Soil nailing in clay for dike reinforcement

Cloutage du sol argileux par renforcement des digues

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ABSTRACT

Within the framework of the project Innovations on Stability Improvement enabling Dike Elevations (INSIDE) a new concept 'dike soil nailing' is developed, which stands for reinforcing river dikes (levees) by soil nailing. This way dike reinforcement can be achieved without widening the dike. In the present paper a feasibility study for the application of soil nailing in a dike reinforcement project along the Dutch river Lek is presented. Soil nailing design calculations are performed using the calculation models Talren and Plaxis 2D. Verification analysis of the design is carried out using Plaxis 3D Foundation modelling the soil nails as embedded piles. The design & verification analyses lead to interesting matches as well as disagreements between the different calculation models presenting sufficient challenges for further research and development. For the dike reinforcement project in Bergambacht-Schoonhoven the application of dike soil nailing is indeed a feasible and cost-effective reinforcement technique.

RÉSUMÉ

Dans le cadre du projet 'Innovations sur le renforcement de la stabilité pour permettre l'élévation des digues (INSIDE)', un nouveau concept a été développé comprenant le renforcement des digues fluviales par cloutage du sol. De cette façon, le renforcement d'une digue est possible sans élargissement de la digue. Cet article présente une étude de faisabilité pour l'application du cloutage du sol pour un projet de renforcement des digues le long du fleuve Lek aux Pays Bas. Des calculs statiques du cloutage du sol ont été faits en utilisant les modèles de calcul Talren et Plaxis 2D. L'analyse de vérification du projet a été faite avec Plaxis 3D Foundation en modelant les clous du sol comme pieux encastrés. Les calculs statiques et les analyses de vérification n'ont pas mené seulement aux résultats intéressants, mais aussi aux désaccords entre les modèles de calculs différents, ce qui présentent des défis suffisants pour la recherche et le développement dans le futur. Pour le projet du renforcement de la digue à Bergambacht-Schoonhoven, l'application du cloutage du sol est certainement une technique de renforcement faisable et d'un rapport coûts/efficacité satisfaisant.

Keywords : soil nailing, dike reinforcement, soft soils, 3D finite elements

1 INTRODUCTION

The Netherlands is located in a low-lying delta, where large rivers such as the Rhine and IJssel run into the sea. The densely populated areas are protected from flooding by river dikes (levees), the height and strength of which need to be increased on a regular basis to anticipate increasing hydraulic loading conditions due to climate change, rising sea levels and ground subsidence. Conventional dike reinforcement techniques (dike widening, berm construction) require adjustments to the dike exterior and use of extra land, which lead to loss of cultural heritage and forced relocation of houses and farms.

Within the framework of the project Innovations on Stability Improvement enabling Dike Elevations (INSIDE) a new concept 'dike soil nailing' has been developed, which stands for reinforcing dikes by soil nailing. This way dike reinforcement can be achieved without widening the dike. The soil nails increase the stability of the dike by improving the structural integrity of the nailed soil mass and by providing additional shearing resistance. The additional shearing resistance is generated by developing tensile forces (anchorage in the soil outside the sliding section) and shear forces (increasing the contact stress at the shear plane).

In this paper a feasibility study is presented for the application of soil nailing in a dike reinforcement project located along the Dutch river Lek between Bergambacht and Schoonhoven. The feasibility study consisted of (1) reference calculations with MStab and Plaxis 2D for the current situation, (2) soil nailing design calculations with Talren and Plaxis 2D and (3) verification analysis of the design with Plaxis 3D Foundation modelling the soil nails as embedded piles.

2 DIKE REINFORCEMENT PROJECT BERGAMBACHT-SCHOONHOVEN

Along the Dutch river Lek between Bergambacht and Schoonhoven the five-yearly check of the dike strength and stability led to the conclusion that the landward stability of the dike is insufficient. This is caused by an uplift situation of the hinterland under flood conditions due to a high groundwater head in the Pleistocene sand layer. Sliding failure will in this case occur through a failure plane just above the Pleistocene sand layer, as can be seen in Figure 1.

Conventional methods of dike reinforcement include the construction of a berm behind the dike to increase the soil weight on the hinterland, which leads to a reduction of the uplift conditions of the hinterland and an increase of the resistance against sliding by a higher shear stress at the failure plane. The construction of a berm would however require an area of at least 50 m behind the dike to be cleared of obstacles. At many places exactly this area is used for housing, refer to Figure 2.

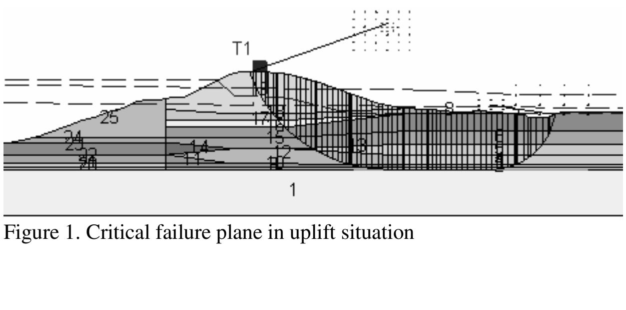

Figure 1. Critical failure plane in uplift situation

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Figure 2. Dike at the reinforcement project Bergambacht - Schoonhoven

Structural solutions for dike reinforcement include the installation of an anchored sheetpile at the toe of the dike or construction of a cofferdam at the crest of the dike. Both solutions effectively increase the stability of the dike but induce high costs, making it even less attractive considering the significant lengths of dike to be reinforced. Cost-effective solutions are therefore required. For this purpose the innovative concept of dike soil nailing has been developed, which introduces the proven method of soil nailing as a reinforcement technique for clay dikes on soft soil. When dike soil nailing is applied the dike can be reinforced at its current position without any additional spatial requirements.

3 DIKE SOIL NAILING: APPLICATION OF SOIL NAILING AS DIKE REINFORCEMENT TECHNIQUE

Reinforcing embankments by soil nailing is a proven method to stabilise steep slopes in granular soils. Soil nailing is often applied where vertical or near-vertical excavations are required. Dutch dikes however generally consist of a clay embankment with moderate slopes on soft soil. There is little experience in the application of soil nailing in soft soils.

In design guidelines for soil nailing (FHWA, 2003; CIRIA, 2005) the application of soil nailing in soft soils is generally considered unfavourable because of (1) low bond strengths at the nail-grout-soil interface, (2) long-term deformations (creep) in highly plastic clays, (3) instability of the excavation during construction and (4) additional swelling pressures on the facing. On the other hand the application of soil nailing in dikes presents a specific design case which deviates in many aspects from the traditional soil nailing practices. This is shown in Table 1 where an overview is presented of the main differences between traditional soil nailing in granular soils and soil nailing in dikes consisting of soft soils.

Table 1. Comparison traditional soil nailing and dike soil nailing

Aspect	Soil nailing (granular soils)	Dike soil nailing (soft soils)
Purpose	Stabilise excavation	Increase stability of existing slope
Slope inclination	45 – 90 degrees	10 – 45 degrees
Predominant loading	Soil selfweight	Flood conditions
Duration of loading	Permanent	Short
Length of nails	about 10 m	> 20 m
Preferable orientation of nails	Perpendicular to failure plane	Parallel to failure plane
F_n contribution [1]	Low	High
F_d contribution [2]	High	Low

[1] F_n = normal force in soil nails, see Figure 3
[2] F_d = shear force in soil nails, see Figure 3

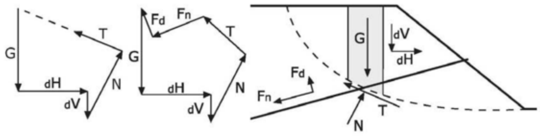

Figure 3. Contribution of soil nails to sliding resistance

The main difference between traditional soil nailing and dike soil nailing is that dike soil nailing is a method to increase the stability of an existing embankment in order to withstand the hydraulic loads during flooding conditions. This means that aforementioned arguments (3) and (4) are not applicable to dike soil nailing, as instability of an excavation and swelling pressures due to excavation do not occur.

Furthermore the nails are only subjected to loading for a short period of time, namely the duration of a design flood (generally a few days). So for the largest part of their lifetime the soil nails are not subjected to significant loading, which implies that long-term deformations (creep) are expected to be small even in soft soil.

In clay soil nails of larger length (20 m and more) are generally required because of low bond strengths compared to soil nailing in granular soils (soil nails of about 10 m length).

Regarding the orientation of the soil nails in dike reinforcement also specific design considerations apply. As shown in Figure 3 both the tensile force in the soil nail F_n and the shear force in the soil nail F_d provide additional shearing resistance against sliding T. The balance between these contributions can be influenced by adjusting the orientation of the soil nail with respect to the failure plane.

In conventional design soil nails are placed almost horizontal or slightly inclined downward. Because of the steep failure plane in granular soils the orientation of the soil nails is in most cases almost perpendicular to the failure plane, which means that the soil nails are to a higher extent subjected to shear forces (F_d in Figure 3) and bending moments, although still the tensile resistance of the nails may be dominant and the bending/shear resistance of secondary importance. For the bending/shear resistance a limiting factor will be the lateral resistance of the soil around the nail in the failure plane interface.

In the case of a dike with moderate slopes on soft soil the failure plane is more horizontal, which gives more possibilities to adjust the orientation of the nails with respect to the failure plane. A more parallel placement of the soil nails seems appropriate for dike soil nailing as the lateral resistance of the soft soil is limited. So the contribution of F_d to the stability of the nailed mass is even less compared to granular soils. So in dike soil nailing the increase of stability is primarily realised by tensile force (F_n in Figure 3). In this case the decisive failure mode is pullout of the nail, and the soil nail should be installed with sufficient anchoring length to mobilise sufficient tension capacity.

A research programme has been executed between 2002 and 2006 to investigate the application of soil nailing as a dike reinforcement technique. The research programme consisted of (1) investigation of the influence of soil nailing on dike stability using analytical methods, (2) large scale direct shear tests to research the behaviour of soil nails in soft clay, (3) prediction and postdiction of the laboratory tests in 2D and 3D FEM models, (4) development of a design method and safety philosophy, (5) execution of a demonstration test with the installation of a number of true-scale soil nails in a riverdike.

The analytical method is based on slip circle analysis for verification of the dike stability with and without soil nailing, a verification of nail dimensions and section forces based on a spring model, and a passive soil rupture calculation to determine the limit value of lateral soil pressure which can be transferred.

To investigate the behaviour of soil nails in clayey soils, large scale direct shear tests were executed with the purpose to explore the strengthening effects with different types of soil nails in clayey soils. Pre- and post-processing analysis were carried out with analytical and finite element methods. In figure 4 the test setup and a deformed nail after testing can be seen. From the test results an increase in shear strength of the soil has been observed of 25% compared to the situation without nails.

The research programme led to the acceptance by the ENW (a governmental organisation) of the soil nailing concept as innovative dike reinforcement technique. The design method of dike soil nailing has been incorporated in a Dutch design guideline (CUR 219, 2007). Also the author is taking part in the TC 288 for the development of the prEN 14490 'Execution of special geotechnical works - Soil nailing' (prEN 14490, 2007).

Figure 4. Large-scale Direct Shear test on nails in clay

4 DESIGN OF SOIL NAILING FOR DIKE REINFORCEMENT BERGAMBACHT-SCHOONHOVEN

In the feasibility study first reference calculations were performed with MStab, Talren and Plaxis 2D for the current situation, to cross-validate the calculation models and to gain a good view of the stability in the reference situation (without reinforcement). The results of the reference calculations are presented in Table 2. The SF (Stability Factor) presented is the result of a calculation in Ultimate Limit State, including all partial safety factors according to the Dutch standards on flood protection.

Table 2. Results of reference calculations

Calculation model	Loading conditions	SF
MStab – Uplift Van	Design high water	0.98
MStab – Bishop	Design high water	1.04
Talren – Bishop	Design high water	1.03
Plaxis 2D – Mohr-Coulomb	Design high water	0.99
Plaxis 3D – Mohr-Coulomb	Design high water	0.99

From Table 2 it can be concluded that the models show good agreement in the current safety of the dike. The Bishop slip circle calculation leads to a slightly higher stability factor compared to the Uplift Van model, which includes a section of horizontal sliding in the slip circle calculation to calculate the failure plane in an uplift situation as presented in Figure 1.

The target SF (stability factor) is 1.27 for this dike section in accordance with the Dutch codes and standards on flood protection. So the stability of the dike should be increased by about 25% to meet the requirements. A soil nailing design has been prepared as presented in Table 3 to meet the stability requirements with the minimum amount and length of soil nails.

Table 3. Design dimensions of soil nails

Parameters	Value
Nail diameter	60 mm (round steel)
Grout diameter	200 mm
Nail length	27.5 m
Angle with horizontal	20 degrees downward
Spacing horizontal	1.5 m
Spacing vertical	1.5 m
Number of rows in vertical direction	3 rows (+0.00; +1.50; +3.00)
Steel quality	FeB500 (f_y = 435 MPa)

Soil nailing design calculations have been performed using the program Talren which applies the Recommendations Clouterre (Clouterre, 1991). The slip resistance q_s of the nails in the clay under the dike has been deduced from the cone resistance measured in CPT tests on the dike crest. A minimum cone resistance of 1.3 MPa has been found for the clay under the dike, which with a shaft friction factor α_s of 0.016 results in:

$$q_s = \frac{\xi}{\gamma_{mb}} \cdot \alpha_t \cdot q_c = \frac{1.0}{1.3} \cdot 0.016 \cdot 1300 = 16 \text{ kPa} \quad (1)$$

The safety factors ξ and γ_{mb} are in accordance with Dutch design standards, for ξ a value of 1.0 can be applied with the requirement that acceptance tests are executed on all soil nails.

It is remarked that clay layers under a dike have better properties than clay behind a dike due to compression by the weight of the dike. Soil properties for soil nailing design should therefore be based on field tests performed at the dike crest.

The design has been checked with stability calculations of the reinforced dike section with the program Talren and with Plaxis 2D (modelling the soil nails as geogrids without flexural stiffness). The results are presented in Table 4.

Table 4. Results of design calculations of the reinforced dike

Calculation model	Talren	Plaxis 2D
SF without nails (reference calc)	1.03	0.99
SF with nails	1.27	1.27
required SF	1.27	1.27
increase of SF by soil nailing	23%	28%

The failure modes of the soil and nails have been checked in the Talren program and include (1) nail pullout, (2) soil rupture in the lateral direction at the soil-nail interface, (3) nail shear failure and (4) nail bending failure. The designed soil nails meet the requirements for all four failure modes.

5 VERIFICATION WITH 3D FE MODEL

Verification analysis of the design has been executed with a 3D FE model. A 3D model has been applied because (1) actual section forces in discrete soil nails can be verified, (2) the influence of horizontal spacing of the nails can be verified and (3) dike soil nailing will often be applied in situations where obstacles lead to 3D situations not easily simulated in a plane strain 2D model.

For the verification Plaxis 3D Foundation has been used, modelling the soil nails as embedded piles. With the new embedded piles option in Plaxis 3D Foundation beam elements can be placed in arbitrary direction in the sub-soil, the interaction with the soil is computed by means of an embedded interface element. The model consisted of a dike section with 1.5 m width and 1 row of soil nails. The mesh with the soil nails as embedded piles is shown in Figure 5.

The reference calculations with Plaxis 3D for the situation without reinforcement showed good agreement (SF=0.99 compared to 1.03 with Talren and 0.99 with Plaxis 2D as presented in Table 2). The Plaxis 3D calculations for the reinforced dike resulted in a safety factor of 1.16 which is significantly lower than the results from the Talren and Plaxis 2D design calculations (SF=1.27). From the output of the Plaxis 3D calculation it can be concluded that the lowest nail does not contribute to the sliding stability of the dike, as both tensile force and shear force are negligible. Also the nodes are not well-spaced in the lowest nail, as can be seen in Figure 7. This explains the significantly lower stability factor as only the two upper rows of soil nails have been taken into account.

In Table 5 the section forces in the upper soil nail as calculated by Talren and Plaxis 3D are compared. There is good agreement in the normal force and bending moments in the nail calculated by Talren and Plaxis, but the shear force reported by Plaxis seems to be incorrect, which may be a post-processing error with a factor 1000.

Table 5. Comparison of section forces in the upper soil nail

Section force	Plaxis 3D	Talren	Evaluation
Normal force	112 kN	125 kN	Good agreement
Shear force	26750 kN	40 kN	Plaxis output not OK
Bending moment	11 kN	9 kN	Good agreement

Conclusive it can be remarked that the model of embedded piles in Plaxis 3D still needs some development. A further developed embedded piles model gives good possibilities for the study of 3D discrete nail effects in tension and bending/shear, equivalent to the study performed by Tan et al (Tan et al, 2005) for soil nails under pure tension.

In a following design stage for this project more extensive 3D calculations are foreseen to investigate the influence of spacing, orientation, and to investigate the contributions in axial and lateral direction for different orientations with respect to the failure plane.

6 CONCLUSIONS AND RECOMMENDATIONS

The design and verification analyses led to interesting matches as well as disagreements between the different calculation models, which presents sufficient challenges for further development of the design method and the calculation models. For the embedded piles option in Plaxis 3D Foundation some effort is needed to improve the node distribution along the elements and the lateral forces (shear/bending) in the nails.

With regard to the dike reinforcement project in Bergambacht-Schoonhoven it can be concluded that the application of dike soil nailing is indeed a feasible reinforcement technique which is also cost-effective compared to a structural alternative like an anchored sheetpile wall into the Pleistocene sand layer.

In a following design stage for this project more extensive 3D calculations are foreseen to investigate the influence of spacing, orientation, and to investigate the contributions in axial and lateral direction for different orientations with respect to the failure plane.

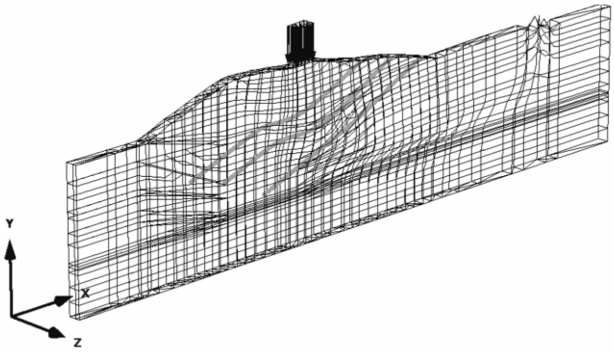

Figure 5. Deformed mesh with indication of deformation of the nails

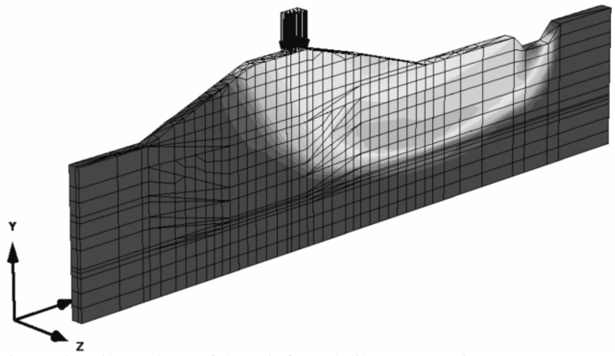

Figure 6. Failure plane of the reinforced dike (SF=1.16)

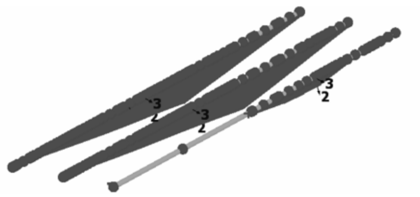

Figure 7. Normal forces and node distribution in nails indicating lower nail modelling problem

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