Plaxis Practice

Simulation of soil nail in large scale direct shear test

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Introduction

In the Netherlands we have a history of living with water. Dikes, both at the sea and at rivers, need to protect us against flooding. The height of the dikes in the Netherlands needs to be increased in the future. Adjustment is needed because of climate changes, raising sea level and ongoing settlements. If raising of the crest level is required, stability is best increased by widening the dike. However, this is not possible in case of existing buildings at the land side and in the case narrowing of the river flow section is not allowed. Within this framework the project INnovations on Stability Improvement enabling Dike Elevations (INSIDE) started in 2001.

Consortium INSIDE Squad, a Dutch co-operation between Boskalis b.v., Van Hattum en Blankevoort b.v., Grontmij b.v. and Witteveen+Bos b.v. developed a new concept “Dijkvernageling”, which stands for reinforcing dikes by soil nailing. This way steeper slopes are possible. Figure 1 shows the typical failure mechanism of a dike and the reinforcing by soil nailing. The soil nails add to the stability of the dike, but do not take over the full load. The dike keeps functioning the way it did for hundreds of years. The soil nails increase the internal strength of the dike in three ways:

- anchorage of the sliding section;
- increasing of the contact stress at the shear plane;
- shear connection of the sliding section.

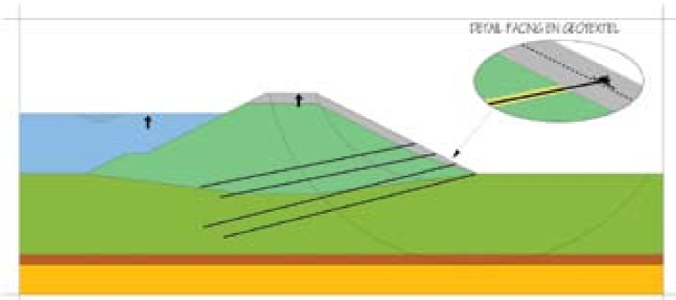

Figure 1: Typical section of reinforced dike by soil nailing

Research

Reinforcing embankments by soil nailing is a proven method to stabilise, especially in case of constructing a steeper slope in granular soils. But how does it work in dikes consisting of soft clay?

The main investigation goals were defined as:

- what is the behaviour of soil nails in soft clay in a direct shear mode;
- what are the 3D and group effects of the soil nails;
- is it possible to develop a design model.

Dike reinforcement by soil nailing is mainly achieved by the anchorage. However, the shear connection by the soil nails is important for the performance of the soil nail. The research is focued on the shear connection in clayey soils, as there is little experience on this subject.

To investigate the behaviour of soil nail in clayey soils, large scale direct shear tests were executed to explore the strengthening effects with different types of soil nails in clayey soils. The tests were executed in the laboratory by two circular steel structures with a diameter of 0.9 m and a total height of 1.2 m. The soil nail was placed centric in the cylinder with a rotation possibility at the bottom. The upper ring could displace by horizontal loading, while the lower ring was fixed.

Before performing the large scale direct shear tests, analytical and numerical finite element analyses (FEM) were carried out to define the soil nail properties such as diameter and bending stiffness in relation to the soil strength and the soil stiffness. After the tests, postdiction analyses were made to understand the behaviour and improve the FEM model.

A total of fifteen large scale direct shear tests have been performed with different soil nails. Three of these tests have been performed without soil nails for reference, six tests have been performed on very soft clay and two tests have been performed with three soil nails in one cylinder.

Typical soil nails that were used are:

- steel rods with a grout body of about 3 to 6 cm;
- carbon rods with a grout body of about 3 to 6 cm;
- HDPE strips with a width of 10 to 15 cm.

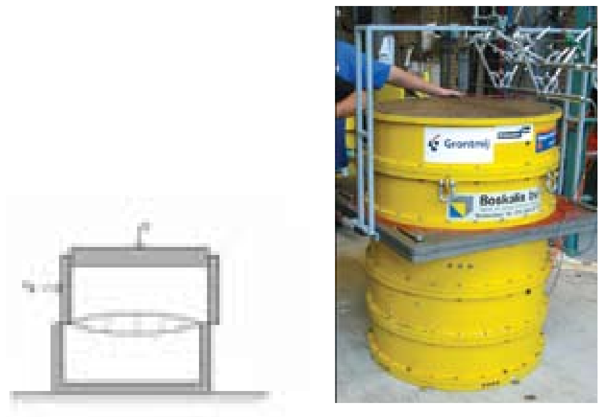

Figure 2: Large scale direct shear test

Soil behaviour in direct shear test

A proper way to investigate the maximum shear stress in soil is the direct shear test. This test shows the relation between the present normal stress and the maximum mobilised shear stress. For a drained situation Coulomb derived the relation as:

$$\tau = c + \sigma_n \tan\varphi$$

In the case of undrained situations, one may asscume $\varphi = 0$ and $c = c_u$. Although the maximum shear stress could directly be obtained, there are some disadvantages about the direct shear test. The location of the deformation plane is prescribed, and the stress situation in the soil sample is not uniformly recorded. In contrast of the simple shear test, the displacements in a direct shear test are not homogeneous but lenticular shaped as shown in figure 2.

Test result

Figure 3 presents the test results of the large scale direct shear tests on soft clay. The saturated density is 17 kN/m³ and the undrained shear strength is 9 kN/m². The total jack force has been normalised by the total undrained shear strength of the cross section; this is called the strengthening ratio. A ratio of 1.0 is equal to the maximum strength of the soil, any increase is caused by the soil nails. The maximum strengthening of 1 soil nail at 20 cm displacement is about 25% (ratio is 1.25). For 3 soil nails it is 75%. The force by 3 soil nails is equal to 3 times that of 1 soil nail. It can be concluded that there is no negative group effect for soil nails in a close grid (less than 0.5 m).

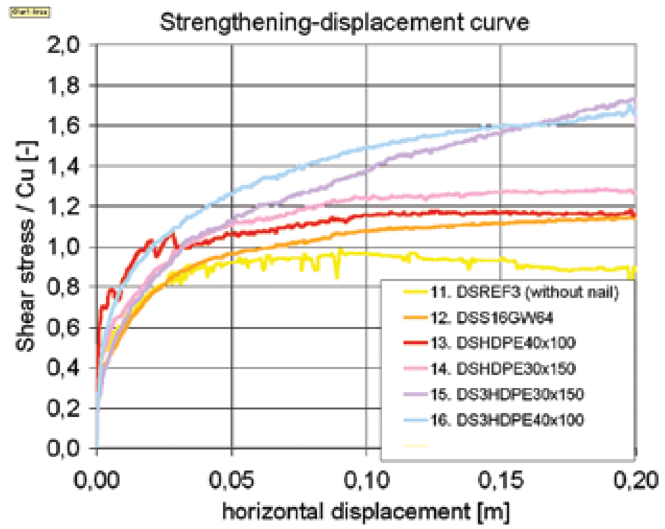

Figure 3: Strengthening by soil nail in direct shear test with soft clay

FE model in prediction analysis

Due to nonsymmetrical loading, numerical analysis was not possible with axi-symmetric 2D calculations. The use of PLAXIS 3D Tunnel makes it possible to simulate these large scale direct shear tests and 3D effects of the soil nailing properly.

In the prediction analysis, several models were developed to simulate undrained behaviour of natural clay, see figure 4. In 3D Tunnel, the tunnel structure will normally be generated in a horizontal *z*-direction. To model an undrained situation without increasing effective stresses in y-direction perpendicular to the tunnel lining, the initial stress condition was created in the first calculation step by using a uniformly distributed *z*-load. The material model used in the prediction analysis is the Mohr-Coulomb model, with $c = c_u$, $E = E_{undr;50}$ and φ set to zero. The different soil nails were modelled by a linear elastic tunnel structure with bending stiffness EI and extension stiffness EA.

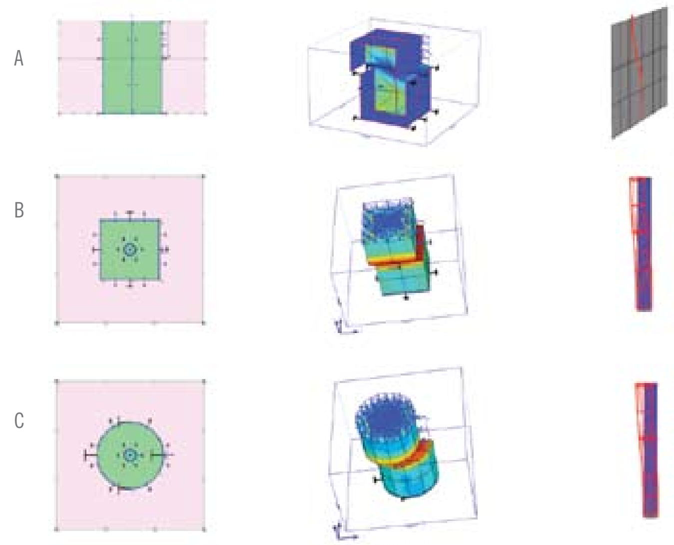

Figure 4: Developed models in prediction analysis

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Continuation

Postdiction model

To postdict the large scale direct shear tests more properly and to obtain more accurate stress results, the 3D Tunnel model was modified by using gravity loading with an adapting gravitation direction parallel to the tunnel lining and with adapted boundary conditions. Moreover, an improved modelling of soil behaviour was considered by using the Hardening Soil model and by distinguishing between effective stresses and (excess) pore pressures using the undrained setting.

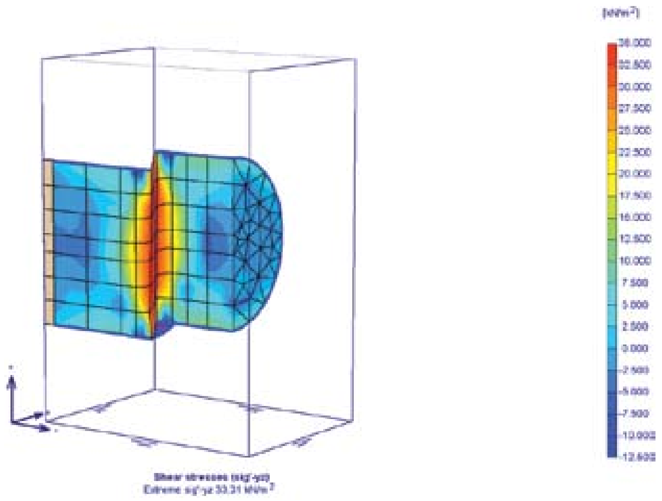

Figure 5: Postdiction reference model without nail, shear stresses

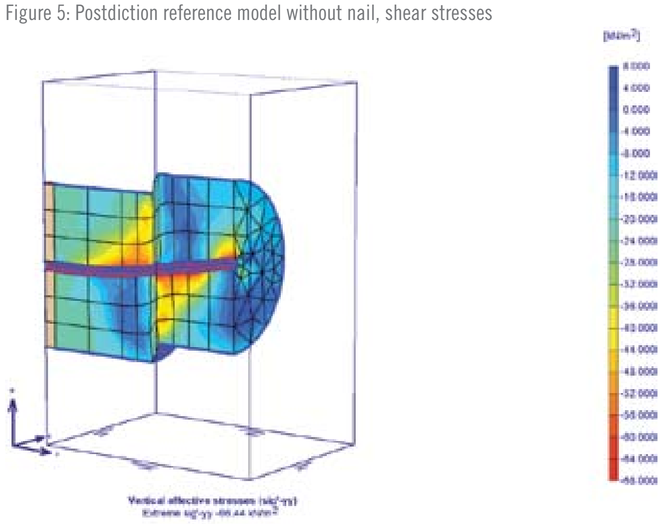

Figure 6: Postdiction model with soil nail, total stresses

Figure 5 presents the postdiction reference model without soil nail (half symmetric). The maximum calculated shear stress τ_{yz} was in fact equal to the input value used for the undrained shear stress ($c = c_u$). The shear stresses in the symmetric cross section also showed a lenticular development. Figure 6 presents the postdiction model with soil nail. There is an obvious interaction between the soil nail and the horizontal stresses.

Soil properties	prediction	postdiction
Model prediction A, B, C	Mohr Coulomb	Hardening Soil
Analysis	drained	undrained
Material type (clay)	undrained	undrained
Unit weight	18.4 kN/m^3	18.4 kN/m^3
Elastic modulus E_{50} (ref.)	700 kPa	700 kPa
Elastic modulus E_{oed} (ref)	-	1973 kPa
Elastic modulus E_{ur} (ref)	-	2100 kPa
Power m	-	0.8
Poisson's ratio	0.49	0.20
friction angle	1°	1°
cohesion	27.5 kPa	27.5 kPa
shear stress	A: x-y plane B + C: z-x plane	z-x plane
initial stress	z-load	gravity loading (drained)

Table 1: Material models and material properties

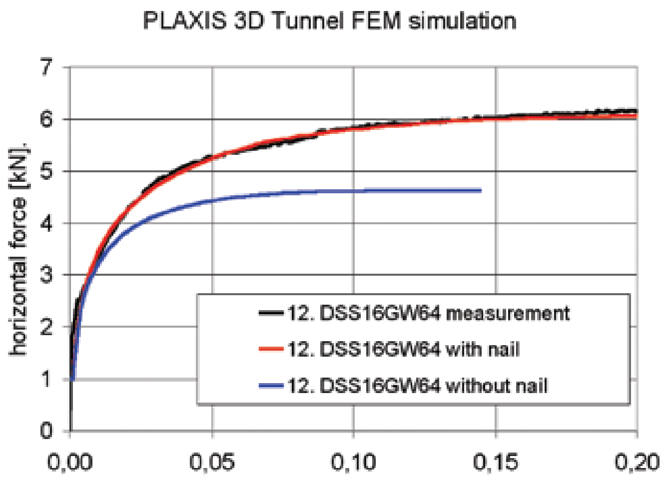

Figure 7: Postdiction model results, load-displacement curves with and without soil nail

The strengthening by a soil nail in a large scale direct shear test can also be determined with the postdiction model. First step is to perform postdiction analyses with soil nail. Second step is to switch off the soil nail and repeat the calculation. Figure 7 shows the difference between load-displacement curves of clay with soil nail and without soil nail. The strengthening ratio can be determined by the ratio of both analyses results.

Comparison of results

The strengthening effect has been determined by the interpretation of the measurements and the postdiction analyses with the 3D Tunnel model. The results of the strengthening ratio are presented in figure 8. The symmetry line represents the ideal relation between measurement and model. Most results do have a margin of less than 10% from this line. The results are very satisfying in particular because a variety of soil nails have been tested in normal and very soft clay. The 3D Tunnel model is capable to perform good postdiction analyses and can be used for future designs.

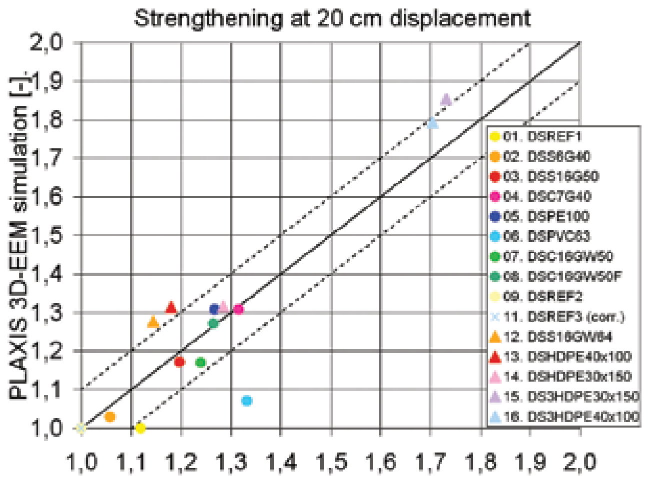

Figure 8: Comparison of strengthening ratio by interpretation of measurements and by the postdiction model

Conclusions on modelling

With regard to the presented results, one can conclude that PLAXIS 3D Tunnel offers a good tool to model the large scale direct shear tests. However, some suggestions how to obtain better results are presented below, as there is always room for improvement.

Mesh refinement with smaller element sizes might lead to even better results, but using smaller elements could increase calculation time dramatically. Using a half space symmetric model was one of the methods to reduce calculation time.

Further investigation on the influence of shaft friction between nail and soil and between soil and inner side of cylinder is recommended. The actual undrained shear strength is not constant in the different stress paths in the used model. Overconsolidation has been taken into account, but the degree of overconsolidation in the used clay after installation in the test rings is not recorded.

One of the advantages of the 3D Tunnel postdiction model is the fact that identical soil conditions are compared with and without the application of a soil nail. In this way, some of the inadequacies in modelling leading to different results can be faded out.