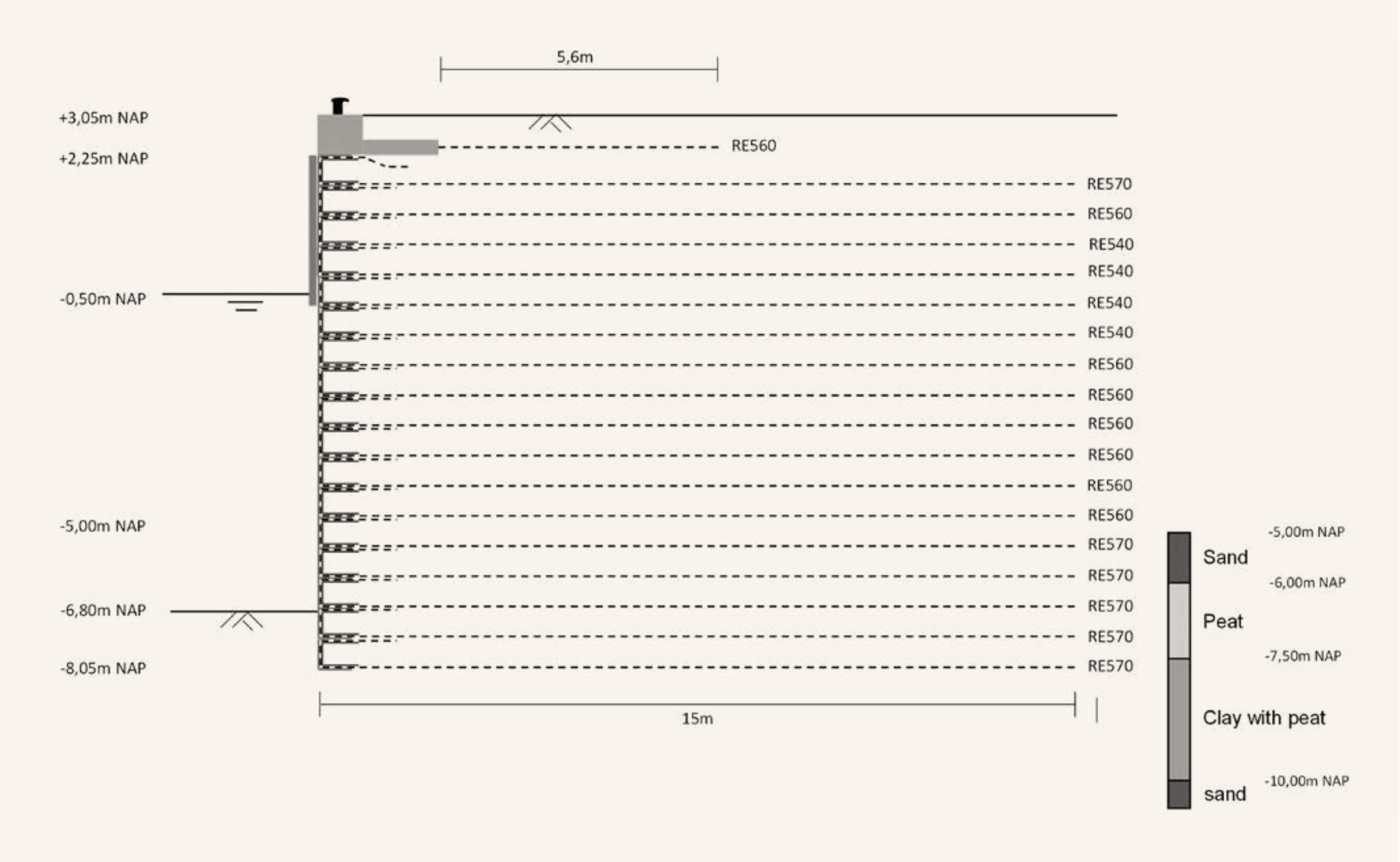

FIGURE 5

Cross-section reinforced soil structure.

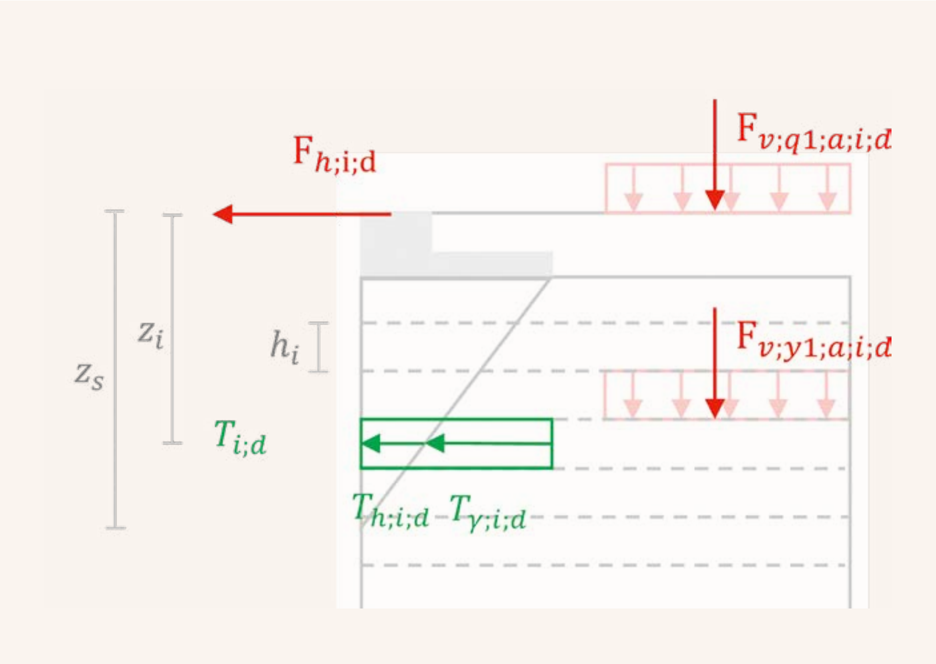

FIGURE 6

Loads leading to internal tensile forces.

Assuming the cantilever wall is a rigid construction, a neutral earth pressure K_n on the wall is applied in the calculations. On the bottom-left side of Figure 3, the soil structure of the case is presented, which has been used for the calculations. A reinforcement calculation is made to gain insight in the internal forces in the retaining wall and to determine the steel quantities.

The cantilever wall is on top of compressible layers of soil. A layer of 2.5 metres of clay with peat causes a settlement of 0.5 metres, which is compensated to add extra height to the retaining wall. Adding 0.5 metres to the initially required retaining height gives a retaining wall height of 9.75 metres. The quay is in varying contact with water; therefore, the concrete structure is classified in environmental class XC4.

Various types of reinforcement carry the tensile stresses in the concrete. The main reinforcement is applied in the wall where the biggest bending moments occur, in the inner corner between the wall and the floor, and in the toe of the floor. The bending moment in the wall decreases once the cut in the wall is made higher to determine the forces. At the top of the wall, the bending moment is 0. By dividing the height of the wall and determining the required reinforcement per segment, a lot of reinforcement can be saved. Besides, compression reinforcement, distribution reinforcement and bollard reinforcement are needed to carry and distribute loads properly.

Uniaxial geogrids such as HDPE reinforcement can carry high tensile loads applied in one direction.

A construction pit of temporary sheet piles with a strut frame makes it possible to excavate approximately 2.5 metres of the soil and lower the water level. After excavating several teams can work in shifts to apply the formwork, processing the reinforcement bars and to pour concrete. Once the construction and backfill have been finished, the temporary sheet piles can be removed.

Anchored sheet pile wall

The steel anchored sheet pile wall is the second traditional quay wall structure that is used for the comparison. The design as shown in Figure 4 is in reality designed and constructed for the Flevokust haven. Because it concerns a validated design, no constructive calculations have been made.

The construction consists of permanent sheet piles with an average length of 21 metres. Two grout anchors per 3-metre quay wall carries the bending moments in the sheet pile resulting in shorter sheet piles.

Construction starts with the installation of sheet piles into a load-bearing layer. Lowering the water level and backfilling sand on the existing soil including preload speeds up the settlement process. When soil is sufficiently settled, the grout anchors can be installed.

Reinforced soil structure

The third design is the innovative reinforced soil structure. The retaining function of the design is derived from the use of a high density polyethylene (HDPE) reinforcement, geotextile and sand. Uniaxial geogrids such as HDPE reinforcement can carry high tensile loads applied in one direction. The elongated perforated structure allows the backfill material to interact with the reinforcement through frictional resistance. Meanwhile the aperture structure of geogrids could cause the backfill material to washout. Geotextile provides a barrier to confine the backfill material. Open graded sand is desired to ensure a drained effect of the backfill.

The design is checked for internal and external stability in accordance with the CUR-198 guidelines. In order to ensure the local internal stability, it is important to know that a reinforced soil structure can internally fail due to two reasons. The first being that the tensile strength of the reinforcement is exceeded causing the reinforcement to break. The second is that the reinforcement can be pulled out due to insufficient bonding when the reinforcement length is not sufficient to transfer the tensile force to the backfill material. A check on pulling out is disregarded because this is only decisive in situations where very short reinforcement lengths are used.

Initially, the tensile force must be determined for each reinforcement layer. There are four types of loads that directly affect the tensile force, taking into account the self-weight, surcharge loads, concentrated horizontal and vertical loads. The self-weight of sand and surcharge loads causes a vertical force in the construction. This vertical force results in a horizontal force due to the active ground pressure because the sand is enclosed by the geotextile. Concentrated vertical loads due to a bearing are not applied to this design.

The total tensile force $T_{i;d}$ is the sum of all the tensile forces due to self-weight, surcharge loads $T_{y;i;d}$ and concentrated horizontal loads $T_{h;i;d}$. Simplified, the equation is as follows:

$$T_{i;d} = T_{y;i;d} + T_{h;i;d} \qquad [1]$$

Calculating the tensile forces due to self-weight and surcharge loads $T_{y;i;d}$ is done by multiplying the active ground pressure factor $K_{1;d}$ with the reinforcement layer height h_i (0.6 metres) and the vertical effective stress $\sigma'_{v;i;d}$.

$$T_{\gamma;i;d} = K_{1;d} \times h_i \times \sigma'_{v;i;d} \qquad [2]$$

The vertical effective stress $\sigma'_{v;i;d}$ is derived by the sum of the vertical forces divided by the effective width.

$$\sigma'_{v;i;d} = \frac{F_{v;\gamma1;i;d} + F_{v;q1;i;d}}{b'} \qquad [3]$$

Determining the influence of the concentrated horizontal load of the bearing in the considered layer, gives the following equation. Basically, the load is spread linearly on the depth z_s depending on the active shear wedge $\theta = 45° - \varphi'/2$ and the distance between the point of engagement (centre bearing) to the facing of the reinforced soil structure.

$$T_{h;i;d} = 2 \times h_i \times \frac{F_{h;opl;d}}{z_s} \times \left(1 - \frac{z_i}{z_s}\right) \qquad [3]$$

As shown in Figure 5, varied geogrid types are used that differ in tensile strength. The tensile force in the geogrids increases once they are lower in the structure due to the increasing ground pressure. The unfavourable horizontal loads are carried by the top layers of the reinforcement resulting in higher required tensile strengths. A deviation in geogrid type can also be found below the water level where the active earth pressure on the geogrids is reduced due to the saturated conditions, resulting in a lower effective weight of the soil fill.

The global internal stability can be calculated with the compound method. A shear wedge with a fixed angle $\theta = 45° - \varphi/2$ produces a load that needs to be caried by the intersected reinforcement layers. The global internal stability check has not led to a normative load case.

Checking the design for external stability resulted in an analysis of consolidation, settlements, tilt stability, vertical load bearing and horizontal sliding. A geogrid length of 13.6 metres provided enough resistance against all these failure mechanisms.

The global circular shear failure mechanism as a final check showed to be normative in determining the geogrid lengths, resulting in a 15-metre-long reinforcement.

The construction consists of 17 layers of soil, each 0.6 metres high; two layers for the embedding depth and 15 for the required retaining height, including settlement compensation. Settlement calculations showed that a settlement of 0.72 metres occurs, resulting in an extra layer of reinforced soil of 0.6 metres to meet the settlement requirement.

The construction of a reinforced soil structure in this case is as following. A construction pit of temporary sheet piles with a strut frame makes it possible to excavate approximately 3 metres of the soil and lower the water level. Then the reinforced soil structure can be built layer by layer. A steel mesh formwork is repeatedly applied followed by rolling out and extracting geogrids and geotextile, and applying and compacting the backfill material. Finally, the geogrids and geotextile are folded back to enclose the backfill material.

Costs

The total costs for all three designs i.e. the concrete, steel and reinforced soil structure can be divided into two categories, construction costs and material costs. Focussing on the material costs, the limited use of steel within the reinforced soil structure results in a solution with the lowest material costs (total material costs 1.950.000 EUR). In the case of both the conventional structures, only the costs of steel are more expensive (cantilever wall: 1.971.000 EUR and sheet pile wall: 2.010.000 EUR) than the total material costs of the reinforced soil structure. For each construction, the backfill material costs are approximately 1 million EUR.

Compared to the material costs, the construction costs are somewhat different. The respectively high construction costs of the cantilever (1.720.000 EUR) and reinforced soil structures (1.106.000 EUR) are caused by using temporary sheet piles to create a construction pit. Therefore, the sheet pile wall is a less labour-intensive construction method resulting in lower construction costs.

Nevertheless, the total investment cost of the geogrid reinforced soil structure is still significantly lower than the total investment costs of either conventional structures. The material and construction costs show that the total investment cost for the soil structure is approximately 3.1 million EUR compared to 5.9 million EUR and 4.1 million EUR for the cantilever wall and sheet pile wall respectively.

The material costs of the reinforced soil structure are considerably lower compared to both the cantilever wall and the sheet pile wall quays.

Environmental effects

During the total lifetime of a project, for each material or construction process it is possible to determine the societal cost to compensate the environmental effects. Using the Environmental Cost Indicator (ECI), the effects can be determined by multiplying the quantified emissions of a material or process per functional unit with the total amount. The outcome of this calculation is for each material or process an environmental impact expressed in euros. It is important to note that all materials are calculated with a life span of 100 years.

The ECI can be divided into different system phases or impact categories. The dividing by lifecycle phase is shown in Figure 8. The production phase of the materials has the highest contribution in the total ECI. Sand mining and transportation is for all three constructions the main cause of this high ECI. This is due to the relatively high density and the large volumes of sand used, and the large number of transport movements required. Both conventional structures further increase these ECIs within this phase due to the large amount of steel. During the production of steel, a vast amount of heat is necessary to deform the material, which in turn effects the Global Warming Potential (GWP).

The environmental impact during construction is almost equal to each other. The three structures include almost the same amount of sand. Processing the sand has in all cases the highest impact and effects the Global Warming Potential (GWP), Acidification (AP) and Human Toxicity (HT) the most.

The last phase assesses to what extent the materials can be reused or recycled for the next production system. Sand and concrete can easily be reused or recycled. Sand is an extremely circular product and mining of new sand can be avoided by reusing the product. Meanwhile, according to the Dutch National Environmental Database, 45% of steel in the sheet pile will be lost during its lifetime due to corrosion. This negative fund is taken into account by reproducing the lost steel. The environmental costs of reproducing the corroded steel do not outweigh the positive funds of reusing sand.

The construction processes other than the application of the materials, such as excavating the soil, water extraction and the temporary sheet piles cover around 50,000 EUR for the cantilever wall and the reinforced soil structure. In case of the sheet pile wall, these costs are only 25,000 EUR by not applying temporary sheet piles.

Instead of using concrete and steel as main materials, the retaining function of the reinforced soil structure is derived from the use of polymers. However, like steel and concrete, polymers also have major environmental impact. High density polyethylene (HDPE) and polyethylene (PE) – the polymers that are used – are mainly obtained from petroleum, yet the reinforced soil structure has significantly lower environmental costs. The low ECI of these polymers originates in the very limited volume that is used. Thin layers of stretched HDPE collectively have a low volume.

The environmental effects can also be expressed in 13 impact categories as shown in Figure 9. Global Warming Potential (GWP), Human Toxicity (HT) and Acidification (AP) are the most notable categories indicated in shades of blue. GWP is caused by greenhouse gasses, such as CO2, methane and nitrous oxide. This category is expressed in an equivalent with CO2 as reference. Greenhouse gasses hold warmth that results in a (faster) rising temperature on earth. Human toxicity includes the emissions of toxic substances that are exposed to human beings. This exposure finds its way by breathing or consuming products like meat and fish. Acidification arises after releasing sulphur oxides. The acidification of soil and water has a negative influence on ecosystems.

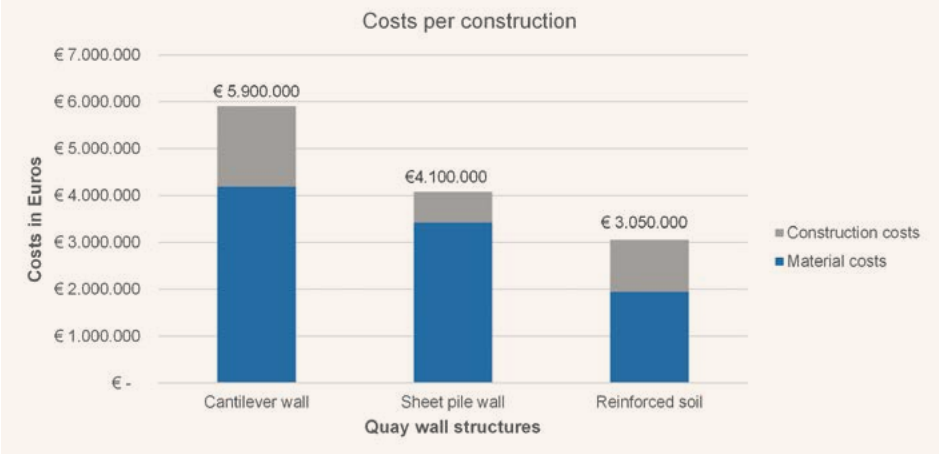

FIGURE 7

Total costs per quay wall structure.

The study showed it is technically feasible to design a reinforced soil structure quay.

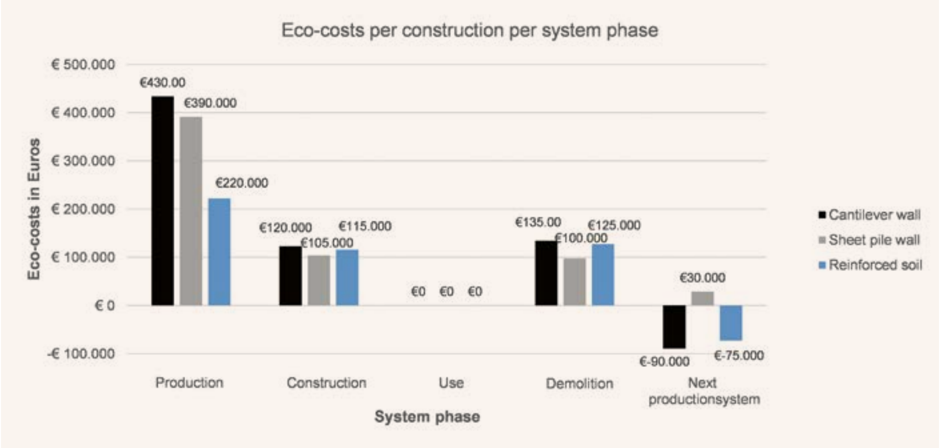

FIGURE 8

Environmental cost indicator (ECI) per life cycle phase.

FIGURE 9

Environmental Cost Indicator (ECI) per quay wall structure.

Conclusions

The purpose of this research was to design a future-proof, inland quay wall structure in a delta area that has the potential to be more cost effective and more sustainable than conventional quay walls. Initially the study showed it is technically feasible to design a reinforced soil structure quay. Solutions to implement quay elements, such as the L-shaped capping beam and the anchored facing panels were necessary to expect a reinforced soil structure to perform properly as a quay. How much the design is in fact future-proof is derived from the following three developments: upgrading the quay wall to receive CEMT-class V vessels, including those with increasing loads and load conditions, and finally by adding 1 metre to the retaining height for extreme weather conditions.

The material costs of the reinforced soil structure are considerably lower compared to both the cantilever wall and the sheet pile wall quays. The combined material and construction costs are 25% lower than the most favourable quay wall structure. The same is true for the environmental costs, which are 35% cheaper with the reinforced soil structure.

Summary

Nowadays, most inland quay walls mainly consist of concrete or steel materials. As a result of ongoing climate change and rising costs of materials, an investigation into more sustainable and more cost-effective structures for inland quay walls has been carried out. Various innovative quay wall structures have been designed after which a Multi Criteria Analysis (MCA) concluded that a reinforced soil structure has the highest overall value for implementation as an inland quay wall. Various solutions to implement quay elements such as bollards were necessary to use a reinforced soil structure as a quay. Designing three quay wall structures under equal circumstances, including the innovative quay and two reference quays of steel and concrete, made it possible to compare the criteria costs and sustainability. By calculating the material and construction costs, a cost estimation could be made. Determining the environmental effects on so-called impact categories was completed using a Life Cycle Analysis (LCA). The result is that a reduction of 25% on investment costs and reduction of 35% on the environmental cost indicator is achievable with a reinforced soil structure.

FIGURE 10

Lars van Rouwendaal receiving the award from Dirk-Jan Walstra, chairman of the Dutch hydraulic engineering prize jury (*Waterbouwprijs*), for best hydraulic engineering graduation research 2022.

Berend Schmidt

Berend graduated in 2022 with a degree in Civil Engineering from Windesheim University, in the Netherlands. Throughout his studies, his interest in hydraulic and future-proof solutions has grown. Berend's internship at Arcadis gave him insights into the world of port and waterway designs. These experiences provided him with better knowledge about these topics during his thesis on innovative quay wall structures. Berend's joint research was awarded the *Waterbouwprijs* – the prize for best hydraulic engineering graduation research of 2022 in the Netherlands.

Lars van Rouwendaal

In 2018, at the age of 16, Lars started the civil engineering programme at Windesheim University, in the Netherlands. The lessons in hydraulic engineering and internships working on both the Afsluitdijk and IJburg projects further inspired his interest in hydraulic engineering and specifically in the offshore wind industry, land reclamation and port development. In November 2022, together with Berend, Lars' graduation thesis on innovative quay wall structures was awarded the *Waterbouwprijs*.

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