Geogrid-anchored sheet pile walls: field test and numerical analyses

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ABSTRACT: The application of geogrids to anchor steel sheet pile walls is an interesting solution for back filling projects. Since the mechanical behaviour of the system is complicated, a large research project is currently in progress that includes trial projects, field monitoring, laboratory experiments as well as numerical and analytical analyses. This paper presents the first results of the research project and discusses a case study and numerical analyses. The project deals with the construction of the 34 wind turbines of 'Windpark Krammer', near a large lock complex in the South-West of the Netherlands. In this project, several wind turbines were built on small peninsulas that were constructed next to the existing breakwaters. The peninsulas were constructed by installing sheet pile walls anchored with geogrid. After back filling, the piles for the foundation of the wind turbines were installed through the geogrid anchorage. The loss of geogrid capacity had been taken into account in the design calculations. One sheet-pile wall anchored with geogrids was subjected to a test load. The wall deflections, total anchor forces at the connection to the sheet pile wall, the differential displacements between sheet pile wall and geogrids and the strains in the geogrids were measured during the loading process (van Duijnen et al., 2020). The measured deflections were smaller than expected. In order to better understand the possible reasons for the large deviations between the measurements and results obtained from the standard design methods, a series of numerical analyses were carried out. Based on these analyses, a first guidance is given on the design aspects of sheet pile walls anchored with geogrids.

1 INTRODUCTION

To optimize the design of sheet pile walls, back anchoring is a common and economical solution. Although steel anchors/nails have been adopted widely for such constructions, using geogrid to back anchor the sheet pile can offer a significant benefit. One of the reasons is the possibility to preload the anchorage already during the construction. In the Netherlands, geogrid-anchored sheet pile walls were applied in the construction of the Krammer Windpark. This wind park in the Southwest of the Netherlands was opened in 2018 and consists of 34 wind turbines constructed on small peninsulas next to existing breakwaters where the open water has a tide. An aerial photo of the windpark Krammer is shown in Figure 1.

In this project, sheet pile walls with for example steel grout anchors were initially planned as the obvious solution. However, installing 32 to 48 driven piles for each turbine between the steel grout anchors was a major risk during the construction stage. To reduce this risk, it was tried to reduce the number of anchors. This resulted in long and heavy sheet pile walls (AZ26 / AZ36). The drawbacks of this solution were the relatively high costs and the environmentally unfriendly impact.

Figure . An aerial photo of windpark Krammer (photo courtesy of Paul Martens)

Finally, the project was realized using short, lighter sheet pile walls (AZ13/AZ18-700), anchored with three to six anchors that each consisted of a double layer of geogrids (Figures 2 and 3): each anchor consisted of one long geogrid that was wrapped around a horizontal steel pipe, which was in turn attached to the sheet pile wall. The main objective of this new design was to: (a) limit the use of raw materials (e.g. steel), and (b) minimize the depth of sheet pile wall.

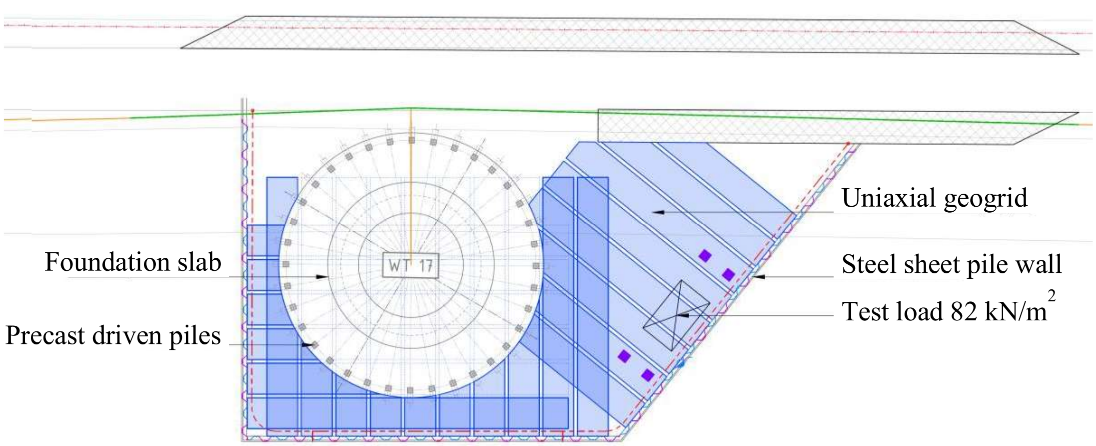


Figure 2. Top view with the geogrid anchored sheet pile walls

The piles for the foundation of turbines had to be driven through the area of the sheet pile wall anchors. This was one of the reasons to anchor the sheet piles with pre-stressed flexible geogrids. The installation of piles was carried out by pre-drilling an installation hole through the geogrids, until just beyond the lowest geogrid, followed by normal pile driving beyond this depth. To compensate the loss in the cross-section of the geogrid at the drilling regions, a geogrid with twice the design tensile strength was applied. The length of the geogrids was designed from bottom to top, assuming the effective anchorage length (green segments in Figure 3) starting from the rear of the underlying anchor. The anchor body of the lowest anchor was defined as the part of the geogrid outside the active wedge. This approach resulted in a long top anchorage layer (anchor 3.1 and 3.2 in Figure 3).

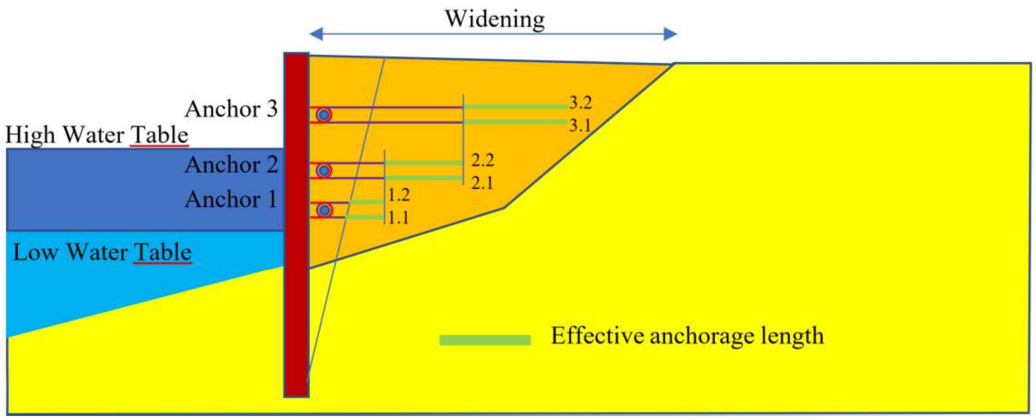
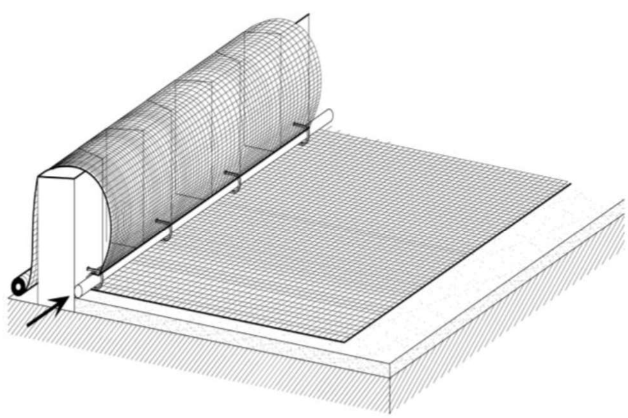


Figure 3. Estimation of the required effective anchorage length of geogrids (in green)

The anchors were connected to the sheet pile wall using a steel pipe ø156 mm that was in turn connected to the sheet pile walls using a special rigid steel construction. This construction could not transfer a bending moment to the sheet pile wall (i.e. hinged connection). Afterwards, the geogrid was wrapped around the steel pipe and laid in the back filled soil body. The details of the connection between the geogrid anchor and the sheet pile is illustrated in Figure 4. As shown, each anchor consists of two layers of geogrid that transfer their tensile load to the soil through soil-geogrid interface friction. In other words, installing three anchors in a system results in six layers of geogrid. After embedding a length portion of the geogrid in the soil, the anchors can be pre-stressed by pushing the steel pipes towards to the wall. Afterwards, the connection between the rigid steel construction and the steel pipe guarantees the position of pipes.

In this project, a large water level difference over the sheet pile wall was prevented by perforating the sheet pile wall.



a) full-width geogrid anchor during installation

b) strip geogrid anchor

Figure 4. Details of geogrid anchor-sheet pile wall connection

Despite the financial and environmental advantages of this solution, there were a number of technical questions. Therefore, a full-scaled load test and corresponding field measurements which were conducted and combined with some 2D finite element (FE) calculations that will be presented and discussed in this paper.

2 LARGE-SCALED LOAD TEST

A field test was carried out on one of the sheet piles. The load was exerted on a semi-rigid footing with an area of 3×6 m^2. The strain in the geogrids, the displacement of the sheet pile wall, the settlement beneath the load and the total force in an anchor layer were measured. A total vertical load of 150 tons (i.e. 1472 kN) was applied. This corresponds to 1472 kN /(3×6 m^2) = 82 kN/m^2 vertical pressure. Figure 5 shows the arrangement of the field load test.

Figure 5. Arrangement of the full-scale load test in the field

The strains in the geogrid layers were measured locally by recording the elongations over a short distance using displacement transducers. The differential displacements between sheet pile wall and geogrid are measured manually using oversized bicycle gear-type cables to measure strains. This system was used before in experiments and field tests as reported Van Eekelen et al. (2020). Each transducer consists of a number of similar steel cables attached alongside to each other to the geogrid.

This way, the changes in distances between five fixed points on the geogrid and the front face of sheet pile were measured. Moreover, the displacement of the sheet piles was measured at two different levels. The total tensile force in a geogrid anchor was measured with four force transducers at the connection between the geogrid and the sheet pile wall. Details can be found in Spingher (2018).

Figure 6 shows the measured anchor forces. The stress relaxation in the geogrid in the early stages after construction is clear. Strange is the absence of tensile force increase just after applying the test load. Figure 6 also shows an increase in the anchorage force when the test load is removed. This can only be explained if the distance between the horizontal steel pipe, around which the geogrids were installed, and the sheet pile wall reduces. In the finite element (FE) calculations, such a mechanism has only been observed when one anchor layer is modelled with two layers of geogrid, with a “steal beam” presenting the steel pipe, and a node-to-node anchor between the sheet pile wall and the pipe. In that case, the calculation shows an increase from 37 kN/m for the situation with top load to 39 kN/m for the situation without top load.

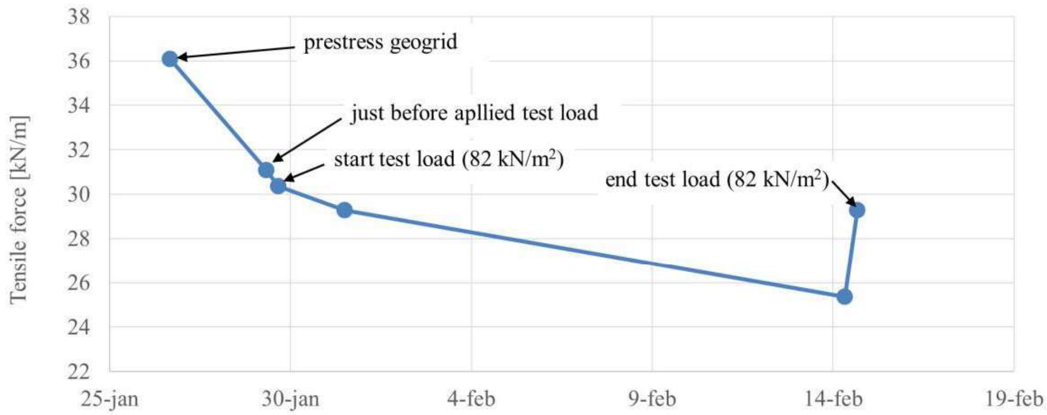


Figure 6. Measured tensile forces in the geogrid

The measurements show that the sheet pile wall moves only a few millimetres. In addition, the application of the top load had almost no influence on the measured anchor forces. This was found to be in contradiction with the design calculations that showed an increase in the anchor forces. In the design phase, the anchors that consist of two geogrid layers, were modelled with only one single geotextile layer. With reference to these discrepancies between the measurements and expectations, Detert et al. (2019) raised the following research questions:

- What is the influence of the construction phase?
- What is the creep/relaxation of the geogrid how does that affect the sheet pile wall deflections?
- What is the impact of the geogrid anchors on the horizontal pressure on the sheet pile walls?
- What is the influence of pre-stressing?
- What is the required strength of the geogrids?
- What is the required minimum embedment depth of the geogrid anchored sheet pile wall?
- How does the structure behave in different applications?

To find technically adequate answers to above-listed research questions, and also to enable a transparent interpretation of the field measurements, a series of numerical simulations was carried out by Spingher (2018). In the following chapter, some of these questions, considered as key questions, will be presented and discussed with the support of the field measurements as well as the FE results of Spingher (2018).

3 RESULTS AND DISCUSSION

3.1. *Influence of the geogrid anchors on the horizontal stress distribution*

The first key research question deals with the influence of the geogrid anchors on the horizontal stress distribution behind the sheet piles. The anchoring affects the horizontal load on the sheet pile wall in two ways:
a) For the situation with three anchor levels, six geogrid layers will intersect the active earth wedge behind the sheet pile wall. This may influence the shape of the active wedge and thus the horizontal load on the sheet pile wall; and b) The geogrids are wrapped around the horizontal steel pipes that is in turn connected to the sheet pile wall by a stiff steel construction

as shown in Fig. 4b. These pipes and the stiff connections absorb part of the horizontal load and limit the horizontal displacements of the sheet pile wall. Accordingly, arching in the fill between the pipes can be formed that affects the load distribution on the sheet pile, so that the load distribution is different from a standard unsupported sheet pile wall. Such an arching mechanism was also observed in geosynthetic-reinforced retaining walls in laboratory investigations by Ruiken (2013) and laboratorium experiments and numerical analyses of Ahmadi (2020). Spingher (2018) conducted numerical simulations of the field test presented in this paper. He included all construction stages, including the fill compaction before the load test. Additionally, he simulated the stiff steel connections between the pipes and the sheet pile walls with some geometrical simplifications. Figure 7 shows the calculated distribution of the horizontal load on the sheet pile, before and after compaction as well as during the test load and after the removal of the test load. The red line indicates the horizontal bedding stress for the test load, calculated with c-phi reduction, with a safety factor of 1.87. Moreover, Figure 7 shows a clear reduction of the horizontal effective stress behind the pipes (black dots).

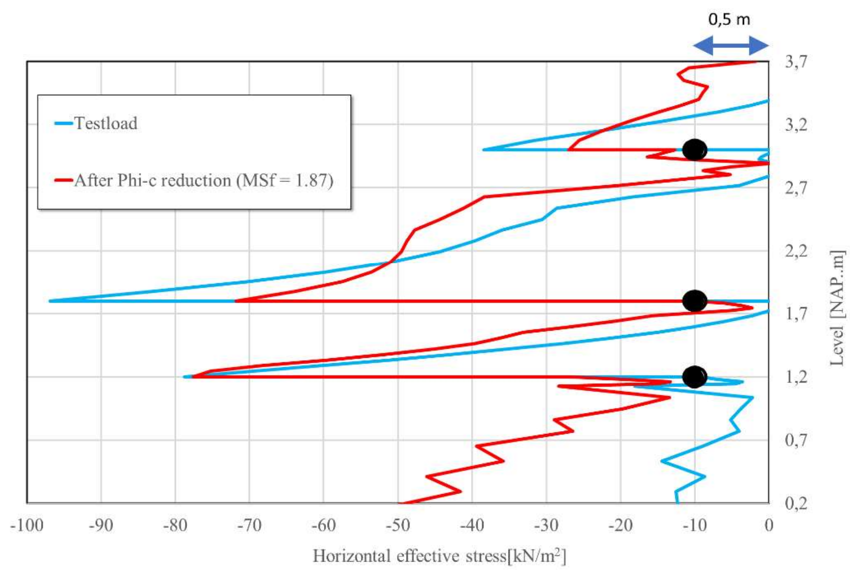


Figure 7. Distribution of the horizontal effective stress on the sheet pile wall. Modified after the results of Spingher (2018), obtained with FE analysis.
(The black dots give the location of the horizontal pipes that are part of the connection between geogrid and sheet pile wall)

In the Netherlands, the elevations are referred to with respect to the normal Amsterdam's sea level (NAP). In this elevation scale, the bottom, middle and top geogrid anchors were installed at NAP +3.0 m, NAP +1.8 m and NAP +1.2 m, respectively. Ground level on the active side of the sheet pile wall lies at NAP +3.8 m. Figure 8 shows the geogrid tensile forces for different distances from the sheet piles between ground level and NAP +0.5 m. The values in this figure were determined by integrating the calculated horizontal soil stress along vertical lines between ground level at NAP +3.8 m and NAP +0.50 m.. The Figure shows that the total load is fairly constant in the vicinity of the sheet pile wall: approx. 65 kN/m, both before and after the application of the test load. During the loading phase, the load at that location increases with 10% to 72 kN/m. Additionally, the possible occurrence of arching was investigated by post-processing the variation of the directions of principal stress vectors in the course of loading. There was no clear pattern recognisable showing whether the arching can be confirmed.

Both Figures 7 and 8 show that the horizontal pipes and the corresponding stiff connections reduce the horizontal load against the sheet pile wall. However, the amount of the reduction, cannot be determined clearly from the measurements. Therefore, additional analyses have been carried out to better evaluate the influence of pipes on the horizontal stress distribution on the sheet pile walls.

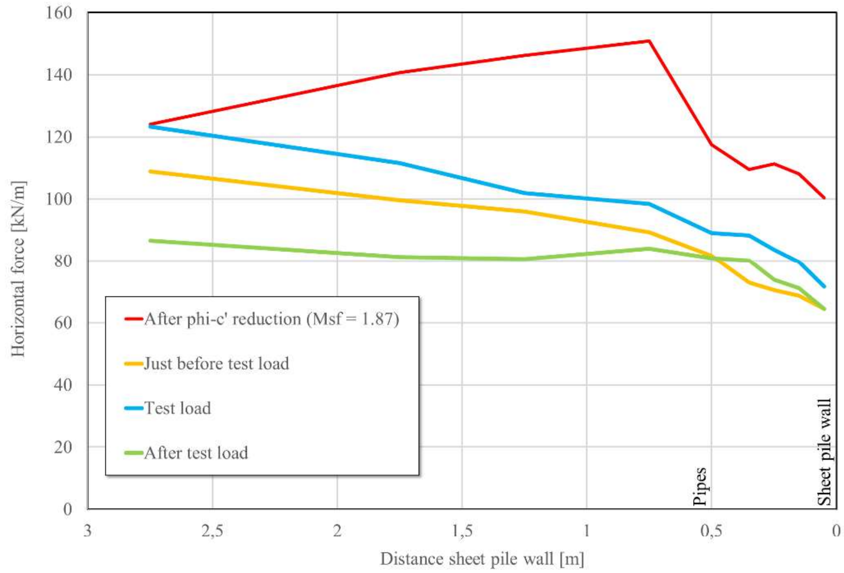


Figure 8. Total horizontal force between ground level (NAP +3.8 m) and NAP +0.5 m, determined by integrating the horizontal stresses along vertical lines between the ground level at NAP + 3.8 m and NAP +0.5 m. Result of FE analysis.

3.2. *Required tensile strength geogrid anchors*

As mentioned before, each anchor consists of two geogrid layers. Here, a key technical question is: do the two geogrid layers work together, or do they behave individually? If a tensile force is exerted on only the bottom geogrid of an anchor, the required strength and stiffness would be twice the values needed for the situation where two geogrids each takes an equal part of the tensile force. To answer this question, Figure 9 shows the calculated tensile force distribution in the individual geogrids of the three anchors.

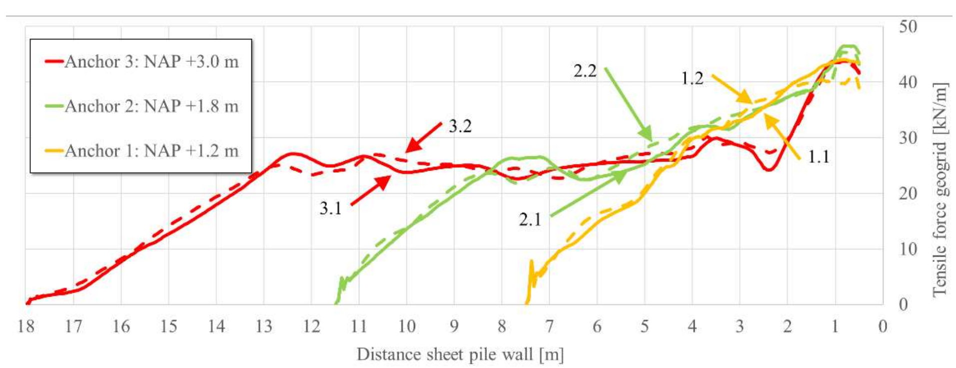


Figure 9. Tensile force in geogrids obtained from FE analysis (dotted line: upper geogrid, solid line: lower geogrid).

As can be seen in Figure 9, two geogrid layers of one anchor at each level work perfectly together. Therefore, the tensile strength and stiffness can be considered as the sum of the 2 geogrids at each anchor level. This is in line with the findings of van Eekelen and Bezuijen (2014) for geosynthetic-reinforced pile-supported embankments.

3.3. *Influence of the length of the geogrid on the active zone*

Another key technical question concerns the way that the length of geogrid can affect the active zone. Apparently, the geogrid must be long enough to transfer the load to the ground properly, without the risk of pulling out the geogrid, or direct sliding of the anchored mass in total. In this frame, it is important to study: (a) where does the geogrid transfer the tensile force to the ground; and (b) is the friction mobilised on both sides or only on one side of a geogrid?

To address the first question, the friction can be mobilised outside the active wedge. However, it is not yet clear what happens if two or more anchors have been installed at a short vertical spacing? Therefore, we assume that the upper anchor only transfers force to the subsoil beyond the end of an underlying anchor. Figure 9 and 10 show the calculated tensile force in the geogrids for the three anchor levels in different scales, where the scale in Figure 9 is on a more readable scale. These tensile forces were determined using a phi-c reduction analysis (Msf=1.87). The origin of the active slip plane is assumed to be located at the shear forces-zero point of the sheet pile wall.

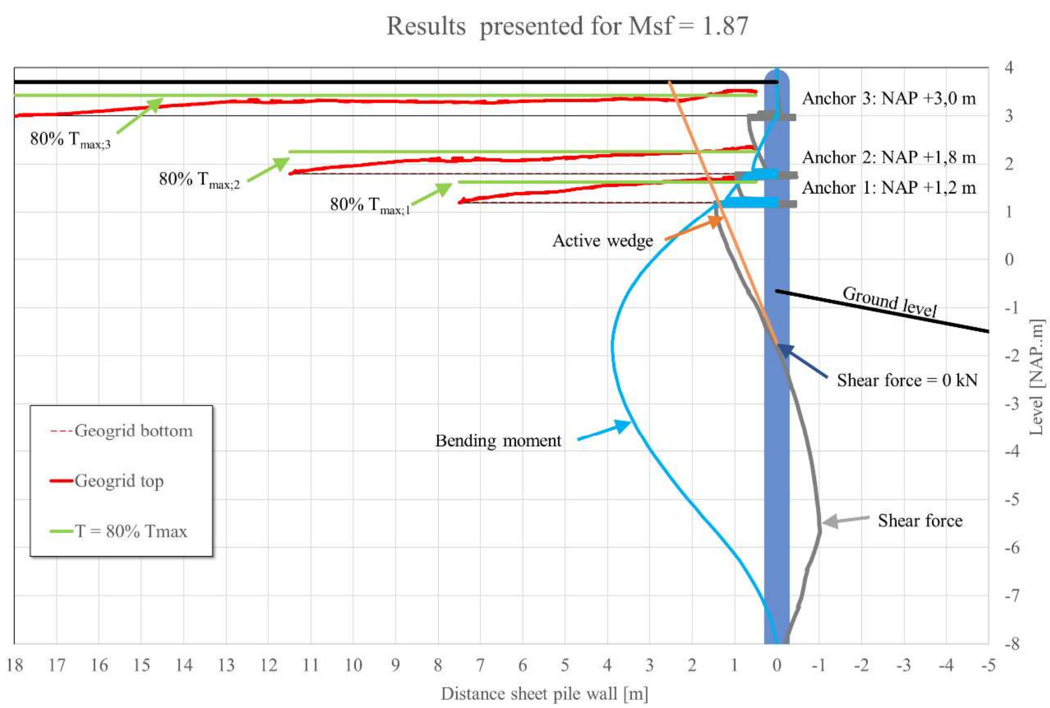


Figure 10. Calculated distribution of the tensile forces in the anchors at the collapse (safety analysis)

The tensile force in anchor 1, which is the bottom anchor, seems to remain fairly constant within the active wedge. However, outside the active wedge, the tensile force reduces relatively quickly (with a rather high reduction coefficient). For anchor 2, the reduction of tensile force outside the active zone is less, while the decrease is much quicker behind the rear of the underlying anchor 1. For anchor 3, which is located on top, the same is true: the tensile force slightly decreases between the edge of the active zone and the rear of the underlying anchor, while behind the rear of the underlying anchor, anchor 3 transfers the major part of its force to the soil, resulting in a sharp decrease of tensile force.

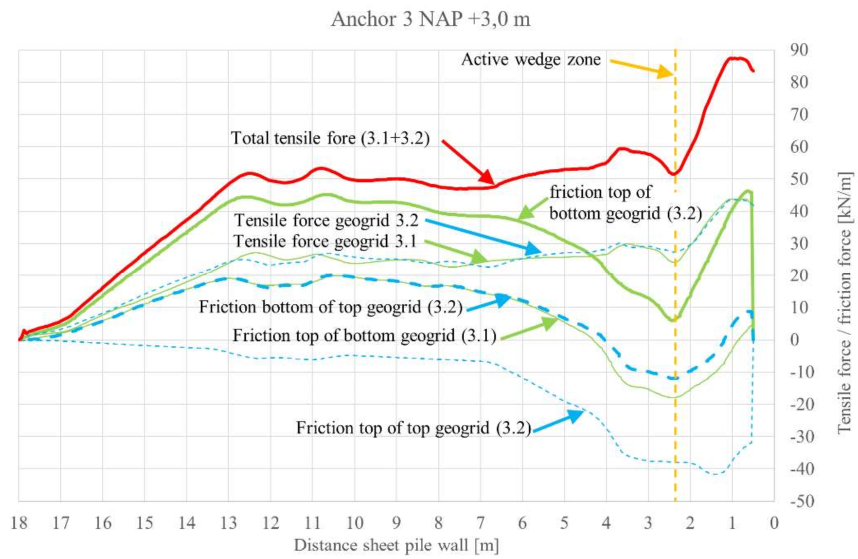


Figure 11. Calculated tensile force in the geogrid and friction force in the interfaces along the two geogrids of anchor 3.

For anchor 3, some friction is mobilised within the active sliding plane too. This is clearly shown in Figure 11; at a short distance from the sheet pile wall, the tensile force in both geogrids decreases from 44 kN/m to 30 kN/m at a distance of almost 3 m from the sheet pile wall. This Figure 11 shows more interesting details of anchor 3; it distinguishes the influence of the top (3.2) and bottom (3.1) geogrids of the anchor and in turn of the top and bottom interfaces of these two geogrids. Figure 11 shows the following:

- Both geogrids of the anchor have the same tensile force. The sum of the tensile forces is also given in the Figure 11 (the thick line).
- From this result, it is recommended to sum the stiffness and tensile forces in the two geogrids per anchor.
- The bottom geogrid (3.1) has the largest mobilised friction along its bottom. At the rear of the geogrid (between 18 and 13 m from the sheet pile wall), the friction along the bottom of the bottom geogrid is even nearly the same as the total tensile force in the two geogrids together.
- Between 18 and 13 m from the sheet pile wall, the mobilised friction along the bottom of the top geogrid (3.2) is similar to the tensile force in the top geogrid.
- The friction along the bottom of the top geogrid (3.2) and the top of the bottom geogrid (3.1) are similar. This shows that these layers work together and that the friction along the bottom of the top geogrid is transferred to the friction along the top of the bottom geogrid.
- A significant portion of the anchor force (approximately 80%) is absorbed by friction along the bottom of the bottom geogrid layer. Although friction at the top is also available, its contribution is limited.
- From these results, it is recommended to design with the development of the friction along the bottom of the bottom geogrid only.

These results confirm the assumption that anchor 1, the bottom geogrid anchor, transfers its force to the soil outside the active wedge. Furthermore, the results indicate that the upper two anchors only transfer their load along their part that is located behind the rear of their underlying anchors. A small part of the anchor force is also transferred outside and even inside the active wedge. The distance between the anchors and the depth in relation to ground level probably has a major influence. However, it seems clear that the design starting point, that most load is transferred along the bottom interface of the geogrid anchors behind the rear of the underlying geogrid anchors, is a safe assumption for analytical calculations.

TECHNICAL SESSIONS

4 CONCLUSIONS

The present study illustrates that the system of geogrid anchored sheet pile walls is complicated and designing such a construction method is challenging. On the basis of the large-scaled load test and numerical analyses that have been carried out in the frame of present research, the following conclusions can be drawn:

1. The geogrid anchoring seems to reduce the horizontal load on the sheet pile. This effect has only been observed around the anchors, at the location of the connection between the sheet pile wall and the geogrid anchor.
2. For the determination of the tensile forces in the geogrid, it is essential to note that the axial stiffness of both geogrids work together. This means that two layers of geogrid at each anchor level act as a single layer with double tensile stiffness. If an anchor layer with two geogrids is modelled numerically as one geogrid, the tensile stiffness and strength of the geogrid should be equal to the sum of the two geogrids.
3. The effective anchor length of the lower anchor starts just outside the active wedge. The effective length of upper anchors starts at the back of the underlying geogrid. Friction develops also outside the active wedge in the case of the upper geogrids. However, this friction is relatively limited and probably depends strongly on the geometry and should not be included in analytical design calculations.
4. A significant portion of the anchor force (approximately 90%) is absorbed by friction along the bottom interface of the lower geogrid layer in a double layer system. Although friction along the other interfaces along the geogrids is also available, its contribution is limited. Based on the presented results, it is recommended to only consider friction along the bottom of the lower layer of the geogrid for each anchor.

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