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Analytical Modelling of the Soil Improvement by Injections of High Expansion Pressure Resin

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Abstract

Polyuretanic resins, providing high-pressure expansion, are used more and more in ground injections. Designing methods for predicting the degree of ground improvement produced by this specific improving technology can be developed by theoretical approaches. A prevision method, based on finite cavity expansion in dilatants soil theory, has been developed and is presented in this paper. A comparison between theoretical data and on site tests results is also provided. Starting from specific laboratory tests carried out on resin samples, a modification was introduced to the previous works on cavity expansion, based on the experimental relationship between resin expansion pressure and confinement pressure offered by the treated soil. The different behaviour shown by cohesive and granular soils depends on their permeability to resin. The resin, in its liquid phase, expands in cohesive soils in a monolithical body and poorly permeates the soil by breaking it along micro-fissures. On the other side, after injection in granular soils, the liquid resin fills the soil voids and originates a composite hard material with a compressive strength comparable to concrete.

Sommario

Le resine poliuretaniche, ad alta pressione d'espansione, sono oggigiorno utilizzate sempre più frequentemente nel consolidamento dei terreni tramite iniezioni. In questa memoria viene presentato un metodo teorico, basato sulla teoria dell'espansione della cavità, volto a quantificare il grado di miglioramento del terreno prodotto dalle iniezioni di resina. Viene inoltre riportato un confronto tra i dati teorici attesi ed i risultati di prove effettuate in situ. Basandosi sui risultati ottenuti con prove specifiche di laboratorio, condotte su provini di resina, i precedenti studi concernenti l'espansione della cavità sono stati modificati introducendo una relazione sperimentale tra la pressione d'espansione della resina e la pressione di confinamento offerta dal terreno trattato. La differenza di comportamento mostrata dai terreni coesivi rispetto a quelli granulari dipende dalla loro permeabilità alla resina. La stessa, nella sua fase liquida, espande nei terreni coesivi in un corpo monolitico e permea assai poco il terreno, rompendolo lungo micro fessure. Al contrario, dopo l'iniezione in terreni granulari, la resina liquida riempie i vuoti del terreno dando origine ad un materiale composito solido rigido con resistenza a compressione paragonabile a quella del calcestruzzo.

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1. Introduction

The need to perform geotechnical sites in difficult conditions, close environments and reduced operation spaces led to the development of specific soil improvement techniques like that presented in this paper, developed by Uretek.

Over the years there has been considerable development in the stabilizing of cracking or jointed building structures. More and more engineers are being asked to undertake this often-worrying problem. Some causes of this structural crack phenomenon are differential subsidence caused by the expansion or modification of building structures, and variations in the permanent weight distribution applied to that structure. In other circumstances the cause of collapse can be ascribed to geotechnical properties variations of the foundation soils: for instance, those caused by variations in the level of the water table in the area, the chemical degradation of some lithological compositions, or leakage from buried pipes.

Sometimes mechanical improvement of foundation soils may also be required when changes of existing buildings have to be carried out by an elevation or variation of the supporting structure.

2. Ground improvement by Uretek technology

Uretek Deep Injections® is a very particular improving technique, consisting of local injections into the soil of a high-pressure expansion resin; this produces a remarkable increase of the geotechnical properties of the foundation soil. The operation steps are relatively simple and do not require invasive excavations or complicated connection systems to consolidate existing and new foundation structures.

After having injected the soil to be treated, resin immediately starts to expand. The pressure, developed by the expanding resin, first leads to the compaction of the surrounding soil and then to the lifting of the overstructure; this movements are checked by a receiver, lighted by a laser emitter and anchored to the building whose foundation is injected.

A wide set of laboratory tests has recently carried out on the Uretek resin for evaluating its main mechanical properties (Favaretti et al., 2004). Vertical compression tests, with free lateral expansion, and vertical expansion, in oedometric conditions, were performed in the geotechnical laboratory of the University of Padova. Compression tests were carried out on 50 mm sided test cubes, according to the Italian Rule UNI 6350-68. Experimental results show how the compression strength σ quickly increases with unit weight γ of the resin (Fig. 1). It can furthermore be noticed that though unit weight (0.5–3.5 kN/m^3) assumes very small values, the corresponding compression strength is rather high (0.25–6.50 MPa). It is, however, more than sufficient to oppose the stress state being in the ground.

Compression tests show initial elasticity modulus E ranging between 15–80 MPa, comparable with moduli generally determined in alluvional soils. This means that all soils treated with this specific resin does not show remarkable variations of their average stiffness, and uncontrolled redistribution of applied pressure should not be expected.

Tests to determine the expansion pressure in oedometric conditions were carried out using a special device that allows the injection of resin inside a rigid, metal cylinder, containing a piston. Immediately after the injection into the cylinder, the resin starts its expansion. The highly rigid device causes the resin to expand vertically only. Expansion pressure was evaluated as that pressure necessary to prevent the piston to move upward. As previously observed, the expansion pressure depends on the resin density (Fig. 2) and varies between 0.2–10.0 MPa in the investigated unit weight range (γ = 0.5–10.0 kN/m^3). Such values are indicative of the pressure that the resin can generate when it is injected in the ground.

The expansion pressure of the resin is depending on the state of stress in which polymerization reaction occurs. The expansion pressure depends on the unit weight of the resin, as well as its degree of volumetric expansion measured at the end of the process.

If polymerization should occur in free-confinement condition, the high expansion pressure resin would solidify at a unit weight equal to 0.4 kN/m^3 with a volumetric expansion level equal to 30.

3. Theoretical view and simulation of the expanding process

The expansion process of the resin, locally injected into the soil according to the scheme plotted in Fig. 3, can be theoretically

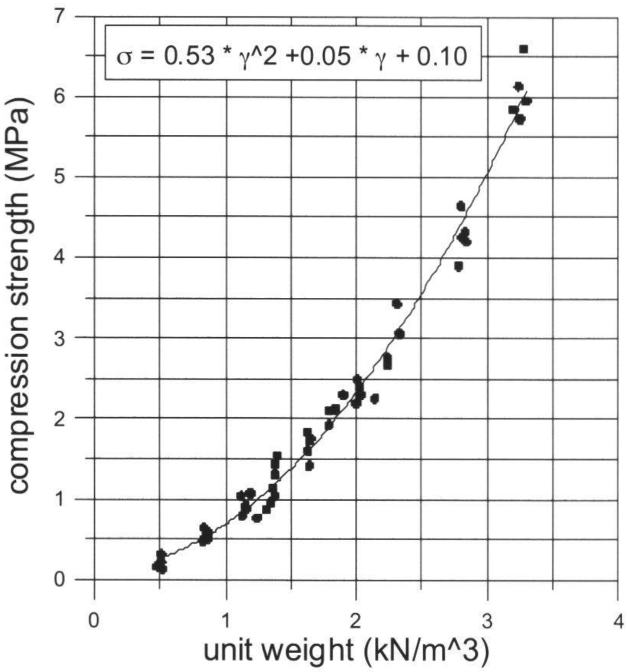

Fig. 1: Uniaxial compression test results: vertical stress σ vs. sample unit weight γ.

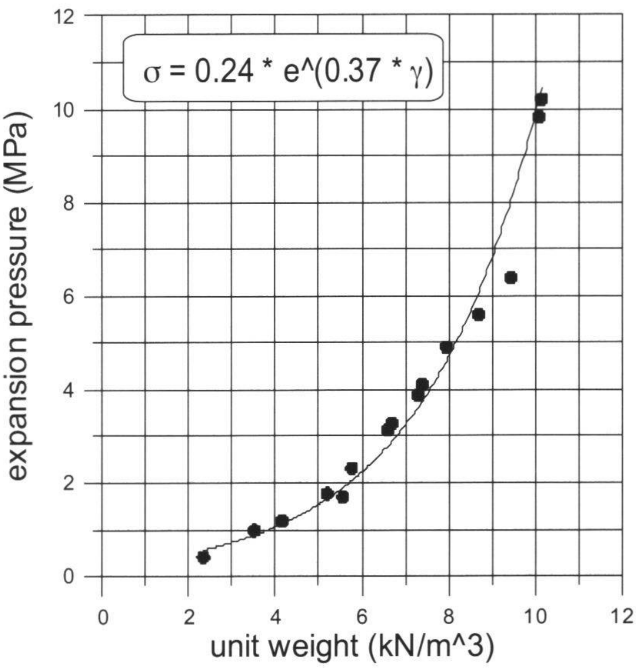

Fig. 2: Expansion tests under oedometric conditions: maximum expansion pressure vs. sample unit weight.

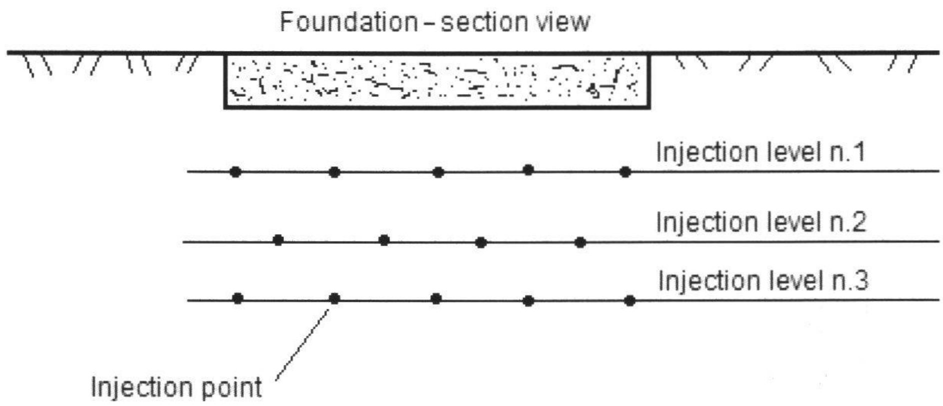

Fig. 3: Schematic representation of the Uretek injection procedure.

studied as a spherical cavity (or cylindrical, if several injections are performed very close each to other, along the same vertical line) expanding in quasi-static conditions.

The soil is modelled as a liner elastic-perfectly plastic material with a non-associated Mohr-Coulomb yield criterion and is considered initially subjected to an isotropic state of stess, with pressure p_0 equal to:

$$p_0 = \frac{1+2\cdot K_0}{3}\cdot\sigma_{v0} + dp$$

where K_0 is lateral earth pressure coefficient at rest and $dp = q_o \times I_c. \times [(B/L),z]$ indicates pressure increment due to the foundation (B × L sized; I_c, influence factor), evaluated at the depth z of the injection, according to the Boussinesq's theory.

Initial vertical pressure (σ_{vo}), calculated at the depth z, is equal to the total or effective stress when soil is respectively cohesive ($c_u \neq 0$; $\varphi = 0$) or cohesionless ($\varphi \neq 0$, $c_u = 0$).

The soil properties considered in the model are the following:

- Young's modulus (E) and Poisson's coefficient (ν), characterizing the elastic behaviour of soil;
- cohesion (c) or undrained shear strength (c_u);
- angle of friction (φ);
- angle of dilation (ψ), set null since settlement problems are generally associated with the presence of granular density being from loose to very loose.

The geometrical properties of the cavity and the elastic and plastic regions are represented by means of (Fig. 4):

- r_a: radius of the spherical cavity; its initial value r_{ao} is assumed equal to 0,006 m;
- r_b: radius of the spherical region in plastic condition; it characterizes the boundary surface between plastic and elastic regions;
- r_c: radius of the spherical region in elastic condition, beyond which $(\sigma_c - p_o) \leq 0.01p_o$ (influence volume of the injection).

During the first part of the expansion process, when the internal pressure of the cavity increases, soil shows an elastic behaviour. After reaching a specific value of the internal pressure value, plastic deformation starts, similarly to the elastic phase, until it reaches the pressure limit (σ_{lim}).

It is assumed that as soon as pressure limit is reached, ratios (r_b/r_a) and (r_c/r_b) keep constant as the expansion progresses, until the resin solidifies.

The expansion process is theoretically treated according to the procedure proposed by Yu and Houlsby (Yu & Houlsby, 1991) adopting analysis at large and small strains, respectively, on the plastic and elastic region. In such hypothesis the ratio (r_a/r_{ao}) between the radius of the cavity under the action of the generic pressure p, and the initial radius of the cavity, can be so formulated (1):

$$\frac{r_a}{r_{ao}} = \left\{\frac{R^{-\gamma}}{(1-\delta)^{(\beta+m)/\beta} - (\gamma/\eta)\cdot\Lambda_1(R,\xi)}\right\}^{\beta/(\beta+m)}$$

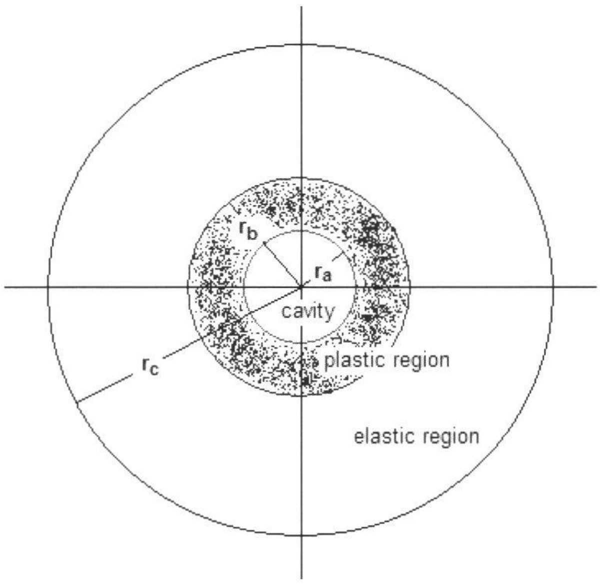

Fig. 4: Schematic representation of elastic and plastic zone surrounding the cavity.

where R indicates the pressure ratio of the cavity:

$$R = \frac{(m+\alpha)\cdot[Y+(\alpha-1)\cdot p]}{\alpha\cdot(1+m)\cdot[Y+(\alpha-1)\cdot p_o]} \tag{2}$$

The coefficient m is assumed equal to 1 for cylindrical cavity and to 2 in case of spherical cavity. The analytical definitions of G, Y, α, β, γ, δ, η, ξ, Λ are the same proposed by Yu and Houlsby (1991):

$$G = \frac{E}{2\cdot(1+\nu)}; \qquad Y = \frac{2\cdot c\cdot \cos(\varphi)}{1-\mathrm{sen}(\varphi)}; \qquad \alpha = \frac{1+\mathrm{sen}(\varphi)}{1-\mathrm{sen}(\varphi)};$$

$$\beta = \frac{1+\mathrm{sen}(\psi)}{1-\mathrm{sen}(\psi)}; \qquad \gamma = \frac{\alpha\cdot(\beta+m)}{m\cdot(\alpha-1)\cdot\beta}; \qquad \delta = \frac{Y+(\alpha-1)\cdot p_o}{2\cdot(m+\alpha)\cdot G}$$

$$\eta = \exp\left(\frac{(\beta+m)\cdot(1-2\cdot\nu)\cdot[Y+(\alpha-1)\cdot p_o]\cdot[1+(2-m)\cdot\nu]}{E\cdot(\alpha-1)\cdot\beta}\right)$$

$$\xi = \frac{[1-\nu^2\cdot(2-m)]\cdot(1+m)\cdot\delta}{(1+\nu)\cdot(\alpha-1)\cdot\beta}\left[\alpha\cdot\beta+m\cdot(1-2\cdot\nu)+2\cdot\nu-\frac{m\cdot\nu\cdot(\alpha+\beta)}{1-\nu\cdot(2-m)}\right]$$

$$\Lambda_1(x,y) = \sum_{n=0}^{\infty} A_n^1 \qquad A_n^1 = \begin{cases} \dfrac{y^n}{n!}\ln(x) & \text{if } n=\gamma \\[2ex] \dfrac{y^n}{n!\,(n-\gamma)}\left[x^{n-\gamma}-1\right] & \text{if } n\neq\gamma \end{cases}$$

The ratio (r_b/r_a) between the radius of the plastic region and of the cavity can be so expressed:

$$\frac{r_b}{r_a} = R^{\alpha/[m\cdot(\alpha-1)]} \qquad (3)$$

The value of the limit pressure (σ_{lim}) can be determined by putting (r_a/r_{ao}) $\rightarrow \infty$ in equation (1).

In the analysis it has been assumed that the expansion of the resin causes the pressure limit to be reached in any case. The volume of resin, which has to be injected, can be calculated in relation to the influence volume radius (r_c) of the required injection. Consequently, imposing the value of r_c, it is possible to evaluate the cavity radius (r_a), the plastic region radius (r_b) and the radial stress of the plastic-elastic interface (σ_b).

The theoretical approach due to Yu and Houlsby (1991) can be then integrated with empirical evaluations derived from back-analysis of several case-histories.

In the calculation of the resin volume to be injected (V_{ri}), it is assumed that part of the post-expansion (or final) resin volume (V_{rf}) occupies the cavity, while the other part penetrates the plastic region, according to a volumetric percentage depending on the soil nature. Calculating the volume of the post-expansion resin, the injected volume can be experimentally determined as function of V_{rf} and σ_{lim}.

The changes, induced on the soil strength parameters by the expansion at the depth of injection, can be evaluated. Such parameters refer to the cone penetrometric resistance (q_c) and to the undrained shear stregth (c_u) derived from CPT. In cohesionless soil only q_c value is considered, as it is assumed that the expansion is not capable to modify the angle of friction of soil.

Strength variations are calculated with reference to the changes of pressure induced by the injection, according to the following expressions:

cohesive soil:

$$\frac{c_u}{\sigma'_v} = 0.22 \cdot OCR^{0.8}; \qquad q_c = 20 \cdot c_u + \sigma_v$$

cohesionless soil:

$$q_c = \sigma'_v \cdot e^{5.241 \cdot \tan(\varphi)}$$

Where the value σ'_v is calculated at a distance from the center of the cavity equal to the distance between the foundation axis and the in situ test location, at the depth of injection.

The quality of the previsions, provided by the analytical model, has been verified on a number of real cases. The reliability of the theoretical previsions increases with the quality of the geotechnical investigation available to the designer.

4. Case History

The effectiveness of the analytical model was verified by means of back-analysis on more than twenty sites performed by Uretek during the last 18 months. The main goal of the in situ test campaign was to evaluate the deviation between the actual penetrometric resistance, measured in situ, and the expected values, calculated with the theoretical model.

The a posteriori use of the model, based to actual quantity of injected resin, allowed to estimate the expected value of the static cone penetration resistance $q_{c\text{-new}}$. This value was then compared to a $q_{c\text{-field}}$ value, indirectly obtained through usual correlations based on dynamic penetrometric tests.

For exemplifying the above-mentioned procedure an interesting case history is reported, referring to the foundation ground improvement of a former rural building in San Giovanni d'Asso (Siena, Italy) interested by diffused cracks in the elevation structure. The building is located on a hilly area characterized by rounded relief forms accentuated by downward incisions. The building, situated on a hillside with an average slope of about 20%, consists of one main nucleus, which dates back to the XIX century, and a secondary outbuilding more recent, built adjacent to the main construction body.

The building has a rectangular shape, dimension being 7,4 m wide and 11,5 m long, on two floors, one above ground and one basement. The structural damages were particularly concentrated in the most recently constructed portion of the building and tended to diminish progressively in a downhill direction.

Three static penetration tests (CPT1, CPT2, CPT3) and one borehole (BH1) were carried out in the investigated area, which is characterized by the presence of clayey soils poorly permeable and is not interested by groundwater flow (Fig. 5).

Based on the results obtained from the investigation, the foundation soil profile can be described by means of two main units (Fig. 6):

Unit Aa - Altered Silty Clay: it represents the soil where the structure is founded. Its thickness ranges between 2 m and 4 m on the uphill side and is about 3 m on the downhill side. It has an extremely variable resistance value, particularly on the uphill zone, depending on the level of alteration and water content. Considering its minimum static cone resistance $q_{c,\ min}$ of 2 MPa, an undrained shear strength c_u of 85 kPa and an oedometric modulus M of 5 MPa can be attributed to the Aa unit.

Unit Ac - Compact Silty Clay: it represents the subgrade soil, underneath the Aa unit, starting from a depth variable between 2 m to 4 m. It consists of an over-consolidated compacted silty clay, whose consistency tends to increase progressively with depth. Considering its minimum static cone resistance $q_{c,min}$ of 5 MPa, an undrained shear strength c_u of 220 kPa and an oedometric modulus M of 15 MPa can be attributed to the Ac unit.

Before the beginning of the injection works, three dynamic penetration tests were performed (DPM1, DPM2, DPM3) with a DPM 30 equipment, having a falling weight equal to 300 N and a falling height of 0.2 m. The intent was to calibrate the instrument with respect to the results obtained with CPT; the following correlation between the static cone resistance q_c and dynamic penetration resistance R_{pd} was found:

$$R_{pd} = \alpha \times q_c \qquad \text{with} \qquad \alpha = 1,4$$

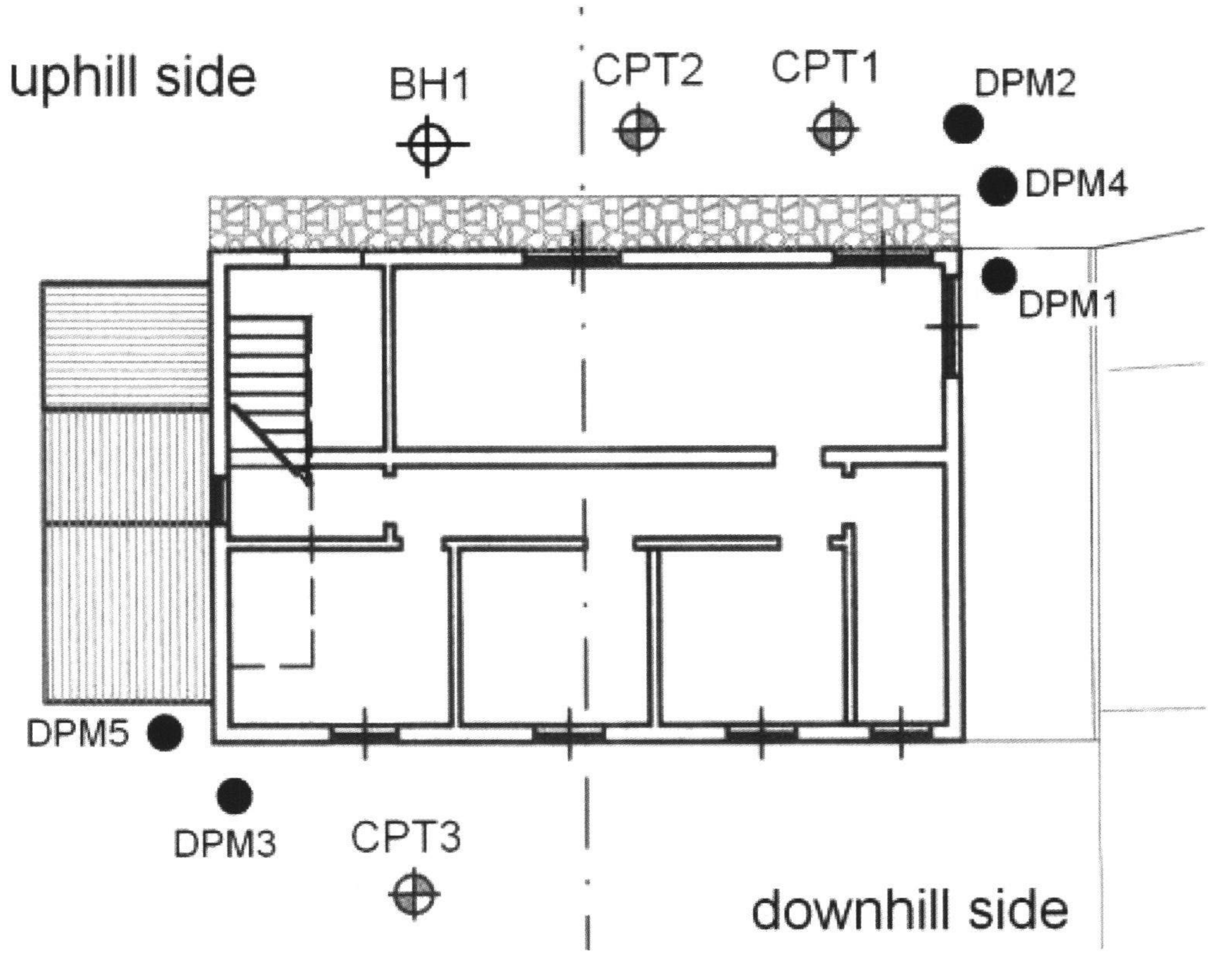

Fig. 5: Plan of the building and in situ tests location.

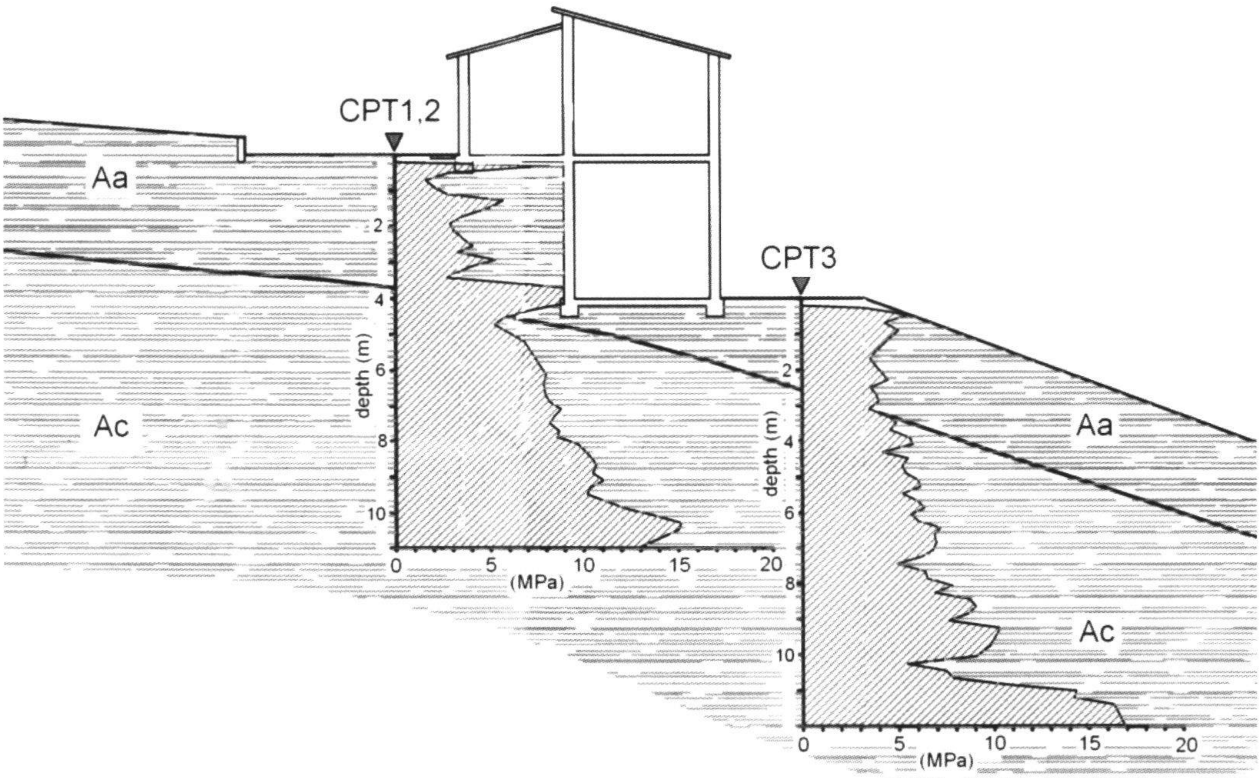

Fig. 6: Soil profile and CPT initial results.

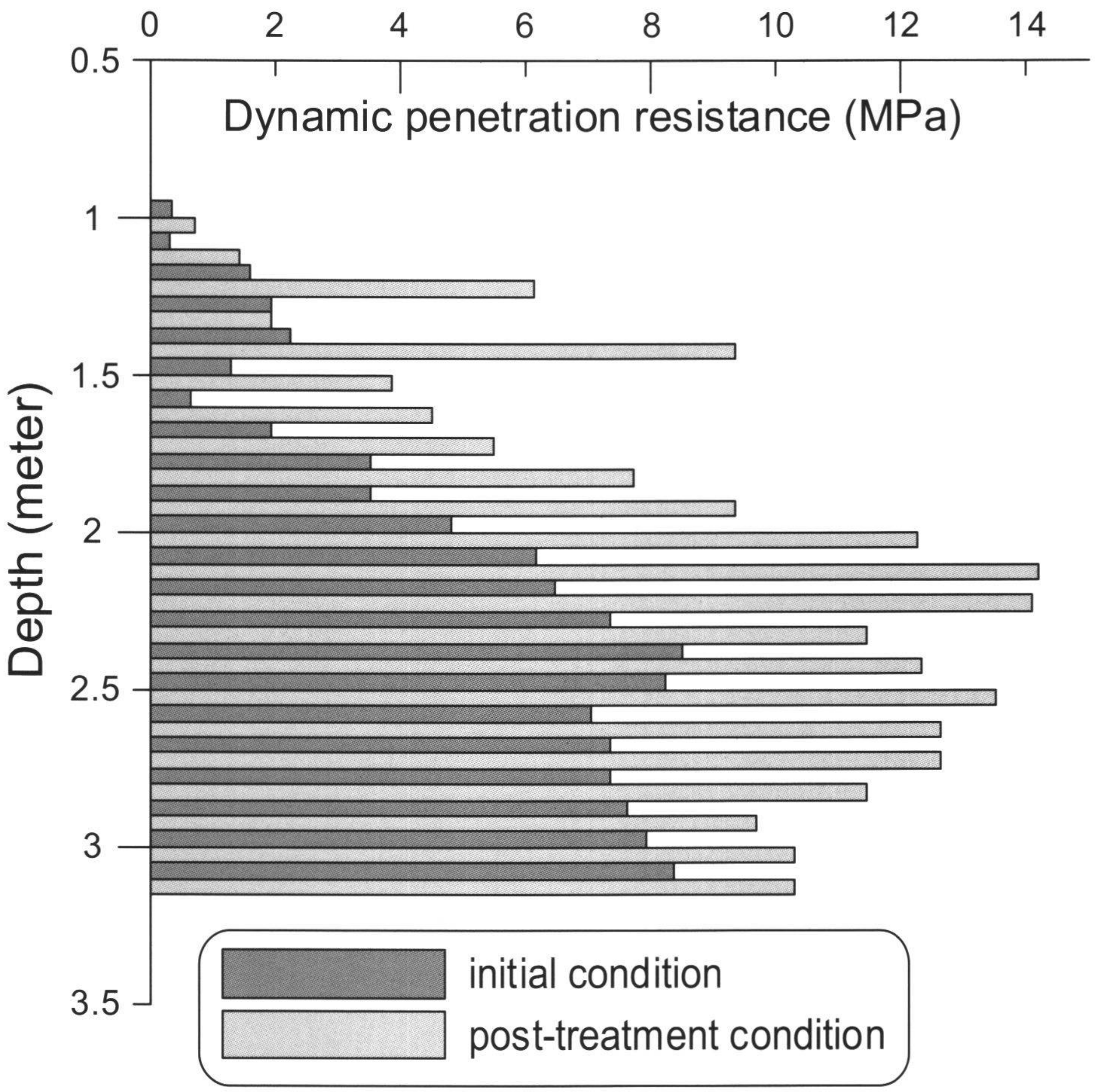

Fig. 7: Comparison between DPM1 and DPM4 test results obtained before and after treatment.

The ground improvement operations, underneath 24 m of shallow strip foundation, took three working days. The average unexpanded volume of injected polyurethane resin was of about 20 dm^3 for each injected point. The check of the injections effects was evaluated by performing two more dynamic penetration tests (DPM4, DPM5, see Fig. 5). In Figure 7 the initial and post-treatment dynamic penetration resistances R_{pd}, derived from DPM1 and DPM4 test results, were plotted. Due to the ground improvement, the R_{pd} increments are also greater than 100%, particularly within 2 m of depth, where CPT had recorded the lowest values of q_c.

It was then possible to compare the theoretical static cone resistance values, ($q_{c\text{-new}}$), derived from the analytical model, to in situ tests values corresponding to original ($q_{c\text{-old}}$) and after-treatment ($q_{c\text{-field}}$) conditions. In this particular case the following values were obtained:

$q_{c\text{-old}}$ = 2,498 kPa
$q_{c\text{-field}}$ = 4,820 kPa
$q_{c\text{-new}}$ = 4,355 kPa

Results show how the qc increment ($q_{c\text{-field}}$ – $q_{c\text{-old}}$), due to ground improvement, is greater than 90%, while the expected value

$q_{c\text{-}new}$ is smaller than 10% of after-treatment actual value $q_{c\text{-}field}$.

This comparative procedure has been carried out in numerous building sites performed by Uretek (Fig. 8). The accuracy of the predicted results is rather satisfactory for pre-treatment cone penetration resistance $q_{c\text{-}old}$ ranged from 2 MPa to 4 MPa. In these initial conditions, involving the most part of soils concerning the Uretek improvement method, the expected $q_{c\text{-}new}$ seems to fit well the experimental post-treatment values $q_{c\text{-}field}$.

Outside this range ($q_{c\text{-}old}$ = 2 MP_a -4 MP_a) the analytical model still needs refinement. The future developments of the software will also include the capability to manage, for example, the effects of voids filling in granular soil and the effects of more superimposed injections, in order to cover the widest possible range of applications the technology can offer.

5. Conclusive remarks

The principal points worthy to be emphasized are the following:

- Uretek Deep Injections® method makes use of a particular resin, capable of expanding immediately after its injection, developing very high expansion pressure in the surrounding ground; its Young's modulus E ranges between 15–80 MPa, comparable with moduli of alluvional soils; expansion pressure varies between 0.2–10 MPa in the range of investigated unit weight (γ = 0.5–10 kN/m^3);
- Expansion process of the resin has been analysed as a spherical (or cylindrical)

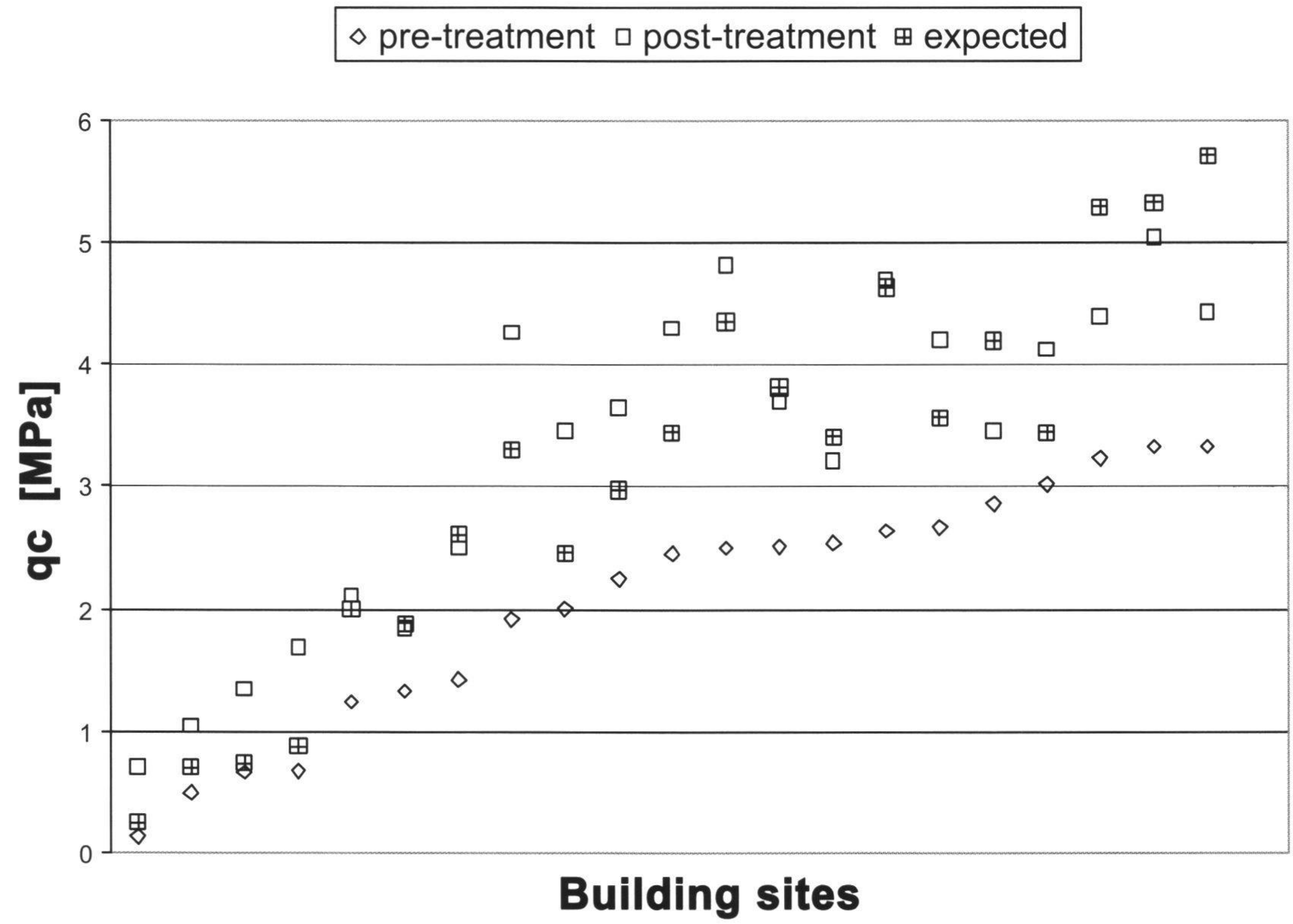

Fig. 7: Comparison among q_c values recorded before and after the ground improvement and calculated by an analytical model.

cavity expanding in quasi-static conditions. Soil was considered as a liner elastic-perfectly plastic material with a non-associated Mohr-Coulomb yield criterion and initially subjected to an isotropic state of stess. After a first elastic expansion of cavity, plastic deformation starts, until the pressure limit is reached;
- The theoretical approach (Yu & Houlsby) was integrated with experimental evaluations derived from laboratory tests on resin samples and back-analysis of several case-histories; changes of soil strength parameters was evaluated, by comparison of the theoretical static cone resistance values, ($q_{c\text{-}new}$), to in situ tests values corresponding to original ($q_{c\text{-}old}$) and after-treatment ($q_{c\text{-}field}$) conditions;
- This comparative procedure has been carried out in more than twenty building sites. Predicted results seems to fit well the post-treatment values, in particular when pre-treatment cone penetration resistance $q_{c\text{-}old}$ ranged from 2 MPa to 4 MPa.

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