THE FEASIBILITY OF REMOVABLE PREFAB DIAPHRAGM WALLS

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ABSTRACT

A diaphragm wall is a cast in-situ reinforced concrete retaining wall applied in, among others, quay walls. The main advantages of this type of retaining wall are that it can be made in almost every preferred length and that it can resist high structural loads. However, there are several disadvantages: sufficient concrete cover on the reinforcement cannot be guaranteed and the wall has a low sustainability score because it requires a large quantity of building materials, which cannot be reused, and is difficult to remove. This study is done to improve the diaphragm wall design by applying prefabricated concrete elements that are connected by vertical prestressing. Research is done on the element dimensions and detailing, constructability, costs and the carbon footprint of the design option. The concept has been developed as an alternative to the quay wall in a reference project, namely the Euromax Terminal in the Port of Rotterdam. An optimized prefab element configuration is developed. The construction costs of the design option appear to be higher than those of the quay wall in the reference project, but the difference in costs reduces considerably when maintenance and removal costs are included in the analysis. The carbon footprints of the prefabricated wall and of the cast in-situ reference wall are almost equal. However, where there is a certain probability that a quay wall will be removed before it reaches the end of its technical lifetime, a prefabricated wall has a considerably better score than a cast in-situ wall; the prefab wall can be removed and its elements can be reused. The design option then has a better score on both costs and carbon footprint.

Keywords: removable, diaphragm wall, prefabricated concrete elements, quay wall, reusable.

1. INTRODUCTION

This paper is the result of the master thesis for the master Structural Engineering, specialization Hydraulic Structures, at Delft University of Technology [1]. The paper discusses the feasibility of applying a removable prefabricated (prefab) diaphragm wall, considering the constructability of the wall as well as the costs and carbon footprint. The study is done on the basis of a reference project, which is the quay wall, with a cast in-situ diaphragm wall, of the Euromax Terminal Rotterdam (see Figure 1).

The main reason to perform the study is that a cast in-situ diaphragm wall has several disadvantages. For instance, with regard to durability, there is no guarantee of sufficient concrete cover because the wall is made in-situ. And the sustainability of the wall can be improved since a large quantity of building materials are required to construct the cast in-situ wall. These materials cannot be (fully) recycled as the wall cannot be removed (easily). The main advantages of this type of retaining wall are that it can be made in almost every preferred length and can resist high structural loads. A possible solution to minimize the disadvantages is by applying a removable prefab diaphragm wall.

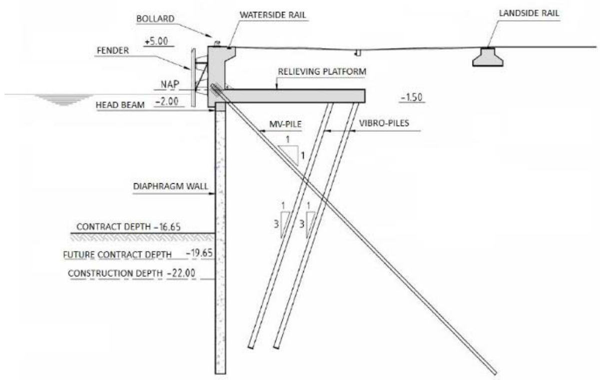

Figure 1. Quay wall applied in the reference project

On the basis of the reference project, two design options were proposed. The difference between the two design options is the applied concrete type for the prefab diaphragm wall: one in normal concrete and the other in lightweight concrete. Other materials, such as wood, are not considered since it appears to be less economical attractive [2]. Since the results of the two design options appears to not differ much, in this paper only the option in normal concrete is considered.

2. PROPOSED DESIGN OPTION

The proposed design option is similar to the quay wall in the reference project. The only difference is the retaining wall. The prefab diaphragm wall consists of wall sections (see left figure of Figure 2). A wall section consists of three prefab concrete elements. To realize the demountable horizontal connection between the concrete elements of a wall section, vertical post-tensioning unbonded prestressing steel is applied. The prestressing steel is anchored at the bottom of the retaining wall and at the top of the head beam.

The lengths of the prefab concrete elements are determined by the position of the horizontal connections (between element 3 and 2 and element 2 and 1). The horizontal connections are positioned at a relatively small bending moment position in order to limit the amount of required prestressing steel; the amount of the prestressing steel is determined by the requirement that the horizontal connections need to be closed (compressive stresses) in the serviceability limit state. The right figure of Figure 2 shows the moment diagram (black curve) for the prefab diaphragm wall only. This leads to the following proposed element lengths: 3.5 m, 15.0 m and 13.0 m.

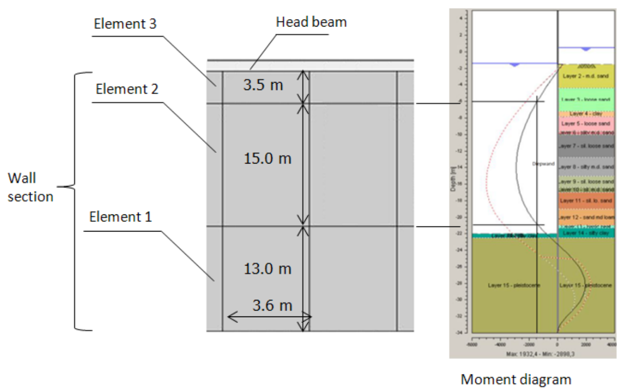

Figure 2. Prefab diaphragm wall (left) and the moment diagram (right)

At the level of the maximum bending moment the reinforcing steel in the tension zone is determined according to Eurocode 2. The width of the prefab concrete elements has been limited to 3.60 m in order to avoid the need for mobile cranes with excessive lifting capacity. Figure 3 shows the cross-section, including the two end parts for the realization of the vertical joint between adjacent wall sections.

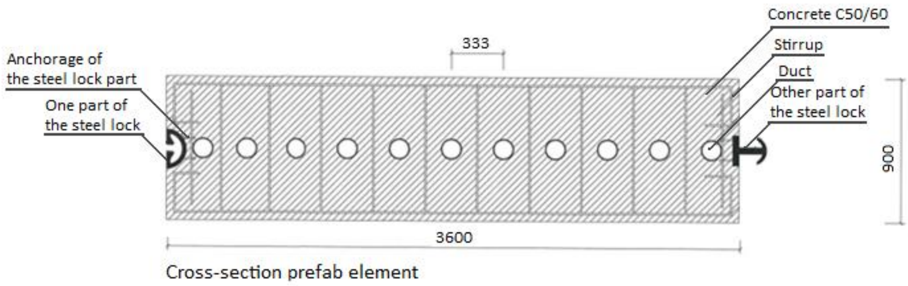

Figure 3. Cross-section of the prefab element (in mm)

3. CONSTRUCTION

The construction of a removable prefab diaphragm wall differs from the general construction of a cast in-situ diaphragm wall. The first steps are similar: placing guide walls, excavation of the trench and replacing the bentonite suspension with a cleaner bentonite suspension. The difference in the first steps is the fact that the cross-section of the trench is larger than the cross-section of the prefab element so that the bentonite suspension can flow along the element during the lowering of the element in the trench.

Then, the prefab elements are placed one by one in the trench by mobile cranes. A solution has to be found to reduce the risks of inclination of the first element due to the fact that the bottom of the trench after excavation is not leveled. A proposed solution is to apply a sand (and gravel) bed before the first element is placed and, if necessary, to apply a (concrete) extended part at the bottom of the first element to ensure that the element is pressed to the already placed wall section (see Figure 4). After the sand (and gravel) bed is placed, the first element of the wall section is placed in the trench. The prestressing strands, which are bundled per duct, are anchored at the bottom of the first element and protected against corrosion.

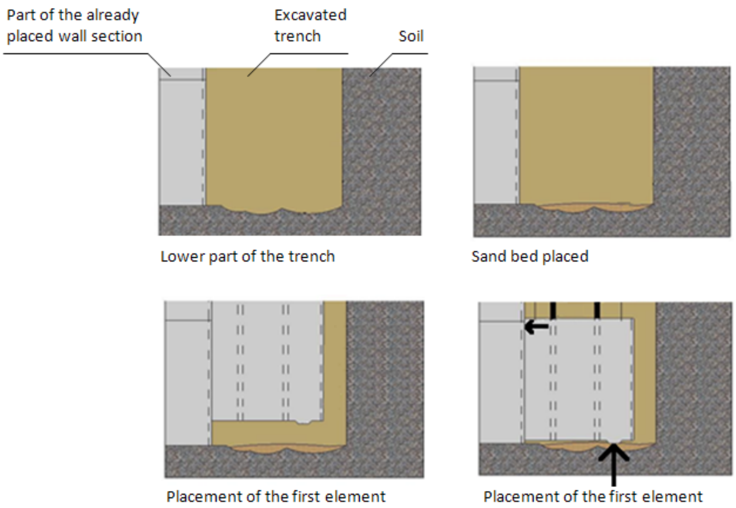

Figure 4. Sand bed and placement of the first element

Vertical guidance of the elements is provided by the vertical joint between the wall sections. The vertical joint is similar to the lock in sheet piling wall. The joint consists of two steel parts (see Figure 3): one part in the already placed wall section and the other part in the element of the wall section that is being realized. The joint is sand- and watertight thanks to the preformed polyurethane interlock seal. To reduce the risk of damage of the sealing during the placing of the elements, a biodegradable lubricant is applied at the joint part of the element being placed.

Next is the placing of the second element on top of the first element. In this construction method, the horizontal connection is realized in the trench (filled with bentonite suspension). During the lowering of the second element the bundles of prestressing strands runs through the ducts of the second element (see left figure of Figure 5, just 2 bundles are drawn). To ensure the correct placement, the horizontal connection consists of a male and a female part (see right figure of Figure 5). No assurance can be given that there will be no soil particles in the connection after it is realized. The fact that (1) the bentonite suspension after the excavation is replaced by a cleaner bentonite suspension and (2) the male part of the horizontal connection is on top of the first element, reduce the risk of inclusion. An additional measure to reduce the risk of inclusion might be injecting with a bentonite suspension (0% sand) or water between the two elements right before the connection is realized.

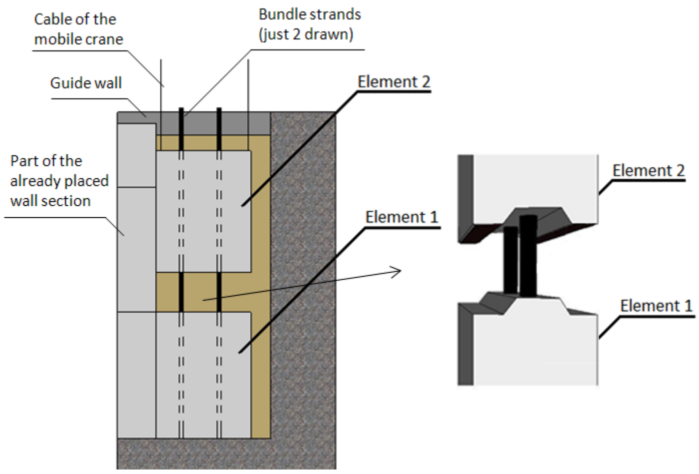

Figure 5. Placement of the second element (left) and detail horizontal connection (right)

The third, or top, element of the wall section is placed in a similar way as in the case of the second element. Before the head beam can be placed, the bentonite suspension filled gap between the wall sections and the wall of the trench has to be filled in order to prevent instability of the trench. In projects where prefab diaphragm walls have been applied, this gap was filled with a self-hardening clay-cement suspension, e.g. parking garage [3]. However, to be able to remove the diaphragm wall, a different solution needs to be applied. In this case, the gap, at both sides, is filled with sand. Next, the head beam and the anchoring of the prestressing strands on top of the head beam are realized.

Finally, the construction of the superstructure and the placing of the required facilities are done in a similar way as in the reference project.

4. REMOVAL

The removal of a quay wall of this scale, total length of 1.9 km and a retaining height of 27 m, has never been done before. In this section a removal method of the proposed design option is presented.

First, a sand layer in front of the diaphragm wall is added in order to prevent instability of the diaphragm wall during the removal of the quay wall and the soil behind the wall of the relieving platform is removed. The next step is the removal of, respectively, the wall and the floor of the relieving platform. Figure 6 shows the situation after the wall of the relieving platform is removed. After the removal of the floor, the soil behind the diaphragm wall is removed until the level where the vibro-piles can be extracted. At that level, the MV-piles are cut in case it is not required that they are fully removed. Then, the soil behind and in front of the prefab diaphragm wall is removed up to a level at which the lowest prefab concrete element can safely be removed.

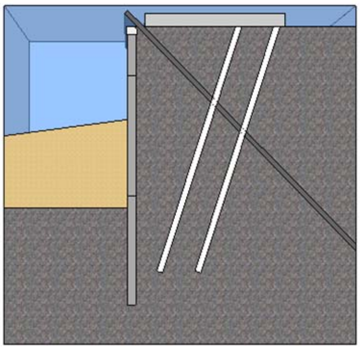

Figure 6. Situation after the wall of the relieving platform is removed

The prefab diaphragm wall is removed per wall section and per element. The steps are shown in Figure 7. First, the head beam is cut at the vertical joints of the wall section and the anchors of the prestressing strands on top of the head beam are removed. This can be done in the dry using a steel watertight caisson. The caisson consists of two parts that are shaped such that they can be connected to each other and to the prefab diaphragm wall. After the removal of the anchors at the top, the elements of the wall section are removed one by one. Provisions, such as lifting anchors, are applied to the elements to enable lifting them, e.g. by a pontoon crane. The top element with the part of the head beam is removed first, then the second element and finally the first placed element, where the prestressing strands are still anchored at the bottom of the first element.

The prefab elements are placed on a pontoon and transported. The quality and the remaining lifetime of the elements and prestressing strands can then be assessed.

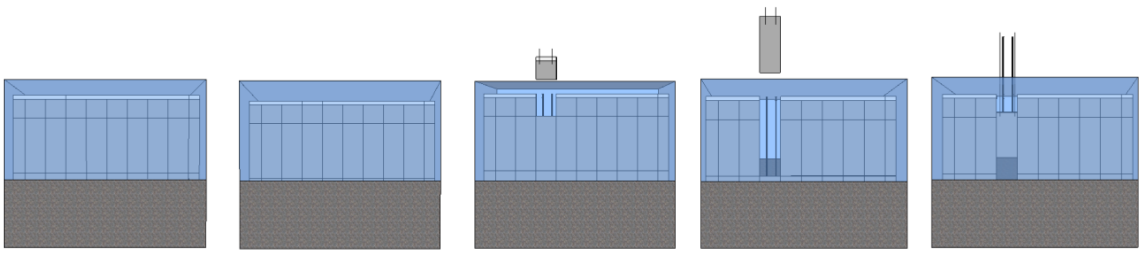

Figure 7. Steps for the removal of a wall section

5. COSTS AND CARBON FOOTPRINT

The costs and the carbon footprint are determined for both the design option and the quay wall in the reference project. The total costs are divided into construction, maintenance and removal costs. The construction costs are based on characteristic values. Both the maintenance and removal costs are based on assumptions using the percentages (related to the construction costs) as given in [4]. It is assumed that (1) the annual maintenance costs are identical for both options and (2) that the removal costs for the design option are lower than for the quay wall in the reference project. Furthermore, in order to sum up the different costs, which are made at different times, the present value of each cost component is determined, assuming that the inflation rate is 2.0% and the interest rate is 3.0%.

Figure 8 shows the contribution of each material component (section) to the total costs of the prefab concrete elements. The prestressing strands appear to have a considerable contribution of 47%.

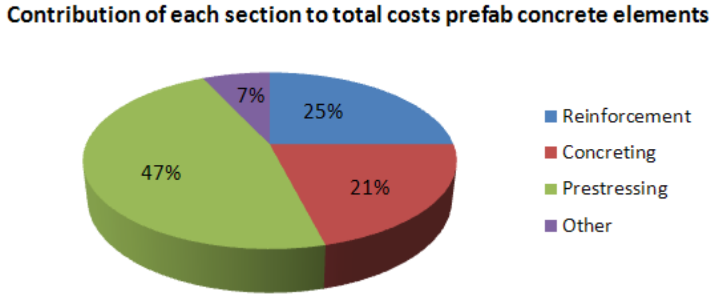

Figure 8. Contribution of each section to total costs prefab concrete elements

Figure 9 shows the different costs for both options. It appears that the construction costs of the prefab diaphragm wall are higher than for the cast in-situ diaphragm wall; the difference is 28%. The cost difference between the two options when taking into account the construction, maintenance and removal costs (considering the removal of the quay wall once the technical lifetime, 50 years, ends) is just 3% of the total costs of the reference project.

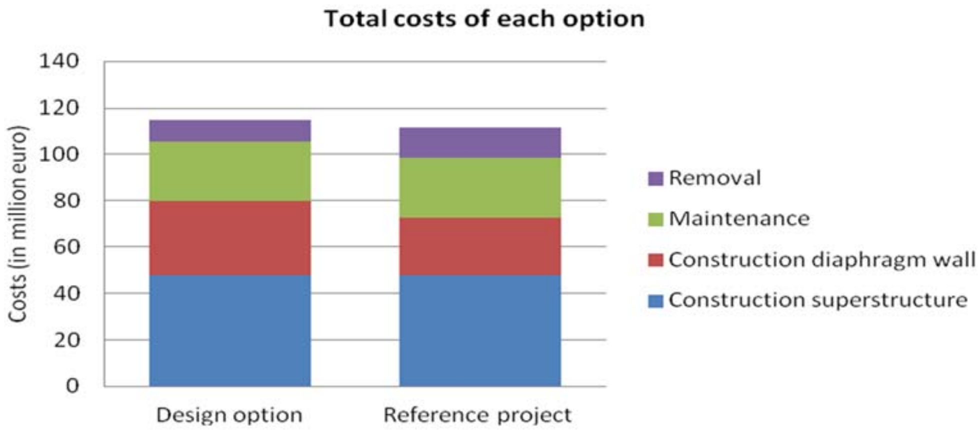

Figure 9. Total costs of each option

The carbon footprint of the construction of each option is determined with the carbon dioxide equivalent (CO_2e) using characteristic values. Most of the characteristic values are based on the data provided by the Interfacultaire Vakgroep Milieukunde. Table 1 shows for each option the carbon footprint (per running meter) and the shadow costs (for the entire quay wall). The shadow costs are based on the carbon footprint of the entire quay wall, with € 0.05/kg CO_2e [5]. The shadow costs for both options show that the difference between the two options is relatively small.

Table 1. Carbon footprint and shadow costs for each option

	Material [kg CO_2e/m^1]	**Transportation [kg CO_2e/m^1]**	**Application [kg CO_2e/m^1]**	**Total [kg CO_2e/m^1]**	**Shadow costs [quay wall]**
Design option	4.9×10^4	3.4×10^3	7.5×10^3	6.0×10^4	€ 5.9 mln.
Reference project	5.1×10^4	2.5×10^3	7.3×10^3	6.1×10^4	€ 6.0 mln.

Due to, among others, changes in functional requirements, a quay wall is relatively often removed and replaced by a completely new wall before it reaches the end of its technical lifetime. Therefore, to consider the possible advantage of removing and reuse of the prefab concrete elements, several cases are considered where the first quay wall has to be removed before the technical lifetime ends. In this paper two cases are considered for both options: a quay wall with cast in-situ diaphragm wall (basic option) and a quay wall with prefabricated diaphragm wall (design option). For case A, the first constructed quay wall is removed in year 10. The construction of the second quay wall (with the same conditions) starts in year 11. For the design option the prefab concrete elements and the prestressing strands are reused for the construction of the second quay wall. Finally, the second quay wall is removed in year 51. The only difference between case A and B is that in case B the assumption is that the prestressing strands cannot be reused and therefore need to be replaced.

Table 2 shows the results for both cases per option, where in the last column a positive value shows that the design option is favourable compared to the basic option. The table shows that the design option is not favourable when the prestressing strands are not reusable and the removal (and maintenance) costs are not taken into account. The difference is however relatively small (see “construction costs – case B”). The design option is in all the other situations (considerable more) favourable. Finally, the difference in shadow costs, for case A and B, shows that for the construction of the two quay walls the design option has a lower carbon footprint.

Table 2. Costs per option for both cases

	Basic option	**Design option**	**Difference**
Total costs – case A	€ 195 mln.	€ 178 mln.	€ 18 mln.
Total costs – case B	€ 195 mln.	€ 189 mln.	€ 6 mln.
Construction costs – case A	€ 138 mln.	€ 129 mln.	€ 9 mln.
Construction costs – case B	€ 138 mln.	€ 140 mln.	-€ 2 mln.
Shadow costs – case A	€ 12 mln.	€ 10 mln.	€ 2 mln.
Shadow costs – case B	€ 12 mln.	€ 10 mln.	€ 2 mln

6. CONCLUSION

It can be concluded that it is feasible to design and construct a removable prefab diaphragm wall. However, the construction method of the prefab option is more complex compared to the cast in-situ diaphragm wall. Innovative solutions are necessary to realize the construction. And by applying lifting anchors to the concrete elements it is possible to simply remove the prefab elements.

The construction of the prefab diaphragm wall is 28% more expensive than of the cast in-situ diaphragm wall. This is mainly caused by the use of a large quantity of prestressing steel. The construction costs of the design option are therefore higher. However, the difference in costs is just 3% when considering the entire quay wall and taking into account the maintenance and removal costs (in case the quay wall is removed once the technical lifetime ends). Further optimizing of the design of the prefab diaphragm wall, e.g. by applying thicker elements which leads to a reduction of the total quantity of prestressing steel, could lead to lower costs and make the design option more favourable. And the carbon footprints of the options are more or less equal.

The design option has a better score (than the basic option) when considering the possibility to reuse the prefab concrete elements in the construction of a second quay wall. It then has a better score on both costs and carbon footprint. To benefit from the advantages of the design option, it is important that the prestressing strands can be reused as well.

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