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An example of a high soil nailed wall in plastic clayey soil

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ABSTRACT: This paper describes a twenty-meter-high nailed wall for a residential and office building built recently in the center of the city of Zagreb. The wall is to serve as a permanent structure. The excavation pit for the building is located between two old buildings with unreliable foundations on a very steep slope, which caused additional difficulties in soil nailing construction. The retained earth is medium to highly plastic overconsolidated clay. The paper presents in situ and laboratory testing results on the basis of which design soil parameters were derived. Deformations brought about during excavation were measured by means of sliding deformeters and compared to lateral movement of survey points at the face of the wall. In addition, results of the finite difference method for calculating stresses and deformations, and stability analysis were also presented.

1 INTRODUCTION

Soil nail technology is generally considered to be applied unsuccessfully in clays. Consequently, very little research has been done on the subject and there is little field experience on soil nailing in the deposits of clays of medium to high plasticity.

The nailed wall presented in this paper is located in Dežmanova Street in the center of the city of Zagreb. The wall encloses the working site for a residential and office building with an underground garage. Layout dimensions of the garage are about 26 x 30 m, and it is 4.5 m below the ground level. The superstructure is 20 m high (4 stories). The structure is surrounded by the street and adjacent buildings. On the west side, at the top of the slope is the old Roko Park with trees running close to the wall. The excavation pit is located on a very steep slope, between two old buildings with unsolid foundations, which caused additional difficulties in wall construction. The back side of the excavation pit, also the highest side, is hardly accessible to heavy machines. As a result, a soil nail wall was selected as the preferred wall type for the given wall location, as it uses conventional shoring equipment. The nailed wall has two functions: a temporary support of the working pit and the permanent support of the retained earth after completion of the building. To increase the factor of safety for the wall, the lower portion - i.e. that of the garage - was planned to be supported with heavy concrete walls. On the street side of the excavation, the bottom of the pit is 4.5 m bellow the street level and the retaining wall is formed from contiguous micro-piles which are 20 cm in diameter and placed on 0.5-meter centers. A plan view and geometry of the excavation are shown in Figure 1.

2 SOIL PROPERTIES AND DESIGN PARAMETERS

The geology of the area consists entirely of stiff overconsolidated clays with a sand layer close to the surface in upper portion of the retained soil. Subsurface exploration was conducted to determine the properties of the soil, in which nails and anchors

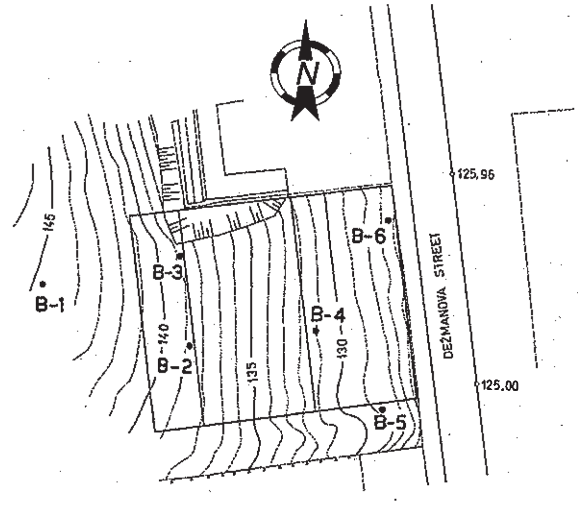


Figure 1. Plan view of the excavation.

were to be installed, and groundwater conditions. The exploration included the following: boreholes of up to 25 m, standard penetration tests, and the collection of disturbed and undisturbed soil samples for visual identification and laboratory testing. Piezometers were installed in the ground in the boreholes shown on the plan view shown in Figure 1. The readings on piezometers, placed close to the wall, generally showed that there was no ground water.

Laboratory testing consisted of standard classification tests, oedometer tests, unconfined compression tests and direct shear tests. Based on the laboratory tests, clays were found to have medium to high plasticity and SPT over 20 blowcounts, and thus classified into stiff to very stiff clays. A characteristic soil-profile with boring logs is shown in Figure 2.

Triaxial compression tests for determining shear strength of clay were not carried out - for reasons beyond authors' control - and direct shear tests were performed instead. Although the authors were well aware that the conventional direct shear tests were not the preferred tests for clay, their use in the case of stiff clay was reasonable, as the results referring to shear strength are comparable to those obtained by the triaxial tests (In the triaxial compression test the effective stress path followed to failure by many overconsolidated samples of medium to high plasticity clay in undrained compression is approximately vertical on a t-s' diagram).

In addition, undrained strength c_u (in our case obtained from unconfined compression tests) is also nearly proportional to s' for heavily overconsolidated clay samples (CIRIA's report 104). With the moisture content and effective stress level pertaining *in situ*, it may be recognized simply as the frictional strength of the soil (like results from direct shear tests). The results of the direct shear tests and unconfined compression tests are presented in Figure 3 together with their least square straight line and design envelope, with $c' = 50$ kN/m^2 and $\varphi' = 20°$. Design unit weight $\gamma = 20$ kN/m^3.

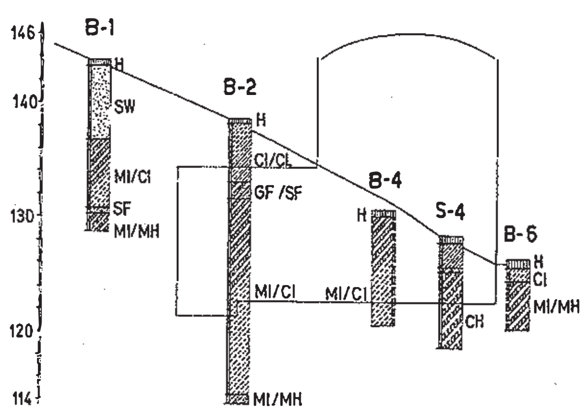


Figure 2. A characteristic soil-profile with boring logs.

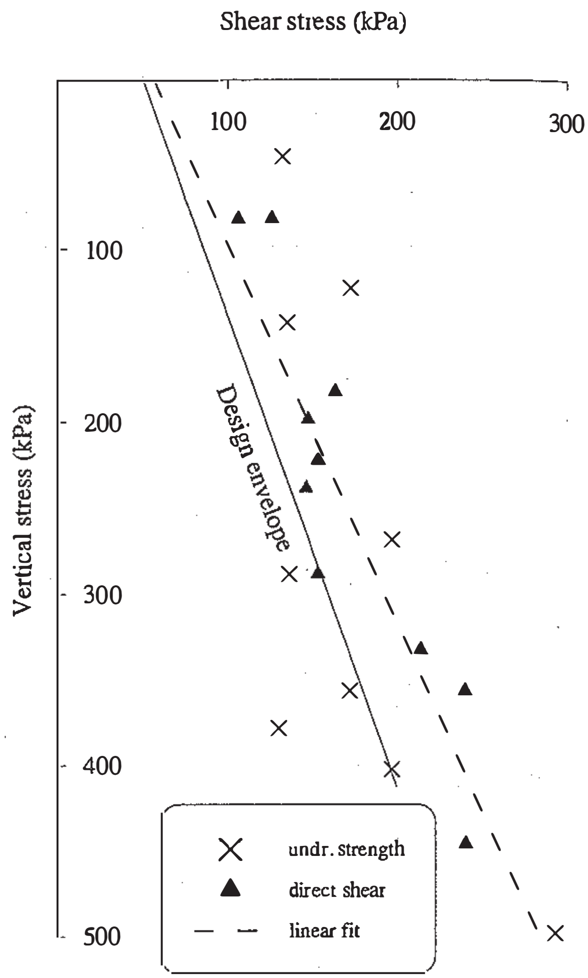


Figure 3. The results of shear stress tests and unconfined compression tests.

The average shear strength parameters of the clay determined from the in situ and laboratory tests were also used for calculating the shear modulus according to the correlation $E = 500 \cdot c_u$. For the purpose of calculation, the retained soil was divided into four zones with equal soil properties. The zones correspond to steps in nail wall facing. The selected design parameters of each zone are presented in Table 1. Strength parameters of $c' = 0$ and $\varphi = 30°$ were assumed for the sand.

Table 1. The selected design parameters of zones.

h*	c_u	E	G
m	kN/m^2	MN/m^2	MN/m^2
0.0 to 5.0	70 to130	35 to 65	11.7 to 21.7
5.0 to 11.5	110 to 170	55 to 85	18.3 to 28.3
11.5 to 15.0	160 to 220	80 to 110	26.7 to 36.7
15.0 to 19.5	220 to 280	110 to 140	36.7 to 46.7

* h ... height of a zone

3 DESIGN CONSIDERATIONS

3.1 *Problems of nailing in clay*

It is widely known that one of the most critical conditions for a nailed wall is pulling out or breaking of the nails, which results in sliding of the wall and retained soil. A main design requirement is to determine an economic spacing and length of nails to stabilize and limit movements of the wall. Nailing in clay, in contrast to sands, brings the following disadvantages:

- shear strength on the contact of nails and soil is lower and
- critical sliding surface extends deeper in the retaining soil.

As a result, nails in clay should be longer and more closely spaced than in sand, which makes nailing in clay less economical.

In standard design, the part of a retained wall with nails is considered as a rigid block loaded with the rest of retained soil. A nailed wall may be assumed to be a rigid block only when nails are spaced closely enough to "nail" the soil between them. In the case of the Dežmanova Street nailed wall there are some deviations from the standard design. In view of the fact that this wall is located between the buildings and that it is extremely high, and in order to prevent the wall and the retained soil movements, nailing was combined with prestressed anchors the lengths of which were adjusted to reach the soil behind the critical shear surface. As a result of this, the nails could be widely spaced but the assumption we started from (standard nailed soil) did not hold any more, and retaining construction had to be analyzed by using a more sophisticated model.

The behavior of the wall under working loads, which pertains to the serviceability limit state, was analyzed by means of a finite difference method; the failure condition, which pertains to the ultimate limit state, was analyzed with standard slope stability method, assuming anchors to be outside tension forces. In addition, we checked whether the nail and anchor tensile strengths were adequate to provide the support force to stabilize the active block, and whether anchors were embedded with a sufficient length into the resistant zone to prevent the pullout failure.

Capacity of the anchors was determined based on experience and according to recommendations by FHWA (Table 3.3) with ultimate bond stress for stiff clay between 40 and 60 kN/m^2. Besides, after having consulted experienced geotechnical engineers, the authors came to the conclusion that actual anchor forces should not exceed 400 kN since clay creeping may occur. As the clay was very stiff, we decided to use this maximum value for the calculation, and obtained the following ultimate shear strength on the soil-anchor contact τ_p:

$$\tau_p = A_t \;/\; (\, 2\, d_o\, \pi\, l_o \,) \qquad (1)$$

$$\tau_p = 400 \,/\, (\, 2 \cdot 0.14 \cdot 3.14 \cdot 8.0 \,) = 57 \text{ kN/m}^2. \qquad (1a)$$

where

A_t ... ultimate anchor force,

d_o ... outside diameter of the anchor drillhole (assumed 0.14 m),

l_o ... anchor fixed length (assumed 8.0 m).

The subsequent three anchor pull-out tests confirmed that the assumption was quite reasonable. According to FHWA, the ultimate pullout resistance tends to be relatively independent of depth below surface for a constant soil type and particular installation technique, which has been attributed to the decreasing significance of soil dilation with depth. It is noted that - for nails that are installed in predrilled holes and grouted under gravity (as in the case of the Dežmanova street nailed wall) - the effect of overburden pressure tends to be diminished by arching around the installation drillhole; this phenomenon also contributes to the observed lack of significant dependence of the ultimate resistance to the overburden pressure.

Concerning the soil-grout interface, only very small displacements between the nail and the adjacent ground are required to mobilize the ultimate bond or adhesion. This means that the nails and the nail grout-ground interface must be sufficiently stiff to ensure that the reinforcing loads can be developed without associated excessive deformations (FHWA). As regards a nailed wall as a unique system, not only a stiff nails, but also a stiff structural facing contribute to overall better behavior of the supporting system, because a stiff facing equalizes the overall deformation and, therefore, helps in uniform distribution of action on nails and anchors.

3.2 *Finite difference analysis*

Serviceability limit state is the limit state that addresses loss of service function resulting from excessive wall deformations. Therefore, serviceability requirements of the design are expressed mainly in terms of limiting displacements.

A plane strain finite difference analysis was carried out by using the FLAC package (Itasca Consulting Group, Inc.). This analysis was used to model the soil as an elastic-perfectly plastic material by obeying the Mohr-Coulombs failure criteria. In conjunction with behavior of overconsolidated clays, initial lateral stresses were based on an earth coefficient at rest of two. High soil stiffnesses referring to the range of small strains (based on the conclusions made by Simpson, 1992) were also taken into consideration.

Drained conditions were assumed in the analysis that simulated excavation in front of the wall in thir-

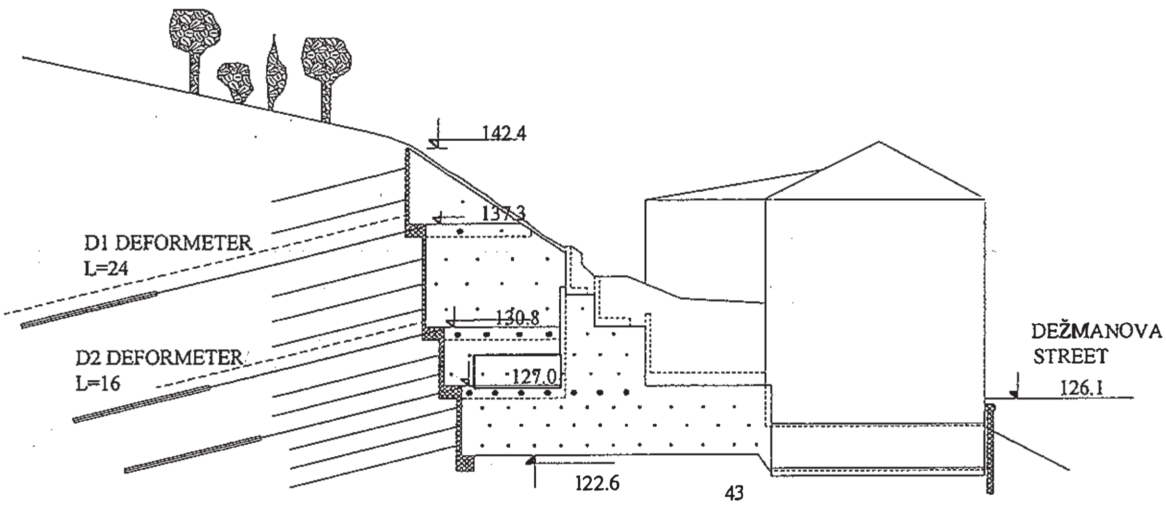
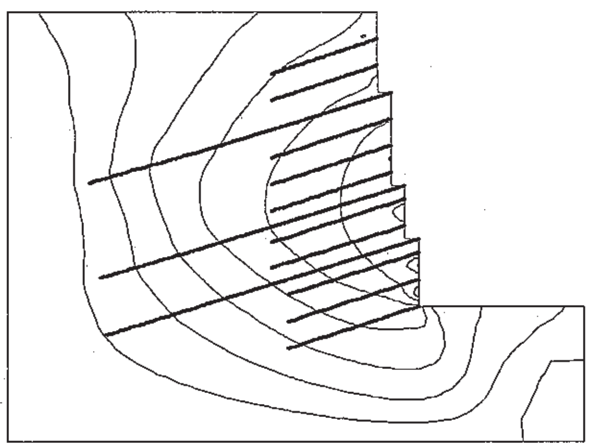


Figure 4. Layout of the facing and ground anchors in the critical cross-section (dimensions in meters).

teen stages of construction. In each stage of the construction, maximum forces in the anchors caused by excavations were determined, as well as distribution of horizontal displacements in soil. Input soil, nail and anchor parameters were as presented in Chapter 2 (higher values of shear moduli from Table 1.). The facing was modeled as a linear elastic material, 0.3 m thick, having a modulus of 30 000 MN/m^2. The 3D effect was represented by adding flexible support to each of the four horizontal beams. Stiffness of the flexible support was derived with assumption that horizontal beams were laterally fixed.

With FLAC predicted wall movements are shown in Fig 5.



Horizontal displacements contours
Min. disp. 0.0
Max. disp. 2.0 cm
Contour interval 0.25 cm

Figure 5. Predicted wall movements.

The predicted movements suggested that, by the completion of construction, the wall would be translated forward and rotated about the base with little deflection due to banding. The maximum movements (20 mm) should take place at facing in the lower portion of the wall.

3.3 *Limit equilibrium calculations*

Limit equilibrium analysis is based on limit equilibrium concepts. At failure, a slip surface is assumed to occur with simultaneous mobilization of the shear strength along that surface. The mass above the slip surface is assumed to move as a rigid body. The driving force causing the development of the slip surface is the weight of retained soil. The resisting forces are due to shear strength of the soil, forces in nails and prestrained anchors, and the resistance of soil in front of the toe of the wall (passive resistance).

Limit equilibrium analyses were carried out by SLOPE/W software (Geo-slope International Ltd.). The safety of the anchored slope is expressed in terms of the factor of safety F_s which is the ratio of the available shear strength to the mobilized strength. For heavily overconsolidated clays an effective stress analysis usually derives a minimum factor of safety; therefore, this type of analysis was applied for the Dežmanova street nailed wall. The geometry of the slip surface with nails and prestressed anchors is presented in Figure 6. The failure analyses include external modes, internal and modes called mixed modes (FHWA) which include pullout of the nails.

Factors of safety were computed automatically for a great number of slip surfaces, most of which passed through the wall toe. The shape of the slip surface could be curved, planar or combination of both. For

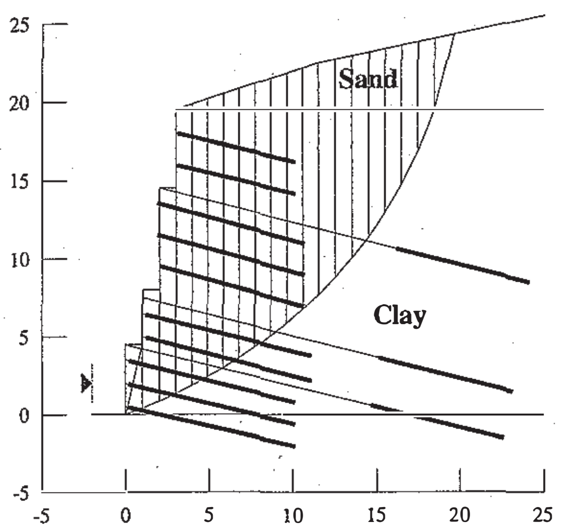


Figure 6. Limit equilibrium analysis with critical slip surface and a minimum factor of safety (dimensions in meters).

almost homogeneous material, an arc of the circle was found to be satisfactory. In the analysis the lengths of prestressed anchors were varied to keep the fixed lengths of anchors behind the critical failure surface. In drained analysis found was the minimum factor of safety of F_s = 1.27. As mentioned above, after completion of the retaining structure, the portion below the street level was supported with concrete massive walls, and the above street portion of the nailed wall remained the permanent construction. For this (upper) part the calculated factor of safety was of the order of 1.5. Factors of safety equal to or greater than 1.25 for temporary construction and equal to or greater than 1.5 for permanent construction were found to be satisfactory.

It may be concluded that the main role in the stability of the wall may be attributed to the long prestressed anchors that, for the critical stability situation, retain the whole sliding mass in equilibrium.

4 CONSTRUCTION AND MONITORING

4.1 *Construction*

The construction began with removal of trees and grass at the end of April of the year 2000. Approximately 10 000 m^3 of soil was excavated. The excavation and construction of the nailed wall was completed in 3.5 months, which was - considering the height and other dimensions of the wall - a rather short time, the more so because/even though the limited working space available for the building site, and the fact that Dežmanova Street is a dead-end street (problems with taking excavated soil away) made the construction even more difficult.

According to design requirements, each facing zone was provided with nails which were horizontally spaced 1.5 m apart, and vertically nails were spaced apart from 2.0 m (8.0 m lengths) in the uppermost zone to 1.2 m in the lowest zone (10.0 m lengths). The prestressed ground anchors were 20 to 24 m long with fixed lengths of 8.0 m. The anchors were installed at an angle of 15° to the horizontal. The bore hole diameter was 140 mm. The strand had the following characteristics: diameter 12.9 mm, cross-section area 100 mm^2, tensile strength 1860 N/mm^2 and modulus of elasticity E = 195±10 kN/mm^2. On the edge of each zone was a horizontal beam whose role was to fix upper and lower facing parts and to serve as a bearing for a prestressed anchor head. The facing was cast-in-place.

Grouting was done in several working steps: filling the casing with grout from the top of the borehole, pulling out the casing to the beginning of the fixed anchor length, primary grouting through the casing, removal of the casing and secondary grouting of the fixed anchor length through inner grouting pipe.

The anchors were stressed ten days after completion of grouting procedure, i.e. after the grout obtained the strength of minimum 30 MN/m^2. Three prestressed anchors pullout testiness were performed during construction. The ultimate pull-out resistance was between 400 and 500 kN, which was within the expected limits.

4.2 *Field instrumentation and monitoring*

According to FHWA the most significant measurement of overall performance of the soil nail wall system is the deformation of the wall during and after construction. For the Dežmanova Street nail wall, movements along the soil mass in the retained soils were measured in two ways: by measuring the movements of three geodetic points, and by means of two sliding deformeters (24.0 m and 16.0 m long) to obtain continuous displacement measurements along the axis of measurement casing.

In Dežmanova Street, sliding deformeters were positioned along the prestressed anchors. Positions of deformeters are presented in Figure 2. Sliding deformeters were installed in a short time after placing the anchors and facing; the measurements were taken fourteen times in the period between 2 May 2000 and 21 November 2000 (Kovačević, 2000). The measurements showed maximum horizontal displacements of 2 mm in the deformeter 1 and 1.5 mm in the deformeter 2. (Figure 7) Similar results were obtained by measuring the movements of the geodetic points. Since October all measurement data in both deformeters have been exactly

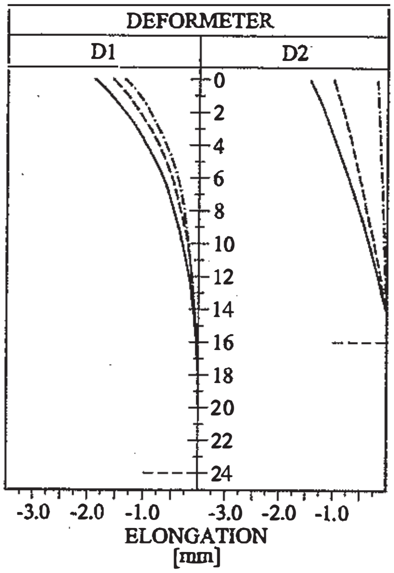


Figure 7. Horizontal movements of facing and the ground as measured by sliding deformeters (Kovačević, 2000).

the same, which means that no creep deformations were observed.

Although the numerical modeling predicted final maximum movements of 20 mm (chapter 3), deformation measurements showed much smaller wall movements. It seems that both the stiff soil in the background and the stiff facing are the reason why the Dežmanova Street nailed wall was deforming less than expected and less than predicted with calculation models. Overall results demonstrate that the calculation should account for a wide range of modes of behavior when assessing the loading effects in service, and that special attention should be given to a 3D effect.

5 SUMMARY AND CONCLUSION

The nailing technology in the Dežmanova Street nailed wall included the combination of passive (nails) and active inclusions (long pretensioned anchors). Stability calculations showed that long anchors could not be avoided because of deep critical slip surface that is typical of cohesive soils at strength limit state. The quality of the clay material and lack of ground water made fast excavation and wall construction possible. Construction work was executed during the summer period, and rainy weather did not disrupt the building schedule seriously. During construction, deformations were measured to monitor the stability situation. Measurements showed that the displacements along the facing were considerably smaller than indicated by numerical analyses.

The Dežmanova Street nailed wall is one of the highest retaining constructions of this type ever built in clays. Its behavior is also beyond every expectation, which indicates that there is still room for more economic nailed wall construction in similar materials.

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