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Soil Nailing

A Laboratory and Field Study of Pull-Out Capacity

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A LABORATORY AND FIELD STUDY OF PULL-OUT CAPACITY

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ABSTRACT

Soil Nailing is a technique for reinforcing soil *in situ*, increasingly utilised as an economical alternative to conventional earth reinforcing techniques. However, today the design is based on an assumed value of the pullout capacity of nails, which later is verified by pullout tests during the construction, which in turn limits the possibility of optimising the design.

The objective of this study was therefore to get a better understanding of the pullout capacity and to suggest a method for more accurate prediction. The study comprised; laboratory tests (to study the influence of overburden pressure, relative density and method of installation) and full-scale field tests (to compare the pullout capacity among different soil nails and with results of site investigation methods). The results were then compared with design methods and results from FEM analysis.

The results show that the pullout capacity in a cohesionless soil mainly depends on; the coefficient of roughness, surface area and normal stress. An increase in relative density, overburden pressure, and volume of displaced soil will result in an increase in pullout capacity. The coefficient of roughness and surface area could be estimated with quite good accuracy while the normal stress against the nail is more difficult to determine. The best prediction of the pullout capacity seems to be obtained from pullout tests on vertical nails.

The greatest pullout capacity was, as expected obtained for grouted nails, but at the test carried out about 300 days after installation a driven expansion bolt and the angle bar gave an almost equals high capacity. A significantly lower pullout capacity was obtained for the ribbed bars, and for these nails no time dependency could be found. The analysis indicates that methods based on the theory of cavity expansion could be used to calculate the normal stress after local calibration.

Key words: soil nailing, pullout capacity, coefficient of friction, normal stress, cavity expansion, sleeve friction, sand, pullout tests, restrained dilatancy

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SUMMARY

INTRODUCTION

Soil nailing is a technique for reinforcing soil *in situ*, which has become more and more popular during the last couple of decades. The main advantages of the method are its simplicity and its flexibility to different site conditions. The method has in many cases proved to be an economical alternative to conventional earth reinforcing methods such as gravity walls, sheet piles and decreasing inclination of the slopes.

The pullout capacity of the nail is the key parameter for design of a soil nailed wall. Today this parameter is often estimated during the design (on the basis of the design engineer's own experience) and then verified by pullout tests during construction. This approach often results in an underestimate of the pullout capacity, which in turn gives an uneconomical design. Therefore, it would be an achievement if the pullout capacity could be more accurately predicted based on the knowledge of the soil and the nail characteristics, in turn enabling an optimization of the design. The overall aim of this work has therefore been to try to understand and predict the phenomenon of the pullout capacity.

PULLOUT CAPACITY

The pullout capacity of a soil nail can be described by four variables; the normal stress acting on the nail surface, σ_N, the coefficient of friction, μ, the adhesion, c_a, between the nail and the soil, and finally the nail perimeter, θ.

$$T_L = (c_a + \mu\sigma_N)\,\theta \qquad \text{(S.1)}$$

These variables will in turn depend on e.g. soil type, nail type, method of installation, stress level, relative density and water content.

The objective of this study was, if possible, to find a method for a more accurate prediction of the pullout capacity, and consequently the influence of the above mentioned parameters had to be investigated. The study comprised the following;

- a literature review
- laboratory tests to study the influence of stress level, relative density and method of installation for a number of different nail types

- field tests to compare the obtained pullout capacity for different types of soil nail and to try to relate results of site investigation methods to the pullout capacity
- analysis to compare results of the field and laboratory tests with predicted pullout capacities (according to different existing design methods and the finite element method).

LABORATORY TESTS

A total of 6 test series were performed in a test box (4 x 2 x 1.5 m^3). During each test series three driven nails were tested at three different stress levels (25, 75 and 125 kPa). Two of the test series were performed to investigate the influence of the installation technique, driving and jacking respectively, while the influence of relative density and nail type was studied during the remaining tests. Four different types of driven nail were used; angle bar (40 x 40 x 4 mm^3), ribbed bar (36 mm), expansion bolt (54 mm) and round steel bar (36 mm). The tests were performed in a dry, homogeneous, poorly graded fine sand.

The results indicate that the residual pullout capacity is independent of method of installation. However, the pre-peak behaviuor is significantly different for the two types of installation method. The driven nails show a distinct peak value about 50 per cent greater than the maximum value of the smooth curve obtained for the jacked nails, see Figure S.1.

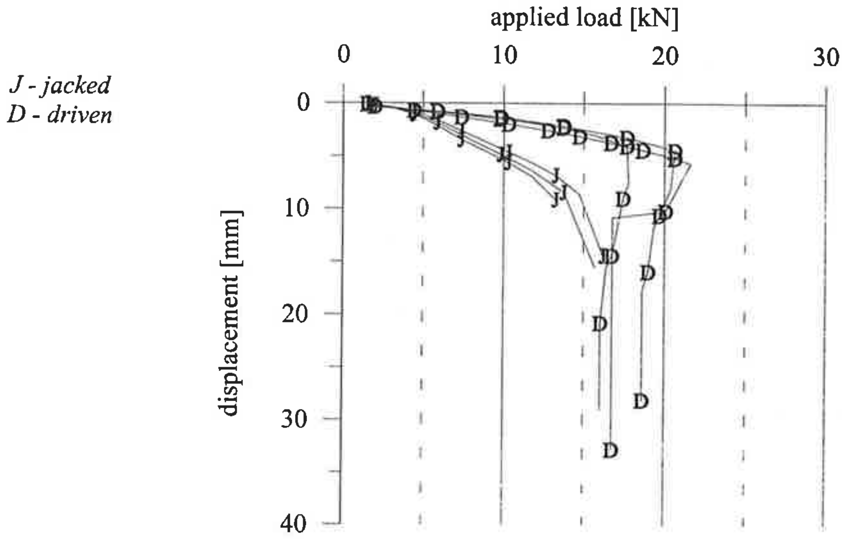


Figure S.1 Influence of method of installation

The results also indicate that an increase in overburden pressure and relative density will give an increase in pullout capacity. Measurements of horizontal stresses during the tests indicate that the normal stress acting on the nail surface after installation will depend on the soil volume that the nail displaces during installation. Whether the nail volume could compensate for the stress decrease caused by the installation (compaction) or not, the normal stress will either be greater or less than the initial *in situ* stress. Consequently, the displaced soil volume is an important parameter, which will influence the pullout capacity.

The increase in pullout capacity if a ribbed bar is used instead of a smooth bar may be explained by the increase in surface area and interface angle of friction, which will be the case when the failure occurs in the soil above the ribs instead of at the steel/soil interface.

FIELD TESTS

The full-scale field tests had mainly two different objectives; to study how the pullout resistance was influenced by the type of nail, and to try to relate the pullout resistance to results from site investigation methods.

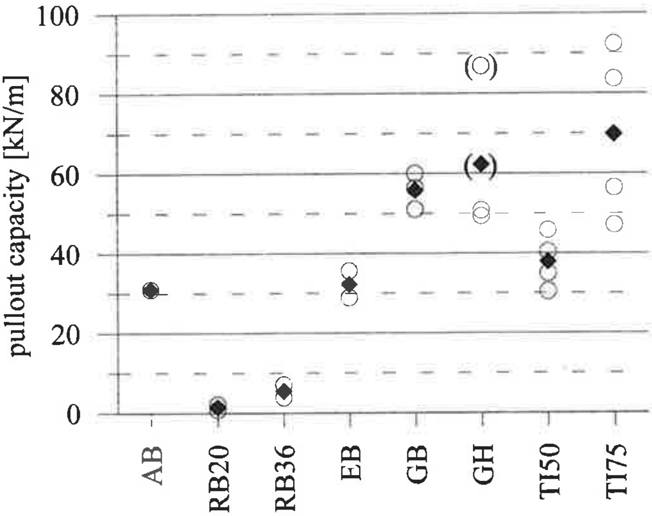
Eight different types of soil nail were installed in a sand slope (about 3.5 m high), consisting of a fairly homogeneous, poorly graded, sand. The driven nails were of the same type as in the laboratory tests (except for the round steel bar that was replaced with a 20 mm ribbed bar). Further, four types of grouted nail were tested. Two different types of installation technique were also used for the grouted nails; pre-drilling and drilling with simultaneous grouting. For the pre-drilled nails, two different types of grout were used (Grout H and Grout Bult). For the nails with drilling with simultaneous grouting two different sizes of drill-bits were used (50 and 75 mm). A total of 48 pullout tests were performed. To study the influence of time between installation and the pullout test, the driven nails were tested on three different occasions (after 1-2 weeks, 2-3 months and 8-9 months).

In Figure S.2[1] the average pullout capacity for the different nail types tested during test period three (8-9 months) is presented.

[1] For most of the grouted nails the average value is based on pullout tests on four nails, while for the driven nails it is based on two nails. Further are some tests excluded either due to incomplete tests or to difficulties to determine a correct nail surface area.

Driven nails
AB- angle bar
RB20 - ribbed bar 20 mm
RB36 - ribbed bar 36 mm
EB - expansion bolt

Grouted nails
GB - pre-drilled - grout bult
GH - pre-drilled - grout H
TI50 - g.s.d. drill-bit 50 mm
TI75 - g.s.d. drill-bit 75 mm



( ) less reliable result
O - *individual value*

◆ - *average value*
g.s.d.- grouted, simultaneously drilled

Figure S.2 Pullout capacity, 8-9 months after installation.

The results indicate that the pullout capacity is about 5 -30 and 40 - 60 kN/m for the driven and grouted nails respectively. For the ribbed bar a significantly lower pullout capacity than the angle bar and the expansion bolt can be observed. However, this is not true for the results from test period I, see Figure S.3, where the angle bar and expansion bolt only have a slightly greater pullout capacity compared with the ribbed bar. This indicates that the pullout capacity of the angle bars and expansion bolts will increase with time. Such time depending can, however, not be found for the ribbed bar.

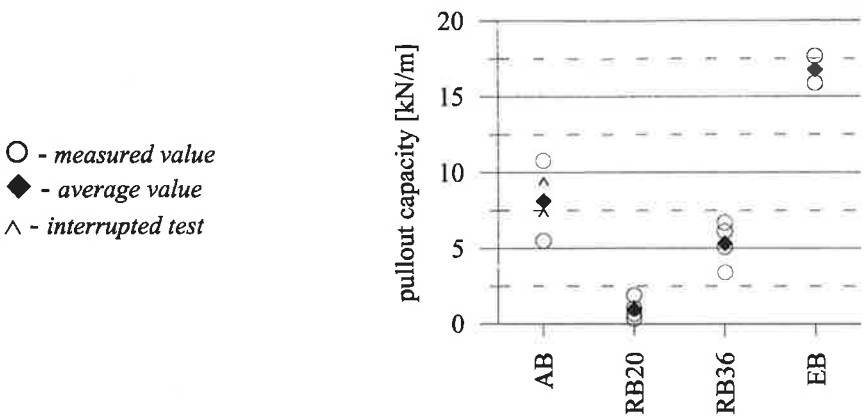


Figure S.3 Pullout capacity for driven nails, 1-2 weeks after installation

The results from the field test do not indicate any significant influence of the overburden pressure on the pullout capacity, which however could be explained by the small difference in installation depth of the nails.

The installation procedure for grouted nails will influence the pullout capacity, even though the results in Figure S.2 indicate that the difference in average pullout capacity for the four types of grouted nail is small. The predrilled nails obtained a texture that was a perfect reproduction of the steel core surface, which in turn will influence the mobilised pullout capacity. The simultaneously drilled and grouted nail with the smaller drill-bit (50 mm) will obtain the smallest surface area and consequently mobilise less pullout capacity.

The grouted nails gave as expected in general greater pullout capacity compared to the driven nails. However, the pullout capacities of the expansion bolt and the angle bar (after long time) were almost in the same order of magnitude, while the ribbed bar gave significantly lower pullout capacity. An increase of 70 - 300 per cent in pullout capacity with time (250 days after installation compared with directly after installation) was found for the angle bar and the expansion bolt, however no such time dependency was found for the ribbed bar.

The second objective of the field tests was to try to establish a relation between the pullout capacity and results of site investigation methods. Therefore the test site was thoroughly investigated using cone penetration, dilatometer and pressuremeter tests. As "an alternative site investigation method" 24 nails (8 angle bars, 8 ribbed bars 36 mm, and 8 grouted nails) were installed vertically behind the edge of the slope.

The results of cone penetration tests in the laboratory had previously indicated that there exists a relation between the sleeve friction/cone resistance and the pullout resistance. However, the expected relation was not obtained in the field tests, which indicates that additional factors, such as differences in stress situation and soil characteristics, probably influence the relation. Based on the results from this study the possibility to account for these factors and then to predict the pullout capacity seems rather complex.

The dilatometer gives an estimate of the soil stiffness, and a relation with the pullout resistance for those nails where the soil displacement is crucial for the normal stress (soil/steel failure) was also obtained. However, the variations were considerable, and therefore the DMT does not seem to be a suitable method for prediction of the pullout capacity.

Only a limited number of pressuremeter tests were performed and it was not possible to establish a relation between the limit pressure from the PMT and the pullout resistance based on the results of this study.

The vertical nails seemed to be the most promising tool for prediction of the pullout capacity, see Figure S.4. Even though the number of nails is small, it seems possible to predict the pullout resistance of a horizontal nail from the pullout resistance of a vertical nail with a reasonable degree of accuracy.

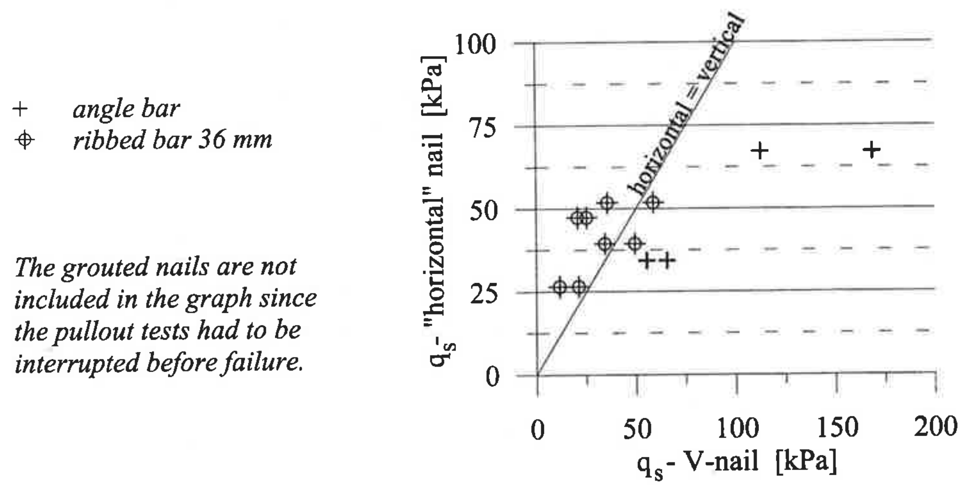


Figure S.4 Pullout resistance for horizontal and vertical nail

ANALYSIS

As indicated by Equation S.1, the pullout capacity in a cohesionless soil depends on the coefficient of friction, the normal stress and the surface area of the nail. Results of shear box tests indicate that the coefficient of roughness (and hence the coefficient of friction) for different types of nail material could be estimated with quite good accuracy. The surface area can also in most cases be estimated either as the perimeter for a driven nail, or as an increased drill-bit diameter for grouted nails. Consequently the most difficult variable to determine is the normal stress. This is also the parameter that varies the most from case to case, and therefore it is the most important parameter.

Based on the results from the measurements of earth pressure, load displacement curves and previously published material, the following hypothesis for the development of the normal stress around the nail was formulated: During installation of a nail, the soil will collapse due to the vibrations and compaction at the nail tip, in turn bringing a decrease in normal stress. This stress decrease will be more or less compensated by a stress increase due to displacement of soil caused by the penetration of the nail. Depending on the magnitude of these two effects, the installation will result either in a stress increase or decrease. Further, an arching effect will develop around the nail, causing the stress decrease close to the nail to be accomplished by stress increase (or vice versa) at some distance from the nail.

This arching effect will, however, decrease with *time* (due to soil relaxation effects), which, depending on the initial stress change will bring an increase or decrease of normal stress.

Back-calculated normal stresses from the field and laboratory tests were compared to theoretical normal stress according to a number of different methods. The results indicate that the simple methods, which only relate the normal stress to the overburden pressure, underestimate the normal stress with a factor of 3 - 10.

The methods based on the theory of cavity expansion overestimate the normal stress, which probably could be explained by their limited possibility to describe the soil's actual behaviour at large deformations. However, the results indicate that there exists a relation between the normal stress calculated according to these methods and the back-calculated normal stress based on the pullout capacity. Consequently, it seems that these methods consider the correct parameters (soil stiffness, angle of internal friction, initial in situ stress and the radial displacement of the soil due to the installation), but can not directly be used to calculate the normal stress. However, it might be pos-

sible to make a local calibration of the relation between calculated and back-calculated normal stress, based on a number of horizontal or vertical pullout tests.

For grouted nails a method used for estimating the normal stress on grouted ground anchors seems to be suitable for estimating the normal stress for grouted soil nails.