Geosynthetics: Leading the Way to a Resilient Planet – Biondi et al (eds)

Numerical investigation of geogrid back-anchored sheet pile walls

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ABSTRACT: In the last decades, geosynthetic reinforcement has been widely used in geotech-nical applications. Recently, geogrid has also been used to back-anchor sheet pile walls. However, this system has not received sufficient attention neither in research nor in construction. Due to the complex interactions between soil, geogrid and sheet pile wall, the applicability of common design guidelines for conventionally back-anchored walls to this particular system has to be proven. To develop a fundamental understanding about the influence of various components of the system on its behaviour, numerical investigations have been conducted within this study. In this paper the influence of geogrid inclination, design of geogrid-sheet pile connection including prestressing and geogrid position on the earth pressure distribution and wall deformation is discussed. The numerical results revealed that the position of geogrid and design of geogrid-sheet pile connection significantly affect the earth pressure distribution. The wall deformations are mainly influenced by the geogrid position.

1 INTRODUCTION

For many years, sheet pile walls have been key construction elements in the design of excavation pits and any types of marine constructions such as ship lock, cofferdams or wharfages. Sheet pile walls can be designed as unsupported walls with fixation in the soil. The use of unsupported sheet pile walls for large retaining heights often leads to large deformations, high embedment depths and thicker sheet pile profile, thus to uneconomical solutions. Therefore, the use of a support system e.g. anchors is selected to obtain a more economical designs. Depending on the boundary conditions, different types of support-systems are possible.

In the case of excavation pits, grouted anchors are often used. In bank construction with backfilled sheet piles, steel anchors with anchored plates or similar constructions are used. A newly alternative to this is the support with a geogrid (Detert *et al*. 2022; Van Duijnen *et al*. 2020, 2022). In this case, individual geogrids are inserted into the soil during backfilling and connected to the sheet pile wall, thus increasing the load-bearing capacity of the sheet pile wall. The advantages of this method are the easy installation as well as the support acting all along the wall, not like punctual support every few meters with anchors. Therefore, it is an economical alternative to other support systems and was therefore used in 2018 in the Netherlands at the Kramer wind park.

 DOI: 10.1201/9781003386889-115

However unlike e.g. conventional anchor systems, the geogrid interacts with the soil along its full length. This results in complex interactions that need to be investigated in detail. The aim of this research is to develop a numerical model that can simulate these interactions with the use of the finite element method and can be used to better understand the whole support system. Furthermore, the influence of different design variables, such as anchor length, on the earth pressure distribution and wall deformation will be analyzed in the following chapters.

2 NUMERICAL MODELLING

For a better understanding of the sheet pile wall geogrid system, small-scale tests (Wittekoek *et al*. 2023) and full scale test (Van Duijnen 2022) have been performed. These tests have been simulated using Plaxis 2D and the system behaviour detected from the numerical model was in a good agreement to the laboratory observations (e.g. in Wittekoek *et al*. 2022). Based on these observation, the creation and the main features of the finite element simulation in prototype scale are described in the following section.

2.1 *Finite element model*

Since sheet pile constructions are line structures, a 2D finite element simulation in plain strain is sufficient, wherefore the numerical model was created in finite element code Plaxis 2D. As shown in Figure 1 the sheet pile wall is embedded in a clay soil layer and is supporting a 10 m thick backfill layer of sand. The geogrid is located in this backfill and connected to the wall. The selection of the model dimension was based on the recommendation from EANG (2014). Thus, twice the backfill height was chosen for the lateral distances from the sheet pile wall to the model boundaries. The distance between the bottom of the excavation pit and the bottom edge of the model was also chosen accordingly. The sheet pile wall was modeled as a plate element and the soil as a volume element. An interface was placed between the wall and the soil to allow a realistic sheet pile wall-soil interaction as well as between geogrid and soil. In Plaxis geogrids exist as a structural element, which is a 5 node line element with two degrees of freedom *(ux,uy)* in each node. The only material constant is the elastic axial stiffness *EA*. To realistically account for the membrane effect of the geogrid, the finite element mesh must be updated during the simulation.

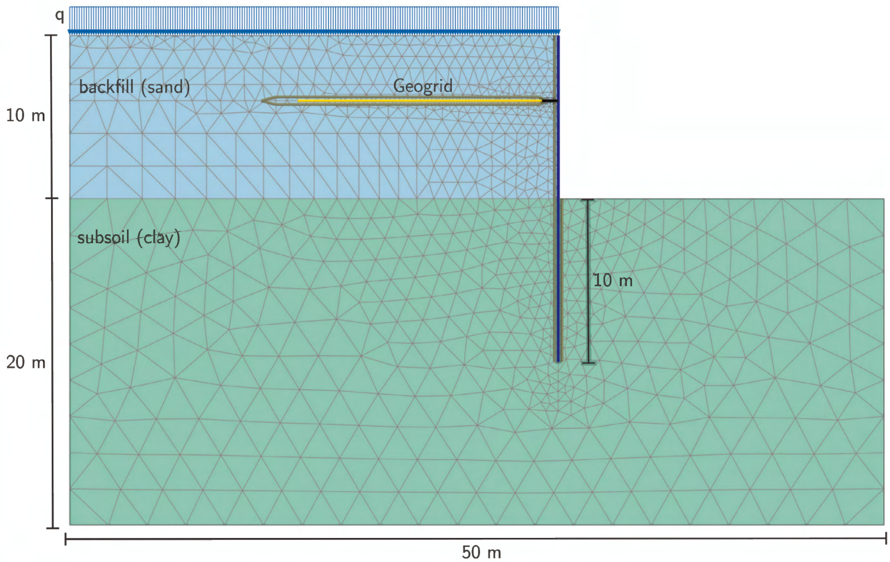

Figure 1. Finite element model of sheetpile wall with geogrid.

Table 1. Constitutive parameters of hardening soil model used in finite element simulation.

Name	Parameter	Sand	Clay
E_{50}^{ref} (kPa)	Secant stiffness	35000	52500
E_{Oed}^{ref} (kPa)	Tangent stiffness	35000	52500
E_{ur}^{ref} (kPa)	Unloading/reloading stiffness	105000	157500
m (-)	Power coefficient	0.5	0.5
ν_{ur} (-)	Poissons's ratio	0.20	0.20
$K_0^{nc}(-)$	K_0 value for normal consolidation	0.5	0.6580
R_f (-)	Failure ratio	0.9	0.9
p^{ref} (kPa)	Reference stress for stiffness	100	100

The hardening soil model (Schanz 1998) was used to obtain a more realistic stress-strain behavior of the soil. The hardening soil model has a double hardening yieldsurface, stress-dependent stiffnesses and Mohr-Coulomb (MC) failure criterion. An important detail of the finite element model is the prestressing of the geogrid. On the construction side the geogrid will be inserted and covered with soil, except 1 m close to the sheet pile wall to allow the prestressing. The geogrid is then pulled towards the sheet pile wall using an excavator, where it the wall, creating a prestress. A slight pre-stressing is needed in-situ to allow a force-fit connection to the sheet pile wall, which should prevent the geogrid from slipping under load. In the finite element model two types of geogrid-sheet pile wall connections were simulated. First the installation and the prestressing of the geogrid was performed close to the reality and is shown in Figure 2. Instead of pulling the geogrid, which showed unrealistic results, a spring element between geogrid and sheet pile wall is used to apply the prestressing. Note, along the length of the spring element no interaction between the reinforcement and the soil takes place. Secondly, the geogrid is directly connected to the wall without prestressing.

The construction of the sheet pile wall as well as the installation and prestressing of the geogrids is modeled by the following 12 construction stages/phases:

Phase 1: Applying geostatic pressure on initial soil (clay)
Phase 2: Activation of sheet pile wall and interface

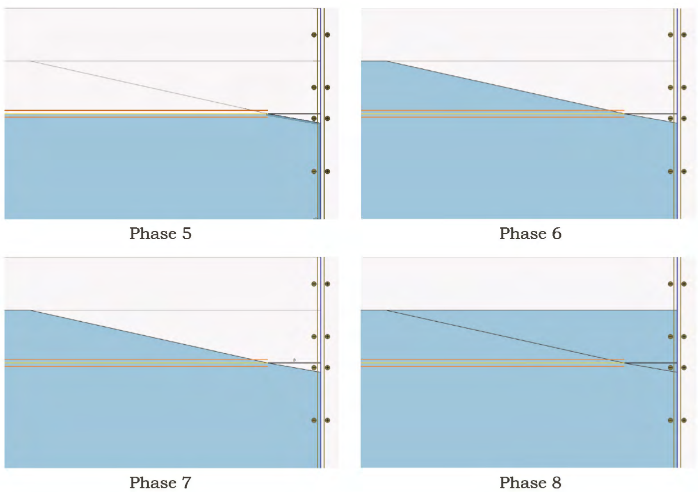

Figure 2. Phases of prestressing of the geogrid in finite element model (Description see text).

Phase 3: Backfilling from -10.0 m to -8.0 m
Phase 4: Backfilling from -8.0 m to -6.0 m
Phase 5: Activation of geogrid with interface and spring (s. Figure 2)
Phase 6: Placing of backfill on the geogrid with a thickness of 1.0 m (Figure 2)
Phase 7: Generate a prestressing force p = 20 kN/m in the spring element (Figure 2)
Phase 8: Backfilling the spring - entire area behind the wall is backfilled up to -5.0 m (Figure 2)
Phase 9: Backfilling from -5.0 m to -4.0 m
Phase 10: Backfilling from -4.0 m to -2.0 m
Phase 11: Backfilling from -2.0 m to -0.0 m
Phase 12: Activate uniform load q = 10,0 kN/m

3 RESULTS AND DISCUSSION

The influence of geogrid inclination, geogrid-sheet pile wall connection and the geogrid depth on the resulting earth pressure and wall deformation will be analysed in the following subsections.

3.1 *Influence of geogrid inclination*

The influence of geogrid inclination in retaining a sheet pile wall is investigated in the following. Therefore, the geogrid position is kept constant at -4 m and only the inclination is varied. Figure 3 shows both, the earth pressure distribution and the related sheet pile deformation for three exemplary geogrids with different inclinations (0%, 4% and 8%) and all prestressed with 20 kN/m. It can be seen that for all three inclinations an almost identical earth pressure develops over the entire height. The magnitude of this is slightly higher than the active theoretical earth pressure within the backfilled area and increases in the area of the sheet pile confinement, so that at the base of the wall the earth pressure generated is as great as the theoretical earth pressure at rest. If the associated displacements of the sheet pile wall are compared, a noticeable difference can be seen. The fact that the use of a geogrid with a greater.

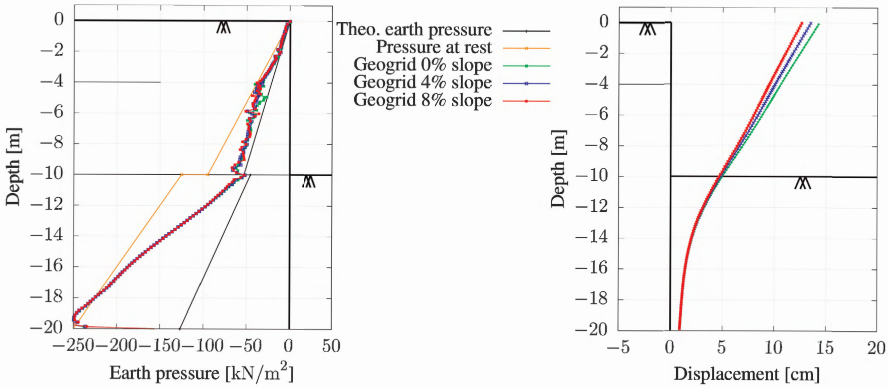

Figure 3. Earth pressure distribution on active side (left) and resulting wall deformation (right) for variation of the geogrid angle in vertical direction.

3.2 *Influence of numerical solution for the wall connection*

As mentioned before, the pre-stressing on site is needed to connect the geogrid perfectly straight and force-fit to the sheet pile wall. Since this is not necessarily needed for finite element modeling, the influence of the wall connection on the earth pressure distribution as well as on the wall deformation was investigated. As shown in Figure 4, the earth pressure distribution and the wall deformation are very similar. However, it is noticeable that the

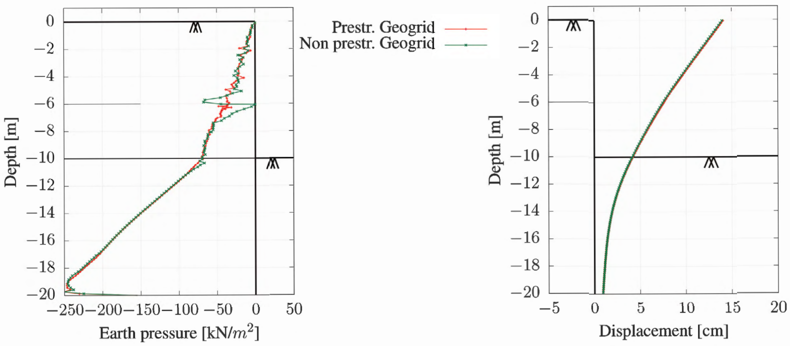

Figure 4. Effect of wall connection for a geogrid at -6 m on earth pressure distribution on active side (left) and resulting wall deformation (right).

calculation without pre-stressing gives jumps in the earth pressure distribution at the height of the geogrid connection. This can be explained by the shielding effect of the geogrid below the connection point. Above the connection point an increase of the earth pressure is visible, which can be explained by local arching effects. The use of a spring eliminates this shielding and arching effects and therefore these jumps are not visible in the earth pressure distribution of the model with prestressing. Which of these wall connection types should be used depends on the in-situ connection of the geogrid to the wall. In the following it is assumed, that the geogrid is installed close to the wall and only a short construction for the connection is designed, so the variant with direct connection is used for further simulations.

3.3 *Influence of geogrid position*

In order to analyze the influence if the geogrid position, different finite element models of the sheet pile walls retained by geogrids were created, in which the depth of geogrid placement was varied. In this publication only three exemplary variants, with the depths of -6.0 m, -4.0 m and -2.0 m are presented. Figure 5 shows the calculation results of the three models with different insertion depths of the geogrid. The earth pressure distribution in the clay layer is nearly identical in the section between -15.0 m and -20.0 m. In the upper 5 m of clay layer, higher earth pressure occurs for deeper geogrid position, which also occurs in the backfilled area from -7,0 m to -10 m. Above this depth, all three variations generally exhibit an identical earth pressure distribution. When comparing the three variations, it can be seen that the

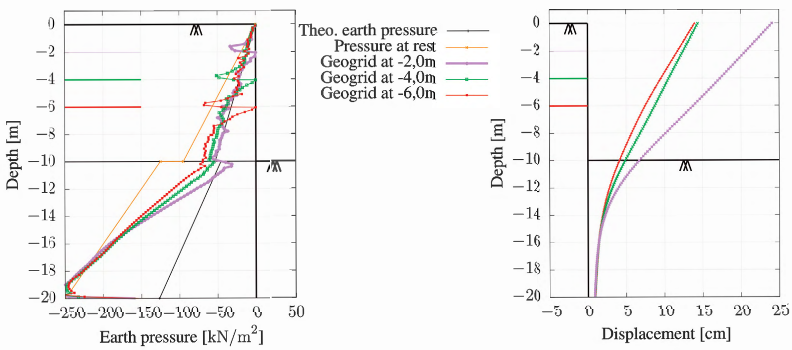

Figure 5. Earth pressure distribution on active side (left) and resulting wall deformation (right) for variation of the geogrid position in vertical direction.

geogrid positions -4 m and -6 m provide an almost identical displacement at the top, whereas the geogrid position -2 m has a significantly higher deformation. To explain this, the wall displacement for all calculation phases of the three variations is shown in Figure 6. Comparing the geogrid positions -4 m and -6 m, shows that the initial deformation prior activating the geogrid in the case of the geogrid at -6 m is lower than at -4 m. As a result, the geogrid with deeper geogrid position is also more loaded, so the maximum geogrid stress for the geogrid at a depth of -6 m is 270.7 kN, 201.2 kN for geogrid at -4 m depth and only 99.7 kN for geogrid at -2 m depth. Nevertheless, in the case of the geogrid position at -4 m, the wall does not deform so much after activation. This can be explained by the more favorable position of the geogrid with respect to the lever arm. In the case of the geogrid position of -2 m, the initial wall deformation is already so high that the geogrid can only reduce the wall deformation to a very limited extent.

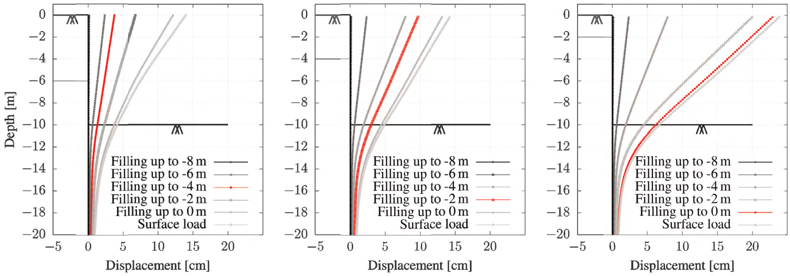

Figure 6. Sheet pile wall deformation for all backfilling phases for Geogrid at -6 m (left), at -4 m (middle) and at -2 m (right).

4 SUMMARY AND OUTLOOK

In the framework of this publication, a finite element model was created that can simulate the behavior of a sheet pile wall back-anchored with geogrids. Different geogrid positions as well as different angles of the geogrids were analyzed. The geogrid position in particular has a great influence on the wall deformation. For a further reduction of the wall deformation, other geogrid positions could be considered in future research.

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