Ground treatments for soft clays below the water table

GEOINGEGNERIA E ATTIVITÀ ESTRATTIVA GEAM

DX.DOI.ORG//10.19199/2024.172-173.1121-9041.005

Ground treatments for soft clays below the water table

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Water in tunnels represents a challenge in any geological condition. When dealing with cohesive material, this aspect might bring additional problems linked to the low permeability, which does not allow effective and quick drainage to stabilize the ground around the tunnel. Ordinary drainage systems are an effective method, especially in higher permeability grounds, but these are losing efficacy in soft clays. This paper focuses on an innovative technique for stabilizing the tunnel face and surrounding ground by using a special soil nail consisting of a fiberglass bar element and an external sheath devised to contain the injected grout, which can also be integrated with a coaxial drain. The advantage of this technique is not only a decrease in the pore water pressure but also an increase of cohesion and elastic modulus over time thanks to the induced consolidation process of the clay and a consequent improvement of the mechanical characteristics.
***Keywords**: ground treatments, water, soft clays, innovative technique, tunnel.*

1. Introduction

Tunnel excavation in geological contexts characterized by clayey soils with poor mechanical characteristics has always been highly complex, as the stability of the excavation face and the contour itself has to be maintained up to a distance of 5-6 times the tunnel diameter. Furthermore, in tunnels dug below the groundwater level, the pore pressure reduces the soil mechanical strength according to the Terzaghi's principle of effective stresses.

An additional difficulty for fine-grained soils such as clays and silts is that the variation of pore pressure due to a disturbance of initial groundwater conditions evolves according to the consolidation process, causing a consequent variation of effective stresses and, thus, the strength of the soil.

The two problems shortly present must be tackled simultaneously in a comprehensive way; indeed, the first one consists of maintaining the stability of the tunnel face and is related to the mechanical characteristics of the soil, and the second one to the control of the pore pressures, associated with the groundwater condition which, once altered, will give rise to a variation of interstitial pressures to be controlled coherently with the realization of the tunnel in the short and long term.

The existing methodologies and the main design methods with related critical issues are illustrated below. These lay a basis for using a technology that has yet to be explored in terms of improvement effects, which would solve many of the aspects discussed.

2. Presentation

Improvement techniques are usually adopted to ensure tunnel stability and an acceptable level of risk before the new excavation profile planned by the advancement is achieved. Particularly, several methods have been developed to ensure the stability of the underground work area; in fact, the improvement techniques aim to control the extent of displacements due to three main phenomena (Lunardi, 2008): displacements at the tunnel face (Face extrusion), radial displacement ahead excavation face (Pre-convergence) and behind it (Convergence), not to be neglected will also be the control of water flows in the tunnel and its surroundings.

In general, the improvement interventions increase both resistance and mechanical characteristics, enabling obtaining a material with much greater stiffness and cohesion (effective/operational). In Figure 1, the most common reinforcement techniques used ahead of the tunnel face and the relative field of applicability are reported according to the classification table realized by Peila *et al.* (2022)

Focusing on the criticalities of two technologies (drains and fiberglass), the most significant criticality for drains is known to lie in the speed with which the flow control action takes place and, consequently, the dissipation rate of the pore overpressures, which leads to an increase in effective stresses and, therefore, mechanical resistance. To simplify, referring to Terzaghi's theory of 1D consolidation, the speed of the process is related to the consolidation coefficient cv. Low cv values are the result of materials with low permeability ($k < 10^{-9}$ m/s) and with low oedometric modulus that consequently leads to a longer consolidation process.

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Auxiliary method	*Cohesive soil*	*Sand & gravel*	*Soil with boulders*	*Fractured rock mass*
Grouting	⦿○	●	○	●
Jet grouting	⦿	●	⦿	
Freezing	●	●	●	●
Drainage	⦿	●	●	●
Fibreglass elements (face and tunnel boundary)	●	●⦿	○	⦿
Pre-cut	●	●		
Steel pipe umbrella	●	⦿	⦿	●

The listed interventions can be combined in order to fulfil the required needs.
Grouting, jet grouting, freezing and dewatering can normally be applied also when tunnelling under the water table, but the drilling operation must be carried out with special care, for example with the use of a preventer, and should manage the water and soil ingress.
Key: ●, applicable; ⦿, applicable with special interventions; ○, difficult but possible.

Fig. 1 – Application fields of reinforcement methods installed ahead of the tunnel face (Peila *et al.* 2022).

Considering fiberglass elements as a reinforcement at the excavation face and at the contour, the biggest problem concerns the number of installations to be carried out, quantifiable as reinforcement density as element/m^2 (Anagnostou & Serafeimidis, 2007). Additionally, to effectively ensure a safe condition in all excavation sequences it is necessary to install the fiberglass element with an overlap length between subsequent fields of reinforcement, as widely discussed (Perazzelli & Anagnostou, 2015) and illustrated in Figure 2.

In recent years, a technology has reconciled and solved the problems illustrated for drains and consolidations at the tunnel face in Italy and other parts of the world (e.g. China): this consists of a soil recompression system coupled with drainage, which takes on different nomenclatures, specifically PERGround© in Italy and Capsule Grouting in China. The scheme of these technologies is shown in Figure 3.

3. Design aspects

In the design process, appropriate dimensioning and optimization of reinforcement intervention are needed during the evolution of the excavation, mainly to avoid oversizing, which reduces productivity and sustainability of the works and directly impacts the economic assets of the entire project.

The approach used in professional practice presents considerable simplifications; indeed, one of the most widely used approaches is the LEM (Limit Equilibrium Method), which concerns the use of a system of forces divided into destabilizing ones due to the progressive breakage of the excavation face (subjected to the previously mentioned deformation phenomena) and to any water inflow entering in the tunnel and contributing with a non-negligible hydrodynamic thrust. Stabilizing forces are instead provided when applying reinforcements, such as fiberglass, which may or may not be grouted during the in-

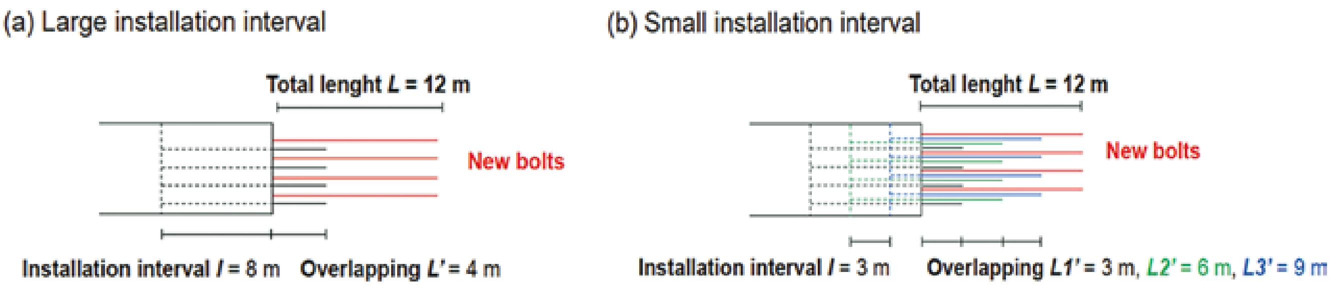

Fig. 2 – Installation scheme with large fiberglass installation interval (Anagnostou & Perazzelli, 2015).

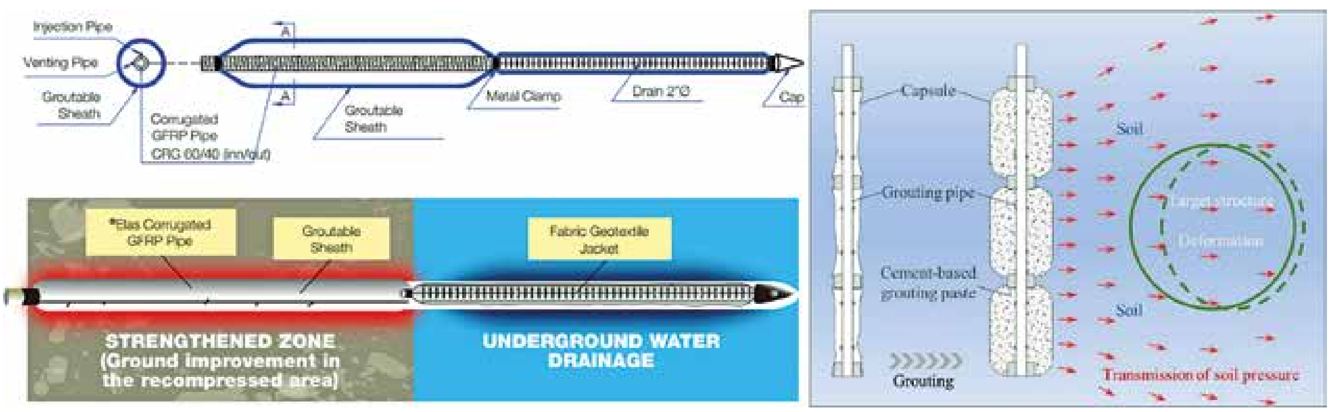

Fig. 3 – PERGround© configuration scheme (left). Capsule grouting configuration scheme (right) (Renda *et al.*, 2011; Sterpi *et al.*, 2013, Xiaopei et al, 2024).

stallation phase. The evaluation of the force to be applied is related to the mechanical characteristics of the fiberglass element and to the geometry of the failure at the excavation face, according to the following formula:

$$F_{VTR} = \min\left[F_1 = \frac{\tau_\alpha \pi D k l}{FS_1}; F_2 = \frac{A f_{yk}}{FS_2}\right] \quad (1)$$

where τ_α = shear strength between the injected grout and the surrounding ground; D = borehole diameter; l = minimum length of bar inside the reinforced ground; k = 1.5, increased diameter factor; A = element section area; f_{yk} = element yield strength; and FS_1; FS_2 = safety factors (equal to 2).

Over the years, the design process following the LEM has been developed and improved, leading to a consolidated and reliable procedure. However, a fundamental aspect, the deformational one, is completely ignored. Avoiding deformational features in more complex contexts (urban area, soft soils, high water level, etc…) is not admissible for many reasons, and the use of a numerical approach is unavoidable.

In numerical methods, the quantification of the improvement effect on the soil can be uncertain and quite variable by soil type, leading again to over or underdimensioning, which affects economic, production, and sustainable aspects.

In Figure 4, the method used for quantification of the stabilizing effect of face reinforcement is tackled by using homogenization approaches, which smears the improvement of the bolts as an equivalent ground with higher strength. The equations from (2) to (7) show the equivalent strength c_c* as a function of the number of elements, inclination, and area of application based on the scheme in Figure 4.

3.1. Radial Improvement

$$A_c = 2\pi L R \quad (2)$$

$$\Delta\sigma_{3c} = N_{VTR} \frac{\min(F_1, F_2)}{A_c} \sin(i) \quad (3)$$

$$c_c^* = c_d + \frac{\Delta\sigma_{3c}}{2} \tan\left(45° + \frac{\varphi_d}{2}\right) \quad (4)$$

where A_c = consolidation area (m^2); L = length of reinforcement (m); R = ratio between consolidated annulus and the excavation (-); N_{VTR} = number of fiberglass bars (-); i = inclination of the bars (∘); c_d = design cohesion (kPa); $\Delta\sigma_{3c}$ = increase on confinement stress state (kPa); and φ_d =design friction angle (°).

3.2. Face Improvement

$$A_{face} = A_{excavation} \quad (5)$$

$$\Delta\sigma_{3f} = N_{VTR} \frac{\min(F_1, F_2)}{A_f} \cos(i) \quad (6)$$

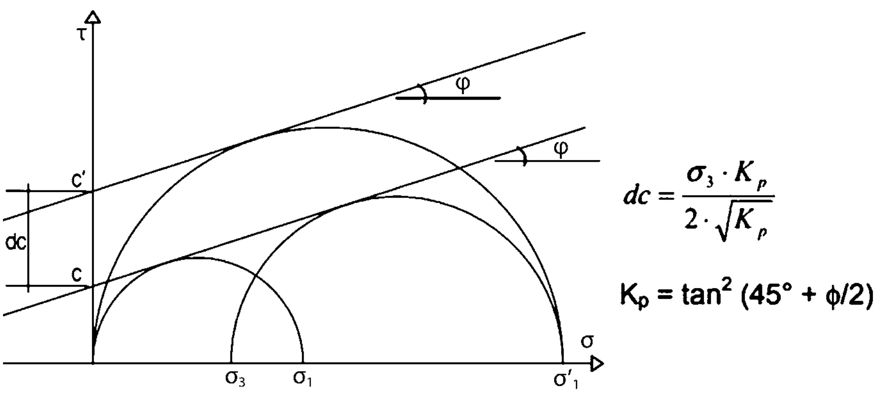

Fig. 4 – Improvement contribution of fiberglass in terms of cohesion in the Mohr-Coulomb plot.

$$c_f^* = c_d + \frac{\Delta\sigma_{3f}}{2} \tan\left(45° + \frac{\varphi_d}{2}\right) \quad (7)$$

In addition, the deformability of the soil (E_t) used in a numerical model must be incorporated by remembering that it is not a fixed variable but evolves and increases due to a more significant state of confinement respect in the initial one. Two formulations for calculating E_t: one from Janbu, 1963 (Eq. 8) and the second from Lade & Nelson, 1987 who incorporated the shear contribution (Eq. 9).

$$E_t = K p_a \left(\frac{\sigma}{p_a}\right)^n \quad (8)$$

$$E_t = K p_a \left(\frac{\sqrt{p^2 + r q^2}}{p_a}\right)^n \quad (9)$$

where σ = lateral confining pressure (*kPa*); p_a = atmospheric pressure (*kPa*); *K*, *n* = parameters specific to a soil (-); *p* = mean stress (*kPa*); *q* = deviatoric stress (kPa); and *r* = function of the Poisson's ratio (-).

4. Enhancement aspects

The improvement effects obtained following the application of recompression and drainage interventions have not yet been determined explicitly and quantitatively, but several studies deriving from pull-out tests (Renda *et al.*, 2011; Sterpi *et al.*, 2013) and laboratory tests (Bhuiyan *et al.*, 2022; Xiaopei *et al.*, 2024) have noted over the years a clear improvement in the characteristics of the reinforcement.

In Figure 5, the results from a pull-out test set-up have been reported. The comparison of results between a traditional fiberglass and a reinforced one with a groutable sheath shows a difference of 1 order of magnitude.

Over the years, different authors

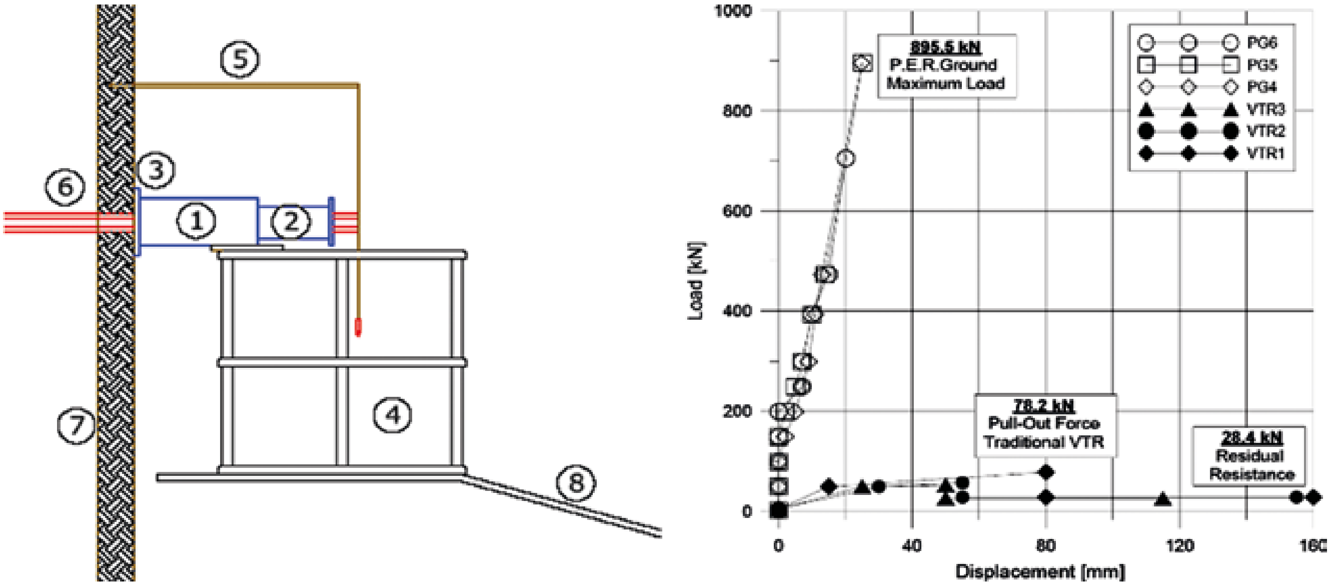

Fig. 5 – Pull out test set up and devices (left): 1) jack, 2) gripper, 3) stiff steel plate, 4) platform for operator, 5) plumbline, 6) reinforcement system, 7) excavation face, 8) mechanical device for platform positioning. Results from pull-out tests on conventional VTR bars and PERGround© (right) (Renda *et al.*, 2011).

have developed numerical models capable of simulating consolidation through the previously mentioned technologies. In particular, the studies conducted by Renda *et al.* (2011) have led to quantifying the improvement effect as a function of the most significant geotechnical parameters, such as the overconsolidation ratio (OCR) and permeability. The modelling scheme adopted for simulating this technology is shown in Figure 6: each element in green and white contains an element able to transmit the recompression and another to drain the contour; instead light blue elements represent a complete drain.

Figure 7 shows the distribution in the model of the undrained cohesion cu after 5 days of improving effects of recompression using inflatable pockets ($k < 10^{-8}$ m/s). The grade of improvement registered in this case is quite relevant; indeed, it increases by 33% between the inflatable pockets compared to the initial value and 100%.

However, the grade of improvement for the same time interval highly depends on the permeability of the surrounding soils (Floria *et al.*, 2008), and so this aspect needs to be considered and monitored during the application of this technology in the field. Other estimations have been realized considering a radial installation of drains without pockets but with a focus on the effect of increasing the number of drains. Figure 8 shows the evolution of effective stress close to the reinforcement over time for different ground permeability and

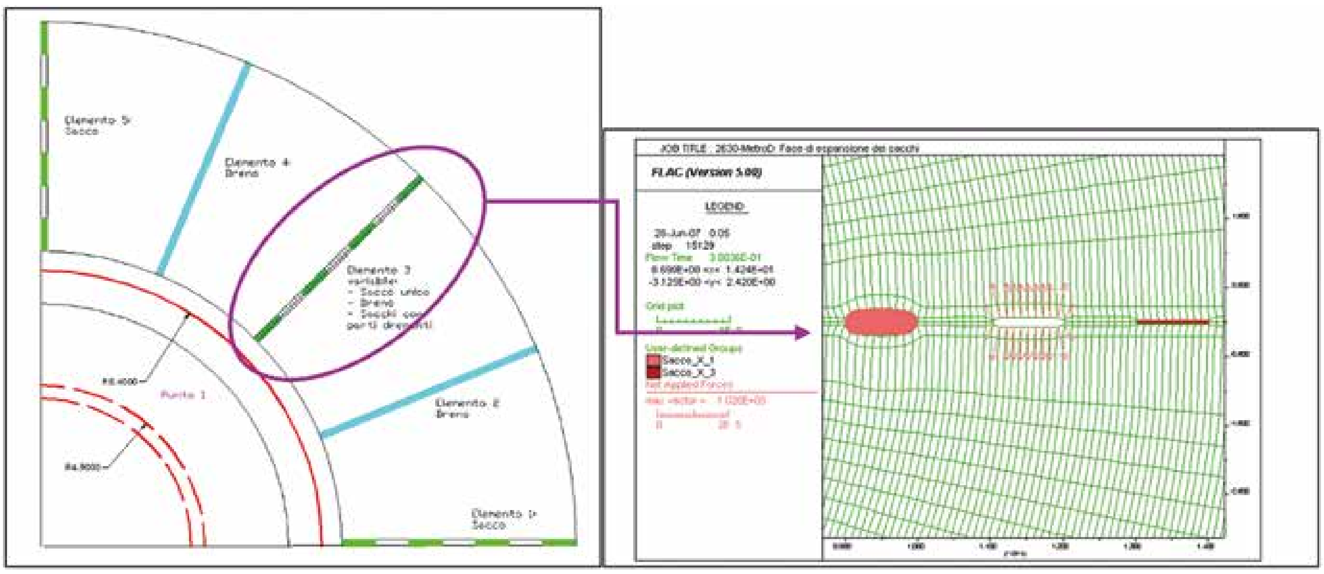

Fig. 6 – Scheme of intervention used into the model (left). Detail of recompression elements (right).

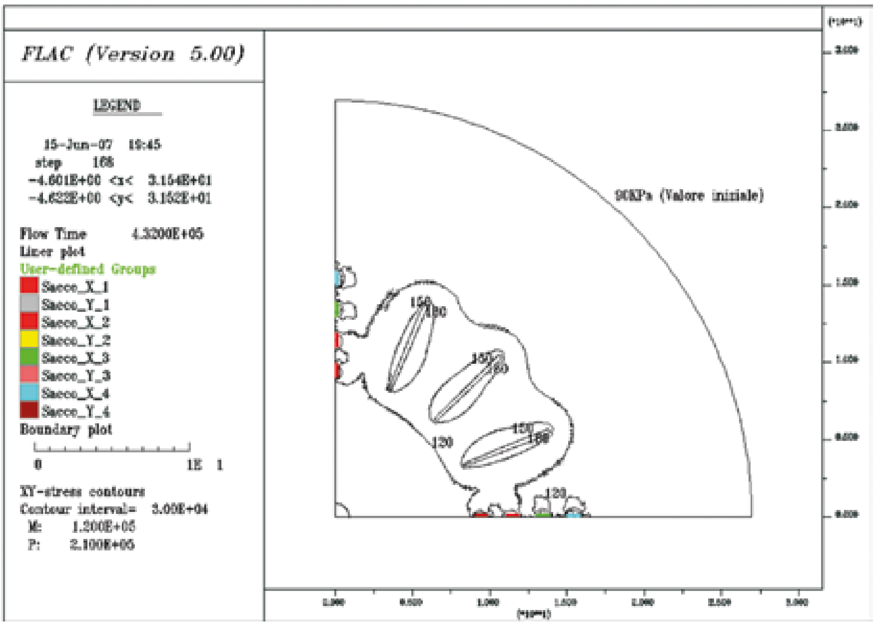

Fig. 7 – Contour lines of cu after 5 days from the recompression.

the trend of the isotropic effective stress with time.

5. State of the art and technological progress

At the current state of the art all over the world in the field of tunnelling, foundation, and transportation geotechnics, several studies have been performed both on numerical and experimental methodologies. Unfortunately, something is missing in the complete understating of the geomechanical process. A comprehensive understanding of all aspects can be obtained by a numerical model able to simulate the evolution of mechanical parameters during the hydro-mechanical process to be coupled with an experimental model for the validation of results.

However, a high level of complexity is justified only in the research field. Indeed, the main goal has to be the transposition of results obtained in a simplified mathematical formulation that can be simply applied in the design process. Additionally, one of the future developments that this article wants to add in the field of consolidation technologies is the implementation of laboratory equipment/set-up initially at a reduced scale and possibly at a real 1:1 scale of the compression and drainage intervention for clayey soils.

It is also essential to cite and give proper credit to other universities, such as the University of Newcastle (Bhuiyan *et al.*, 2022), and companies from different countries (Geodata Engineering and Elas) that have, over the years, improved their knowledge of this technology and effectively applied it in the field. As example, a laboratory setup (Fig. 9) and a field application (Fig. 10) have been reported.

6. Conclusions

The present paper wants to emphasise the future importance of existing technology able to couple drains and reinforcement at the excavation face and profile in

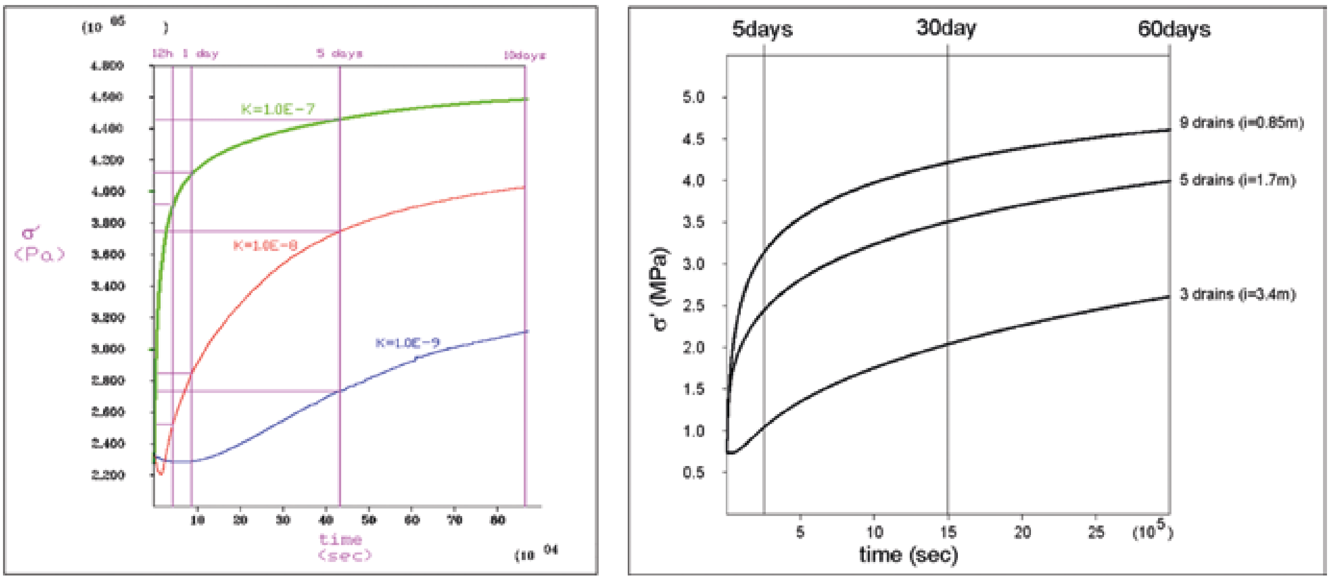

Fig. 8 – Evolution of effective stress close to the reinforcement over time for different ground permeability (left). Trend with time of the isotropic effective stress at a location 30cm far from a drain respectively for 3, 5, 9 drains per quarter (right).

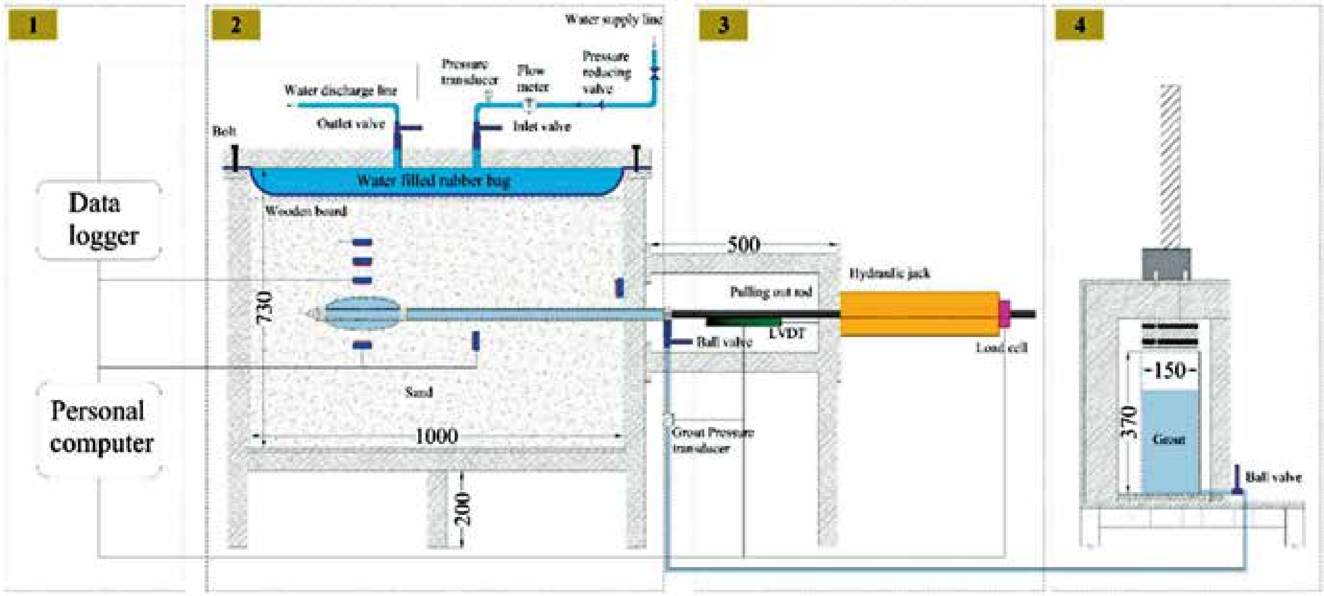

Fig. 9 – Scheme of the test device: (1) data acquisition system; (2) physical model box including surcharge system; (3) pullout system; (4) volume-controlled grouting system (dimensions in mm).

Fig. 10 – PERGround© bar removed after injection (left). Tunnel face improved by means of PERGround© (right).

difficult ground conditions. The advantage that could arise from a numerical and physical model is a mathematical formulation that quantifies the improvement in mechanical strength. In addition, the possibility of formulating a mathematical relationship will facilitate the application of reinforcement techniques for designers worldwide.

Moreover, the efficiency of this reinforcement class has already been recorded by spot cases of application around the world, but what has not been clearly defined are the positive effects regarding other areas of interest, for instance, higher speed in the construction process, lower consumption of materials used, and consequently a better sustainability of the process.

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