Prediction of pullout capacity of soil nails

Prédiction du traction limité pour des clous

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ABSTRACT: Pullout capacity is one of the main parameters for design of a soil nailed structure. An accurate estimate of this parameter will result in an economical and safe design. This paper discuss the possibility to make such an estimate based on results from commonly used site investigation methods and whether it is possible to calculate the pullout capacity based on known soil properties. The results indicate that the correlation depends on the type of nail, and even though some of the methods could be useful as a tool for a first estimate, the design should be based on pullout tests performed either in advance or in the inital stage of the construction.

RÉSUMÉ: Le traction limite du clou est une des paramètres principaux pour la conception d'une structure clouée par sol. Une évaluation précise de ce paramètre aura comme conséquence une conception économique et sûre. Cet article discutent la possibilité pour faire une telle évaluation basée sur des résultats à partir des méthodes généralement utilisées de reconnaissance de sols et s' il est possible de calculer la traction limite du clou basée sur les propriétés connues de sol. Les résultats indiquent que la corrélation dépend du type du clou, et quoique certaines des méthodes pourraient être utiles comme un outil pour une première évaluation, la conception devrait être basé sur des essais de la traction limite exécuté à l'avance ou à l'étape inital de la construction.

1 INTRODUCTION

Soil Nailing is a method for reinforcing soil in-situ. The method has increased its popularity during the last decades and has a wide range of applications; stabilising natural slopes, reinforcing steep excavated slopes and reinforcement of existing walls. In many cases the method constitutes an economic and practical alternative to more conventional methods such as sheet piling or reconstruction of a wall. However, to enable an economical and safe design, it is necessary to make an estimate of the pullout capacity of the soil nail, and of course it is advantageous if this could be made in an early stage. The accuracy of such an estimate will influence the economy of the project.

It would therefore be of great value if a reasonable good estimate of the pullout capacity could be made based on results from field investigation methods, (such as CPT, DMT or PMT), or if the pullout capacity could be accurately calculated from the soil parameters. To investigate these possibilities NCC and Chalmers University of Technology in Sweden initiated a research project. The study included laboratory tests, full-scale field tests and numerical simulations.

Based on the results from the full-scale field tests and the numerical simulation, this paper discusses the following subjects;

- The possibility to predict the pullout capacity based on results from commonly used site investigation methods.
- The possibility to use pullout results from vertical nails as an indication of the pullout capacity of horizontal nails.
- The possibility to estimate the pullout capacity of the nail based on known properties of the soil and nail

2 PREDICTION BASED ON RESULTS FROM FIELD INVESTIGATION METHODS

2.1 *Full-scale field test*

The full-scale field test was carried out in an abounded sandpit 30 km north-east of Gothenburg on the west-coast of Sweden. The sandpit is located in a glaciofluvial delta, mainly consisting of sand, created during the latest deglaciation. The sand is classified as medium fine sand with a mean grain size d_{50} of 0.23. The sleeve friction measured by CPT varied between 50 and 100 kPa for depths between 0 and 4 meter.

A minor part of the slope was classified as coarse sand. Before installation of the soil nails, the site was thoroughly investigated using the following site investigation methods, dilatometer, CPT and pressuremeter. At the test site 4 different types of driven nails and 4 different types of grouted nails were installed (8 nails of each type).

2.2 *Dilatometer results*

The dilatometer is suitable for the types of soils there soil nails commonly are installed. The dilatometer also gives an estimate of the soil stiffness, which in turn could be expected to mirror pullout capacity (since the installation of the nail will result in soil displacement, in turn governing the normal stress.c.f. section 5.2).

The pullout capacity of the different types of soil nails were compared to the average dilatometer modulus determined for the soil layers close to where the nails were installed. In Figure 1 the correlation between the pullout resistance and the dilatometer

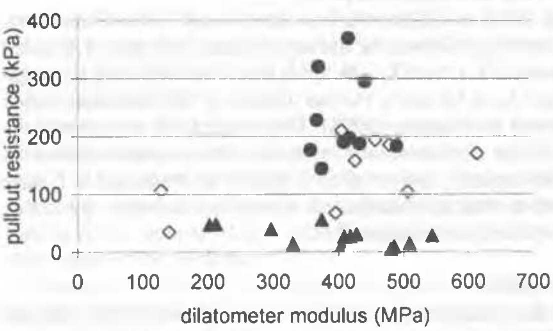

Figure 1 Correlation between dilatometer modulus and pullout resistance. Three groups;

◇ steel-soil failure e.g. angle bar, expanded steel tube
▲ soil-soil failure e.g. ribbed bar
● grout-soil failure e.g. grouted nails

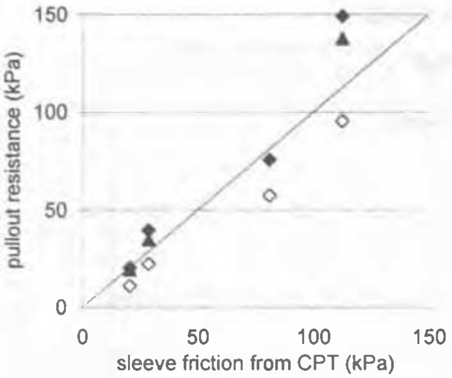

Figure 2 Correlation between the sleeve friction and the pullout capacity according to results from laboratory tests.
◇ steel-soil failure, angle bar
◆ steel-soil failure, expanded steel tube
▲ soil-soil failure, ribbed bar

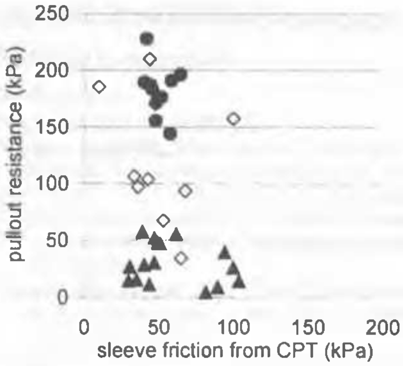

Figure 3 Correlation between the sleeve friction frcm the cone penetration test and the pullout capacity for field test.
◇ steel-soil failure e.g. angle bar, expanded steel tube
▲ soil-soil failure e.g. ribbed bar
● grout-soil failure e.g. grouted nails

modulus is presented (the *pullout capacity* of a soil nail (kN/m) is defined, as the average shear force that can be mobilized per meter nail. The pullout capacity divided by the nail perimeter is defined as the nail *pullout resistance* (kPa)). The nails are divided into three groups depending on where the failure occur;

- between the steel surface of the nail and the soil
- at a soil-soil surface
- between a grouted nail surface and the soil

However, there is no obvious correlation between the initial dilatometer modulus and the pullout capacity. For nails with a steel-soil failure, there might be a trend indicating that an increase in soil stiffness will give a higher pullout capacity, even though the scatter is great. However, for nails with a soil-soil failure as well as for the grouted nails no clear trend was observed.

For nails with a steel-soil failure (mainly driven bars) the dilatometer modulus might be used for rough predictions of the pullout capacity. Based on the performed field tests, a prediction based on DMT results for the other types of nails do not seem very promising.

2.3 *Cone Penetration test results*

The mobilized sleeve friction is continuously registered as the CPT cone penetrates the soil. There are obvious similarities between installation of a driven nail and the cone penetration test, and it therefore seemed reasonable to b·lieve that there would be a correlation between the pullout capacity and the sleeve friction.

2.3.1 *Laboratory test*

Laboratory tests were performed as one part of the research project. These tests included pullout tests of three different types of driven nails at different stress levels and relative densities. The tests were performed as half-scale tests with nails 1.5 meter long in a 4 x 2 x 1.5 m (L x W x H) box filled with dry homogenous sand (d_{50} 0.16 mm). Further details of the laboratory tests can be found in Franzén, (1998). Horizontal CPT tests were performed during the laboratory tests, and the correlation between the pullout capacity and the sleeve friction is presented in Figure 2. The results indicate that there is correlation between the sleeve friction and the pullout capacity.

2.3.2 *Field tests*

In the field tests, the soil conditions were not perfectly homogeneous. Therefore the corresponding CPT sleeve friction was determined as the average sleeve friction between the lower and upper nail installation level. The relation between sleeve friction and pullout resistance is shown in Figure 3. Like in the case of the DMT the scatter is great and no obvious correlation is found.

That the correlation between pullout resistance and sleeve friction found in the laboratory tests, not was found in the field tests could be explained by many factors.

In the laboratory tests the CPT tests were performed horizontally in a similar way as the nails were installed. Consequently the normal stress fields were similar around the nail and the CPT. In the field test the CPT tests were performed vertically and hence the CPT was effected primarily by the horizontal stress in the soil, while the nails were installed more or less horizontally thus effected by both vertical and horizontal stresses.

The shape and volume of the grouted nails are different from the CPT-probe and consequently the displaced volume of sand will be different which in turn will give different normal stress.

In the laboratory, the sand was homogenous with well-documented properties, while the natural variation in properties will influence the results in the field tests.

The sand in the laboratory was completely dry while in the field the moisture content may be different in different parts of the slope which will influence the mobilized friction both along the CPT probe and the soil nail.

Time between installation and pullout is another factor which will influence the pullout capacity of the driven nails with steel-soil failure. The pullout capacity will increase with time after installation which complicates the use of a simple field investigation method for prediction of the pullout capacity (Franzén & Jendeby, 2000).

Thus, there is most probably a correlation between sleeve friction and pullout resistance, but it may be very sensitive to variations in soil conditions. Even very limited variation in gradiations, relative density and water content may bring that a prediction based on CPT sleeve friction will be unsure.

A similar analysis were performed for the correlation between the cone resistance, q_c and pullout resistance. The cone resistance gives an estimate of the relative density and friction angle for the soil. Both these parameters influence the normal stress and the friction along the nail surface, and thus it seems reasonable to believe that the cone resistance could be used to predict the pullout capacity. For nails with a soil/soil failure there might be a trend that an increase in cone resistance will give an increase in pullout resistance, but the scatter is high and no obvious correlation could be established.

2.4 *Pressuremeter results*

The limit pressure, p_l, from the pressuremeter tests gives an estimate of the soil stiffness. During the full-scale field tests pressuremeter tests were performed (using a pre-boring pressuremeter of the type Menard BG). Previously published results by Schlosser *et al.* (1991) indicate that there exists a correlation between the limit pressure and the pullout resistance.

However, the number of pullout tests close to the pressure-

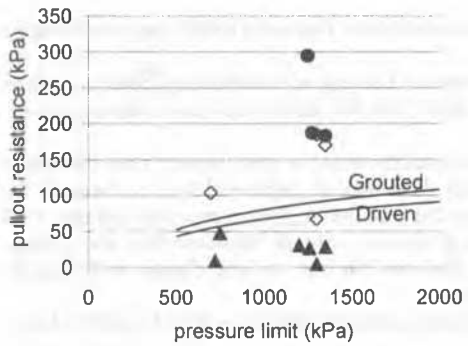

Figure 4 Relation between the limit pressure and the pullout resistance. Lines indicate the relationship between limit pressure and pullout capacity proposed by Schlosser *et al.* (1991).

◇ steel-soil failure e.g. angle bar, expanded steel tube

▲ soil-soil failure e.g. ribbed bar

● grout-soil failure e.g. grouted nails

meter tests was in this case few, and it was therefore difficult to find any clear relation, see Figure 4. For the driven nails, the results did not directly contradict a relationship similar to the one proposed by Schlosser *et al.* (1991), but the spreading is considerable. However, for the grouted nails the pullout capacity seems to be heavily underestimated by the proposed correlation.

3 PREDICTION BASED ON VERTICAL NAILS

The best prediction of the pullout capacity will of course be obtained if pullout tests are performed at the building site before the final design. However, in many cases (*e.g.* excavations) it is difficult to perform a horizontal pullout test prior to the construction work. A different approach was therefore tested during the full-scale field test; nails identical to the ones installed horizontally in the slope were installed vertically from the top of the slope. The hypothesis was that by installing the same type of nail in similar soil conditions a correlation might be obtained between the pullout capacity for vertical and horizontal nails.

Even though the scatter is considerable the results indicate a correlation between the horizontal and vertical pullout capacity for identical nails.

The main difference between the vertical nail and horizontal nail is the stress field. Similar to the CPT, the vertical nail is influenced by the horizontal stresses while the horizontal nail is mainly influenced by both the horizontal and vertical stresses. The vertical nails seem, however, to be a better tool for prediction than CPT. The reason could be that for vertical nails of the

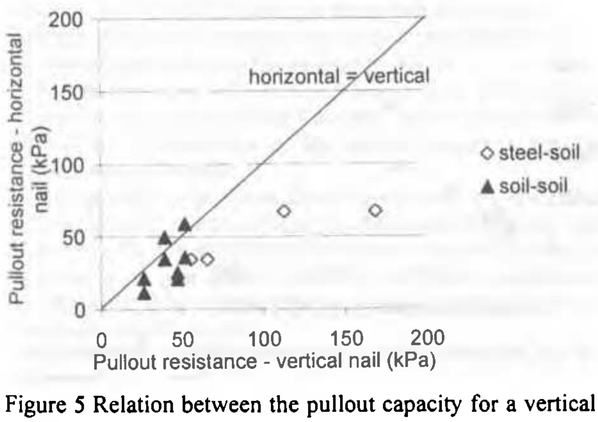

Figure 5 Relation between the pullout capacity for a vertical and a horizontal nail. (Driven nails)

◇ steel-soil failure e.g. angle bar, expanded steel tube

▲ soil-soil failure e.g. ribbed bar

same type as the horizontal ones, the influence of the difference in shape and installation procedure is eliminated.

4 SUMMARY OF FIELD INVESTIGATION METHODS

None of the investigated methods gave an acceptable prediction of the pullout capacity of soil nails. The main reason may be the difficulty to perform the test at conditions identical to those of the nail (and after installation of the nail). Stress situation, soil conditions, installation method and shape of the probe are some of the factors influencing the pullout capacity.

The number of test data in this study is, however, limited and with a greater amount of test data from different types of site conditions, it might be possible to find a correlation for some of the above methods. Considerable scatter and thus inexact predictions could, however, be expected. Based on the results from this study, the recommendation is to perform horizontal pullout test at the site before or during the initial state of the construction to confirm the assumed pullout capacity.

5 PREDICTION FROM ANALYTICAL MODELS

5.1 *Factors influencing pullout capacity*

The pullout capacity of soil nails will depend on three main parameters;

- nail surface area
- soil/nail friction
- normal stress acting on the nail

The pullout capacity can then be expressed as;

$$T_L = \sigma'_N \, \mu\theta \qquad (1)$$

where σ'_N= normal stress during pullout; μ = coefficient of friction; and θ= nail perimeter.

For driven nails the nail surface area is fairly easy to determine, and even for grouted nails a reasonable estimate can be made. The coefficient of friction between steel and soil is rather well documented as well as that between grout and soil. The factor that definitely is most difficult to determine is the normal stress acting on the nail. The normal stress is influenced by a number of factors such as soil conditions, installation method and type of nail (soil displacement), and will also change with time.

5.2 *Estimation of the normal stress*

A number of methods for estimation of the normal stress have been suggested in the literature.

Jewell (1990) (*Method a*) suggested a simple correlation where the normal stress was said to vary between 0.7 and 1.0 σ'_V.

Jewell & Wroth (1987) (*Method b*) suggested a method which includes the installation angle and the angle of effective internal friction. For an angle of internal friction between 30° and 45° the normal stress will be in the order of 1.3 to 2.3 σ'_V for an installation angle of 10°.

The design manual HA68/94 (*Method c*) uses a modified coefficient of active earth pressure and the angle of internal friction. For a ϕ_{cv} between 30° to 35° the normal stress will be about 0.82 σ'_V. This method could be expected to give conservative values of the normal stress since they do not consider any positive effect of the dilatancy.

Carter *et al.* (1986) (*Method d*) suggested a method based on the theory of cavity expansion for non-cohesive soils. This method considers not only the vertical stress, but also the soil stiffness, the internal angle of friction and dilation. Consequently the method indirectly also accounts for relative density, coefficient of uniformity and shape of grains. For an angle of internal friction between 30° and 45° the normal stress will be in the order of 6 to 8 σ'_V for a shear modulus of 10 MPa.

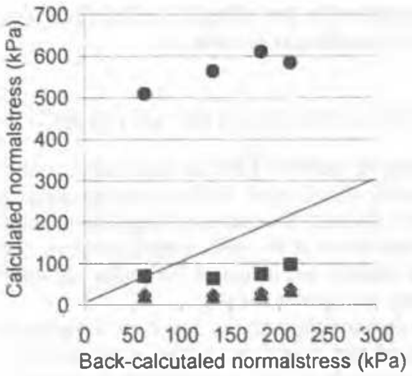

Figure 6 Normal stress for a driven angle bar back-calculated from field test vs. calculated stresses.
◇ Method a, Jewell (1990)
■ Method b, Jewell & Wroth (1987)
▲ Method c, HA68/94
● Method d, Cartier *et al.* (1986)

The normal stress acting on the different nail types during the full-scale field-test were back-calculated using known values of surface area and estimated values of the coefficient of friction. In Figure 6 the normal stresses back-calculated from the field tests are compared to the normal stresses estimated by the above four different methods.

Method a, b and c seem to underestimate the actual normal stress (except for low normal stresses for method b) and may be used for prediction of a design value on the safe side, but not for determining the actual pullout capacity.

The calculated normal stress according to method d is much too high. However, the relation between calculated and back-calculated normal stress is clear, and if the method could be calibrated with a couple of pullout-tests for the same type of nail at similar soil conditions, the method might be a useable.

5.3 *Normal stresses measured in laboratory tests*

To obtain a better understanding of the different factors influencing the normal stress during a pullout test, the variation in horizontal stresses around a nail during the different stages in an installation/pullout cycle was measured. The results are summarized in Figure 7 while the instrumentation and test procedure is

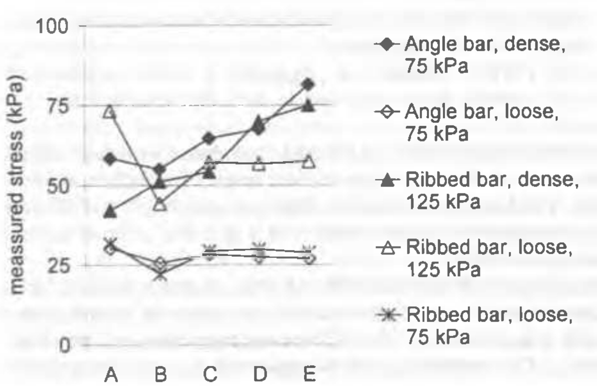

Figure 7 Variation in normal stress (horizontal) around the nail during the laboratory tests (loose and dense sand, vertical stress 75 and 125 kPa). Earth pressure cell at 200 mm distance from nail center.
A before installation
B immediately after installation
C before pullout test
D at failure displacement
E immediately after pullout test

more thoroughly described in Franzén (1998), (see also chapter 2.3).

The stresses measured during an installation – pullout cycle at a distance of 200 mm from the nail center can be summarized as follows;

Due to the nail *installation* (A → B in Figure 7) the horizontal stress will decrease. This may be explained by a collapse of the soil skeleton due to the installation (vibration). This collapse will bring a reduction of the soil volume. However, the nail volume will compensate this, and the net volume change will thus be governed by nail type.

The stress will *increase* with *time* (B → C in Figure 7) due to stress relaxation, i.e. the arch created around the nail (due to the soil collapse) during the installation will slowly break down.

During *loading* the stress will *increase* (C → D in Figure 7), mainly due to the effect of restrained dilatancy. It should be noticed that this effect is more pronounced in dense sand. For dense sand the stress *increase* will continue *after failure* (D → E in Figure 7) due to restrained dilatancy.

These results indicate that the normal stress around the nail mainly depends on the installation method and the volume of sand, which the nail will displace during the installation.

There are similarities between driven soil nails and driven piles in sand. It is therefore interesting to make a comparison with results from a study performed for concrete piles driven in sand (Axelsson, 1998). The results are similar to the results presented above for soil nails. Increases in horizontal stress around the pile with time due to stress relaxation was observed and during loading a stress increase due to restrained dilatancy occurred.

5.4 *Theory of cavity expansion*

Method d, which is based on the theory of cavity expansion was used to calculate the normal stress acting on the nail during the laboratory tests. In Figure 8 these calculated normal stresses are compared to normal stresses back-calculated from the pullout tests (based on a known surface area and coefficient of friction).

A clear relation between calculated and back-calculated normal stresses is obtained in this case, even though the absolute value is strongly overestimated. It therefore seems like methods based on the theory of cavity expansion accounts for the correct factors that influence the pullout capacity, *e.g.* relative density, dilatancy, and vertical stress. The relationship is however, not 1 to 1 and therefore a scaling factor or function has to be determined.

The calculated normal stresses for some of the nails in the field tests are plotted vs. the back-calculated stresses in Figure 9. For steel-soil failure (angle bar) and for soil-soil failure (ribbed bar) a correlation might be found even though the scatter is much

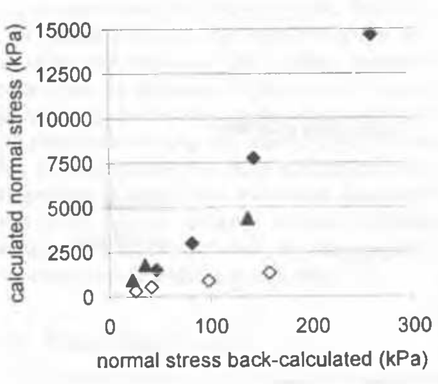

Figure 8 Calculated normal stress according to Method d vs. back-calculated normal stress for results from the laboratory tests.
◇ steel-soil failure, angle bar
◆ steel-soil failure, expanded steel tube
▲ soil-soil failure, ribbed bar

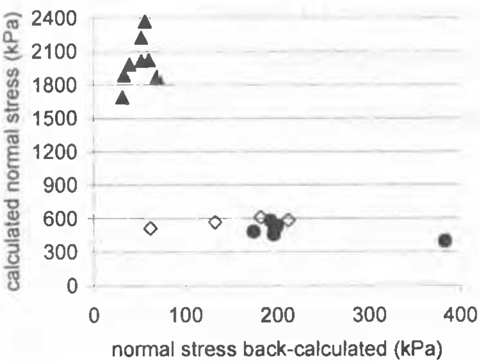

Figure 9 Calculated normal stress according to Method D vs. normal stresses back-calculated from field tests.
◇ steel-soil failure, angle bar
▲ soil-soil failure, ribbed bar
● grout-soil failure

greater than in the laboratory tests. For grouted nails no obvious correlation exists. One explanation could be that method D does not account for the influence of the grouting procedure.

Method D and other methods based on the cavity of expansion seem to be the most promising approach to calculate the actual normal stress acting on the nail, even though the scatter is high. Since the absolute values are much too high, a local calibration is necessary. However, the method needs to be further developed to account for the effect of different installation techniques such as grouting and also for variation in moisture content and soil properties. If the method should be used at the present state for prediction of the pullout capacity, it has to be calibrated with pullout tests of identical nails in similar conditions, since the scale function has to be determined.

6 DISCUSSION

The results above indicate that there is no simple way to accurately predict the pullout capacity for all types of nails.

There are numerous parameters that have to be considered to obtain a good correlation; variation in soil conditions, variation in stress situation and variation in nail shape. Further, many parameters will change due to nail installation and also with time.

The best prediction of the pullout force is of course obtained if pullout tests are performed at the test site before the design. In some cases it is not possible to make these tests and then other methods must be utilized for a first estimate. Since the accuracy of such an estimate is very limited, all assumptions must be verified by pullout tests during the initial stage of construction.

For driven nails with a soil-steel failure (e.g. angle bar, expansion bolt) vertical nails in combination with calculation methods based on the theory of cavity expansion may be a tool for an early prediction of the pullout capacity.

For driven nails with soil-soil failure (e.g. ribbed bars) the pullout tests on nails installed vertically seem to be the most useful method for prediction of the pullout capacity (even though the accuracy is limited).

For grouted nails where the failure occurs between the soil and the grout it seems difficult to directly correlate the pullout capacity to the soil properties. Parameters such as grouting pressure and grout type greatly influence the pullout capacity. Consequently for grouted nails it is necessary to make the assumption based on pullout tests.

7 CONCLUSION

The main conclusions of the present study can be summarized as follows;

- Installation and pullout tests of vertical nails in advance seems to be a method that could be developed to give a fairly good prediction of the pullout capacity for driven nails.
- The collapse of the soil skeleton during installation of the nail will cause a decrease in stress (especially in loose soils), which depending on nail will be completely or partly compensated by the stress increase caused by the volume of soil displaced during installation.
- During loading the normal stress acting on the nail will increase due to restrained dilatancy.
- Methods for calculating the pullout capacity only considering vertical stresses and the angle of internal friction will give very conservative values, probably due to the fact that restrained dilatancy is disregarded.
- Methods based on the theory of cavity expansion seem to have the best potential for prediction of pullout capacity. However, to obtain the correct magnitude, the method has to be calibrated using results from pullout tests of the same nail type and at similar soil conditions.

To be able to establish a more general correlation between different site investigation methods and the pullout force of soil nails a greater amount of data from pullout tests of different types of nails and soil conditions are needed.

Based on today's the knowledge, some of the methods in this paper might be used to give a first estimate. However, considerable variations can be expected, even in relatively homogenous soils. Further, the result is influenced by a number of "unknown" parameters such as moisture content, local stress field and local deviations concerning soil type. Therefore, the initial estimate must always be verified during the initial stage of construction by pullout tests.

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