Some remarks on the effect of soil-nail interface stress state on the determination of pullout resistance of driven nails

Quelques remarques sur l'effet de l'état de contrainte à l'interface sol-clou sur la détermination de la résistance à l'arrachement de clous battus

Di Fonzo G., Flora A., Nicotera M.V.
Department of Hydraulic, Geotechnical and Environmental Engineering, University of Napoli Federico II, Italy

Manfredi G., Prota A.
Department of Structural Engineering, University of Napoli Federico II, Italy

ABSTRACT

At the University of Napoli Federico II a comprehensive research programme was started to study soil nailed structures in the soft pyroclastic silty sands (*pozzolana*) widely spread in the subsoil of Napoli. The program includes tests on nails instrumented with strain gauges in a large pullout apparatus and 3D numerical analyses. In the paper, the preliminary results obtained with the latter will be presented and compared with some of the experimental pullout test results. Installation of driven nails induces a stress disturbance at the soil nail interface, which is essentially a reduction of normal stresses and a tendency of the stress state to become isotropic. It is argued that numerical testing can be usefully adopted to understand the true soil nail interface failure mechanism and to highlight the link between it and the overall pullout strength, instead of being used just to fit the experimental pullout curves.

RÉSUMÉ

À l'Université de Naples Federico II un programme complet de recherche a été lancé afin d'étudier le clouage des sables limoneux pyroclastiques (pouzzolane) largement répandus dans le sous-sol de Naples. Le programme comprend des essais sur des clous instrumentés avec des jauges de déformation dans un grand appareil d'arrachement et des analyses numériques en 3D. Dans cet article, les résultats préliminaires obtenus avec ces derniers seront présentés et comparées avec quelques-uns des résultats expérimentaux des essais d'arrachement. L'installation des clous battus produit une perturbation dans l'état de contrainte à l'interface sol-clou, qui est essentiellement une réduction des contraintes normales et une tendance de l'état à devenir isotrope. Il est fait valoir que la simulation numérique peut être utilement adoptée en vue de comprendre le vrai mécanisme de rupture à l'interface sol-clou et de mettre en évidence son lien avec la résistance globale à l'arrachement, au lieu d'être utilisée seulement pour rechercher le meilleur accord avec les courbes expérimentales d'arrachement.

Keywords: Soil nailing, installation disturbance, pullout strength, numerical simulations

1 INTRODUCTION

In soil nailing design, the calculation of pullout safety factor is affected by large uncertainties, as the estimation of both a nail working load and of a soil-nail interface shear strength are far from being routine calculations.

The average shear strength at the interface of a soil nail at the generic abscissa x along the nail can be written as:

$$\bar{\tau}(x) = \frac{1}{2\pi}\int_0^{2\pi} \tau_{xn}(x;\vartheta)\cdot d\vartheta \qquad (1)$$

where:

$$\tau_{xn} = \sigma_n(x,\vartheta)\tan\delta \qquad (2)$$

being n and θ defined in Fig. 1. The frictional characteristics of the interface, summarized by the variable δ, are influenced both by soil mechanical properties and by geometrical and mechanical nail properties.

The normal stress at the interface σ_n varies along the nail perimeter and is affected by the initial stress state and by the installation procedure. In grouted nails, the latter usually dominates on the former, and the normal stress $\sigma_n(\vartheta)$ is uniformly distributed and proportional to the grout injection pressure. The available shear strength at the soil-nail interface is therefore the same on the whole interface, and can be somehow reliably predicted using eqs. (1) and (2). In driven nails, which are displacing nails, the initial stress state may be either reduced or increased depending on nail shape, volume and installation procedure. Such a change in stress state is difficult to predict. Whatever it is, $\sigma_n(\vartheta)$ is far from being uniformly distributed around the nail and as a consequence, for these nails, the available shear strength varies along the perimeter as well. Then, both because of the unknown distribution of $\sigma_n(\vartheta)$ and of the non uniformity of τ_n around the nail, the prediction of the average shear strength given by eq. (1) is in this case not straightforward.

The mean overall pullout shear strength τ_{po} of a nail (which is the needed design parameter) can be expressed as a function of the average local shear strength (eq. 1) as:

$$\tau_{po} = \frac{1}{L_p}\int_0^{L_p} \bar{\tau}(x)\cdot dx \qquad (3)$$

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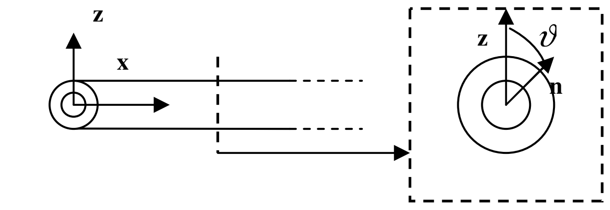

Figure 1. Definition of the generic normal n(ϑ)in the nail cross section.

where L_p is the ‘passive’ length of the nail. From a design point of view, it is crucial to be able to calculate τ_{po} in a reliable yet easy way, and because of the previously mentioned uncertainties eq. (3) is of little help for driven nails. Some simpler expression is therefore usually adopted in design calculations, like:

$$\tau_{po} = \mu \cdot \sigma_z \tag{4}$$

in which μ is a frictional coefficient depending on soil nail interface friction angle δ and soil stress state around the nail, and σ_z is the relevant vertical stress prior to nail installation (sum of the lithostatic stress and of a possible external vertical load). Eq. (4) can be also used to define a local value of the frictional coefficient μ_{loc} by referring to the mean value of the shear strength in the considered nail cross section. For driven nails, eq. (4) is attractive from the designer point of view because of its simplicity, all the complexity being hidden in μ. The same expression can be used for grouted nails, even though for them alternative expressions may be proposed as a function of grout pressure. In literature, μ is typically expressed as a function of soil friction angle ϕ, and values of μ=0.9·tan(ϕ) and μ=(0.4÷0.5)·tan(ϕ) are for instance suggested respectively for grouted and driven nails by Jewell (1990).

Because of the above mentioned difficulties in quantifying the overall pullout shear strength τ_{po} for driven nails, laboratory and numerical tests are needed to get an insight on their ‘true’ behaviour at the soil nail interface (represented by the distributions of $\tau_{xn}(\vartheta)$ and $\sigma_n(\theta)$). So doing, complexity can be kept at the research stage and research evidences can be used to suggest reliable values of μ in eq. (4).

In the paper, a contribution on this topic is given, with reference to an experimental and numerical research activity currently under course at the University of Napoli Federico II on the use of soil nailing in unsaturated pyroclastic silty sands (*pozzolana*).

2. EXPERIMENTAL EVIDENCE AND NUMERICAL SIMULATIONS

A comprehensive experimental testing programme has been carried out in a large pullout box, testing on different nails driven into unsaturated *pozzolana* (Di Fonzo, 2008). Tests were carried out on nails either driven or put in place during specimen preparation. The latter were intended to represent an ideal installation procedure, with the lowest possible disturbance of the initial soil nail interface stress state. Fig. 2 shows three of these ‘low disturbance’ tests, at three different vertical confining stresses (50, 100, 150 kPa), in terms of average mobilised shear strain. The failure value is therefore the mean overall pullout shear strength τ_{po} (eq. 3). The tests shown in Fig. 2 were carried out on cylindrical steel nails with a rough surface, having a diameter of 33 mm. The soil is unsaturated pozzolana (c=0, ϕ=37°) having fairly constant state parameters.

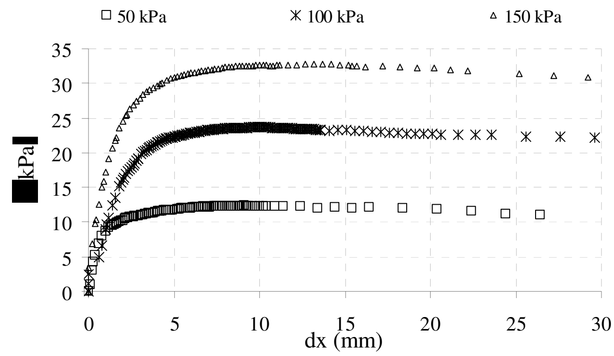

Figure 2. Results of three pullout tests at different vertical confining pressure (dx is the nail axial displacement).

The pullout strength increases as confining stress increases, and is reached for nail displacements (dx) between 5 and 15 mm.

By interpreting the three tests with eq. (4), using the relevant values of the total vertical stresses (50, 100 and 150 kPa), a rather constant value of the frictional coefficient μ=0.22=0.29·tan(37°) is obtained. Notwithstanding the care in placing the nail within the box, such a frictional coefficient is lower than the values suggested in literature for driven nails. Numerical simulations were then carried out using a commercial finite element code (*Plaxis 3D tunnelling* ver. 2.2) to simulate these three tests and to get an insight into the soil nail interaction mechanism.

The use of numerical analyses to this aim may be very effective, and has not been used extensively as far as soil nailing is concerned. Examples of both 2D and 3D simulations are given for instance by Smith et al. (1997), Zhang et al (1999) and Sivakumar Babu et al. (2002), even though in all these mentioned cases no special attention is devoted to the complex behaviour at the soil nail interface.

The three-dimensional model (see Fig. 3) has the same dimensions of the laboratory pull-out box (i.e. L=2.00 m, B=H=0.8m). The adopted mesh consists of 23088 wedge 15-nodes elements (62998 nodes and 138528 stress points in total). The top, the bottom, the rear and the side extremes of the sample coincide with the boundaries of the numerical model, while the front plane is confined by a solid steel face simulating the pull-out box front wall.

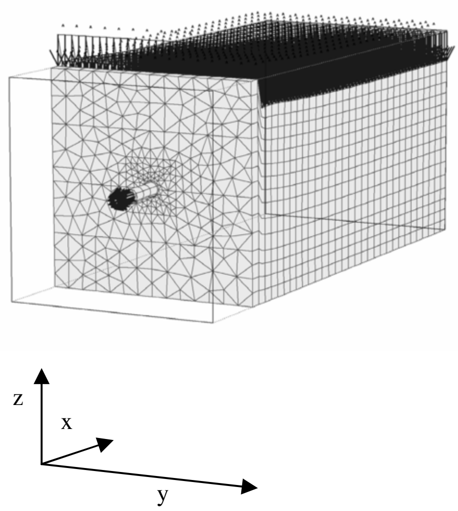

Figure 3. 3D deformed mesh of a pullout tests.

For the soil, a simple elastic perfectly plastic model with a Mohr-Coulomb failure criterion was adopted (γ=16 kN/m^3, E=10 MPa, ν=0.3, c=0, ψ=0, ϕ=37°). Even though this is a simple model, the parameters were calibrated on the large amount of experimental evidence collected on pozzolana by the authors.

The nail was simulated as an elastic steel tube (D=35 mm). Interface elements were placed between the soil and the nail to allow relative displacement with a reasonable computational effort. The boundary conditions consist of totally restrained displacements on the bottom boundary; restrained displacements in the normal direction on side boundary and rear boundary; free displacements along the front boundary (i.e. the steel face of the box). The condition on the top boundary varies along the simulations (i.e. free displacements during initial stress generation; prescribed constant stresses during loading and pullout test).

The first simulations (tests A1, A2, A3, respectively at 50, 100 and 150 kPa of vertical confining stress) were carried out assuming no disturbance at the soil nail interface (ideal installation) and hence interfaces elements had the same mechanical properties of the surrounding soil. Each simulation consists of the following subsequent calculation phases: 1) generation of the initial stress state in the reconstituted sample by incrementally activating the unit weight of the sample itself; 2) application of the prescribed vertical load on the top boundary of the sample; 3) activation of the nail by switching the material of the corresponding elements; 4) incremental application of the pull force at the extreme of the nail. The results of three simulations performed at the same vertical confining stress of the tests in Fig. 2 are represented in Fig. 4.

The simulations are not satisfactory, as they largely overestimate both the average stiffness and the pullout strength. The value of the overall frictional parameter μ (eq. 4) inferred by these numerical simulations is 0,40=0.53·tan(37°), twice as large as the experimental value previously mentioned. By looking at the local results along the nail, it can be observed that μ_{loc} is not constant along the nail, being the overall value μ=0.40 a mean one of a more complex distribution. Tab. 1 reports the values of μ_{loc} calculated in different nail sections at the end of the simulation. Since at soil nail interface a complete mobilisation of shear strength has certainly taken place at the end of simulation (very large displacements), that is τ_{po}=cost, the different values of μ_{loc} indicate that σ_z is not constant along the nail. In particular, these differences are not so large but close to the nail pull section, where very low values of μ_{loc} indicate a large local disturbance of the stress state because of the interaction among the nail, the soil, and the steel caisson face.

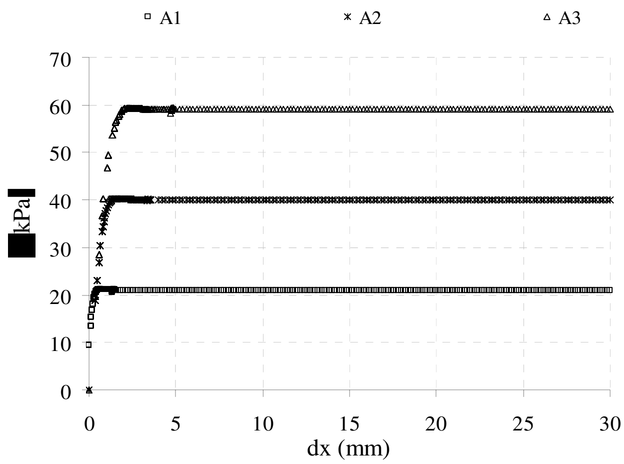

Figure 4. Results of three pullout tests at different vertical confining pressure without stress release at soil nail interface (dx is the nail axial displacement).

Tab. 1. Values of the local frictional coefficient μ_{loc} in different nail sections.

x (m)	0,20	0,40	0,80	1,20
A1	0,35	0,38	0,41	0,42
A2	0,35	0,38	0,39	0,41
A3	0,35	0,38	0,42	0,43

The aforementioned results imply that some disturbance at the soil nail interface has to be taken into account to correctly reproduce the experimental results. As a matter of fact disturbance may be a consequence of one or both of the two following phenomena: 1) the shear strength at the soil nail interface is smaller than the shear strength of the soil, that is the interface friction angle δ differs from ϕ'; 2) the actual stress state around the nail is conditioned by some kind of arching effect developed since the specimen compaction and nail installation, and further modified during the pullout test.

Even though in principle either phenomena could be considered in the numerical analyses to better fit the experimental results, it is important to understand which is really likely to happen. A number of direct shear tests were therefore carried out to measure the soil/nail interface friction angle δ (Di Fonzo, 2008). The tests were arranged with a flat interface having the same superficial roughness of the nail. Test results indicated that the shear strength at the interface was almost identical to soil shear strength. As a consequence, the first phenomenon previously mentioned was not considered. Then, the reason why simulations were not able to reproduce the experimental tests must be a reduction of the normal stresses acting at the soil-nail interface.

Even though it is basically impossible or at least very difficult to carry out any experimental measurement of this modification, it could be reasonably argued that upon nail installation the stress state around the nail is deeply modified.

These observations suggested some improvements in the numerical simulations; an extra calculation phase was therefore added between phases 2 and 3 to model the stress disturbance around the nail. Such an extra phase consists of a progressive and proportional release of the stresses exerted on the surrounding soil elements by the soil elements which have to be substituted by the nail upon installation simulation.

A trial and error procedure was adopted to calibrate the amount of release, with the goal of reproducing the experimental results. In this way, the disturbance induced to the stress state at the nail boundary is roughly simulated. Three numerical simulations (R1, R2, R3 respectively at 50, 100 and 150 kPa of vertical confining stress) were then carried out with this procedure.

The results of these new simulations are satisfactory in terms of final pullout shear strength (Fig. 5).

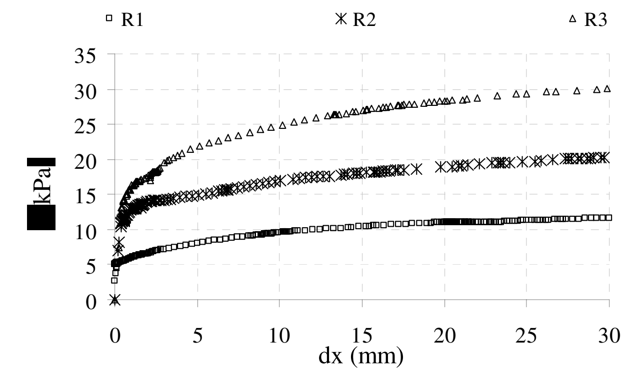

Figure 5. Results of three pullout tests at different vertical confining pressure without stress release at soil nail interface (dx is the nail axial displacement).

The overall results of the experimental tests and of all the simulations are finally reported in Fig. 6 in terms of maximum value of the pullout strength versus vertical confining stress.

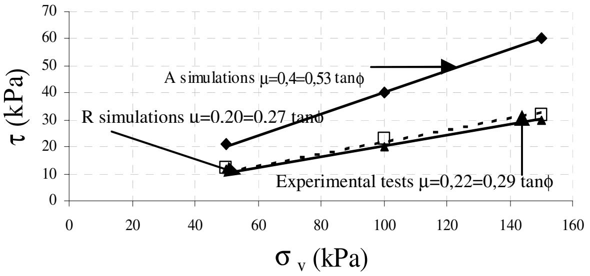

Figure 6. Summary of experimental and numerical results.

3. DISCUSSION OF RESULTS

In Fig. 7 the evolution of the shear strength mobilisation on a vertical plane located in the soil nearby the middle height of the nail cross section is reported: at the end of the calculation phase simulating the nail installation disturbance (i.e. stress release) the shear stress on the plane is vertically directed (point I); as the pullout test proceeds the direction of the shear stress changes becoming progressively parallel to the nail axis (path I-F).

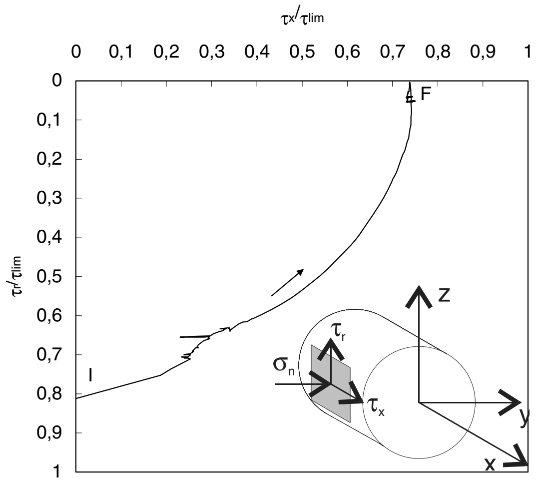

Figure 7. Evolution of the mobilised shear strength components along the test from nail installation (point I) to the end of the test (point F).

The shear strength mobilisation (represented by the norm of the shear stress vector) is almost constant along the simulation (that is, failure is attained at soil nail interface from the very first steps of the numerical simulation), even though only the component τ_{nx} (which increases from point I to F) contributes to pullout strength.

The differences in stress state among the A and R simulations can be seen in Fig. 8, with reference as an example to simulations A3 and R3, having the same vertical confining stress of 150 kPa. In the figure, for the two simulations the normal stress acting at the soil nail boundary after nail installation is represented for the two cases of $\sigma_n=\sigma_v$ and $\sigma_n=\sigma_h$, being respectively σ_v and σ_h the vertical and horizontal stresses. For simulation A3 (ideal installation without stress release) the stress state around the nail is practically undisturbed, with some discrepancy only near the nail head due to the interaction between the soil and the caisson face. It is worth noticing that far from this disturbed zone the ratio between the normal stress at the middle height of the nail side (point 2 in Fig. 8) and at the crown (point 1 in Fig. 8) is equal to the ratio K_0 between the horizontal and vertical stress.

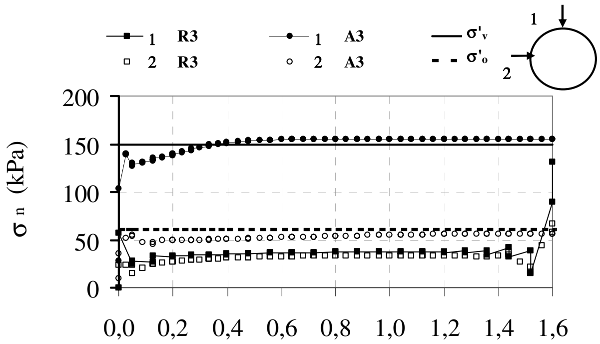

Figure 8. Normal stresses on top and on the side (σv and σn) of the nail along its length for the two simulations at confining vertical stress of 150 kPa, with and without stress relesase.

In the second simulation (R3), the stress state around the nail with stress release is largely reduced and close to be isotropic. Similar results were obtained for the other confining stresses.

Then, installation disturbance has two main effects: a reduction of the stress state (which in the case of the numerical simulations was imposed, but likely to be true for the above reported observations), and an increase of the stress ratio K from K_0 to nearly 1. This latter evidence is confirmed by the fact that if the pullout shear strength τ_{po} found with the three R simulations is divided by tan (ϕ'), an average normal stress σ_n close to the numerically found (almost isotropic) one is retrieved (respectively σ_n(R1)=16, σ_n(R2)=26, σ_n(R3)=38). These values indicate a reduction of the mean stress from the initial value $(1+K_0)\sigma_v/2$ ranging between 65% and 70%.

If this is true, by dividing the experimentally found pullout shear strength on site for the known value of the interface friction angle δ (which in this case is equal to ϕ') a reasonable estimate of the normal stress acting on the nail can be done. The results obtained in this research indicate that an improvement in installation procedure has to be achieved.

4 CONCLUSIONS

A FEM model implemented by means of a commercial code (Plaxis 3D) was used to try and simulate laboratory pullout tests carried out on driven nails in soft pyroclastic silty sand (pozzolana).

The simulations have shown that eq. (4) is oversimplified because it doesn't take into account the true stress state around the nail, which is obviously affected by the value of the boundary horizontal stress, by the nail installation simulation procedure, and by the box boundaries as well. In fact, the frictional coefficient μ of eq. (4) relates the average shear stress along the nail lateral surface (which is far from being constant) to a reference constant vertical stress (which is neither the relevant stress variable nor has a constant value at the end of tests).

The numerical simulations shown in the paper demonstrate that, by taking into account the relevant stress variables and values, the pullout strength can be retrieved and justified in terms of soil-nail interaction and mobilised shear strength.

The simulations also indicate that the low experimental values of the frictional coefficient μ may depend on both stress anisotropy and installation disturbance. The results show that the two factors are alternative, as the previous may be relevant only if close to ideal installation is considered, while its effect tends to fade when installation disturbance increases and the stress state around the nail becomes isotropic.

Even though the numerical simulations cannot have the role of finding the operative values of μ to be adopted for design, they have shown to be of great help in understanding interaction mechanisms and in explaining at least part of the large variation the frictional factor may show on site.

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