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Mechanical analysis of jet grouted supporting structures

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ABSTRACT: Due to the well known defects of jet grouting columns (diameter, position), the real shape of supporting structures made of overlapped elements, as shafts or tunnel canopies, is often far from being geometrically regular, and defects have to be taken into account. The design of such structures cannot be but probabilistic or semi-probabilistic, because it may hide unforeseen risks if a deterministic approach is adopted. As a consequence, this is the typical case in which sophisticated numerical analyses may just give the illusion of being refined, if possible defects are not correctly taken into account. In the paper, the results obtained in previous works by the authors adopting such an approach with reference to shafts and tunnel canopies are summarized. Even though these approaches represent a progress in the design of jet grouted supporting structures, they do not take into account soil-structure interaction and the truly three-dimensional behaviour of these structures. In the paper, it is shown that soil-structure interaction strongly reduces stresses in the jet grouted soil, and discontinuities can be accepted in the structure without necessarily implying structural failure as long as they keep smaller of a given limit value. These improvements are a first step towards a less conservative design procedure of jet grouted structures.

1 INTRODUCTION

The use of jet-grouting with earth supporting functions has greatly increased in recent years. At the design stage, however, there is still a relevant degree of uncertainty, mainly due to the lack of reliable methods for predicting the diameter and the position of the columns, as well as the mechanical properties of the cemented soil (soilcrete), all varying along columns axis due to a number of reasons. As a matter of fact, these defects make jet grouted columns far from being perfectly cylindrical, homogeneous bodies. It follows that, most times, jet grouting is designed on the basis of subjective rules of thumb, subsequently refined on site by means of trial and error tests (trial fields). In order to improve the reliability of design analyses, two complementary research efforts are needed: on one hand, field trials must be carefully analysed to find the relevance of columns defects in the largest possible variety of subsoil conditions and jet grouting technology; on the other hand, more satisfactory design methods taking into account the intrinsic variability of jet columns must be conceived. This paper focuses on this second aspect, with reference to the particular case of provisional support in tunnelling (open structure, Fig. 1.a) or in shafts (closed structure, Fig. 1.b), realized in cohesionless soils (ideal for jet grouting effectiveness) or at

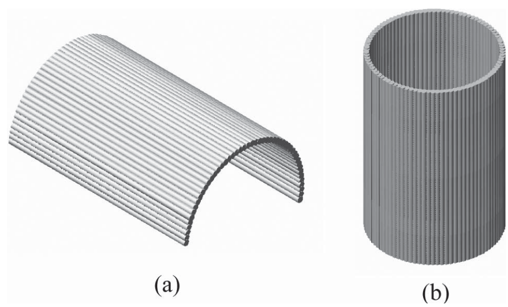

Figure 1. Typical jet-grouted supporting structures for tunnels (a) and shafts (b).

the most soft clays. These structures have the common property that the supporting action is committed to the arching effects given by overlapping of columns. Considering the potentially dramatic effect of defective, not interpenetrated columns, design analyses must necessarily combine careful prediction of columns properties and mechanical schematisation.

In previous papers, (e.g. Lignola et al. 2008, Flora et al. 2007, Croce et al.; 2006; Croce et al. 2008) the authors have suggested to simulate geometrical and mechanical defects of columns by means of probabilistic models to be calibrated with statistical analyses of the results of available field trials. These models have been then introduced into mechanical analyses, carried with different approaches, to take into account defects into the design of jet grouted structures. The first part of this paper is devoted to a brief summary of this activity with reference to the above mentioned supporting structures (Fig. 1); in the second, the limits of the proposed predictive methods are highlighted, and possible improvements suggested. These latter have been commented by reporting the results of preliminary analyses.

2 PROPERTIES OF COLUMNS

Regardless of accurate control in the execution of treatments, jet grouting columns are generally acknowledged to be far from being cylindrical and homogenous bodies. The main reasons for such discrepancy are related to soil properties and defects in jet grouting execution. The previous is relevant as subsoil conditions may sharply vary even within a few meters: this frequent heterogeneity of soils in grading and stress history results into very different (and variable) values of undisturbed soil mechanical parameters, say stiffness and strength. Then, extremely variable interactive mechanisms with the injected fluids take place, with the result that the dimensions and mechanical properties of the cemented soil can be largely variable along the axis of each single column.

Furthermore, although particularly sensitive instrumentations are now available to control the initial positioning and alignment of the perforation equipment, errors must be expected, and deviations from the prescribed direction systematically take place due to some deformation of the battery of rods.

These problems may sum up, possibly becoming critical for the jet grouted supporting structures: for shafts, mostly in the case of a considerable length of the columns; for tunnels, due to the fact that sub-horizontal columns deviate more from their ideal axis (Croce et al. 2008). In order to evaluate the implications of these defects on the performance of the supporting structures it is convenient to distinguish geometrical and mechanical variables and to derive their typical variation from statistical inferences of the results collected from field investigations.

2.1 *Geometrical properties*

From the available documented site tests, it can be generally seen that the diameters of columns are randomly scattered around their mean value with symmetric bell shaped frequency distributions (Croce et al., 2004). According to this result, a Gauss probability function, customised to the particular case by an average value and a coefficient of variation CV(d), can be conveniently adopted to simulate diameters variability. Although mean values and standard deviations should be evaluated by performing specific field trials in the same conditions (subsoil and injection techniques) of the studied case, their values can be preliminarily estimated on the bases on published evidences (e.g. Croce et al., 2006) for the different soil types (Table 1). The table shows that both the mean values and the coefficients of variation generally increase as the soil gets coarser, and as a consequence larger columns with larger variability must be expected for coarser soils.

Misalignment of columns from their prescribed directions can be defined by the statistical distributions of α and β, respectively representing (see Fig. 2) for a vertical column the angle formed by the axis with the assigned direction and the orientation with reference to a fixed plan direction (azimuth).

Neglecting deviations induced by systematic factors, not meaningful on the relative alignment of columns and thus on the continuity of structures,

Table 1. Diameters of columns for different original soil types and injection systems (modified after Croce et al., 2004).

Soil	Average diameter D_{col} (m) Single fluid	Double fluid	Triple fluid	Coefficients of variation CV (D_{col})
Gravely	0.7–1.1	1.0–1.5	2.0–2.4	0.05–0.25
Sandy	0.5–1	0.7–1.5	1.2–2.0	0.02–0.10
Silty clayey	0.4–0.6	0.6–0.9	1.0–1.5	0.02–0.05

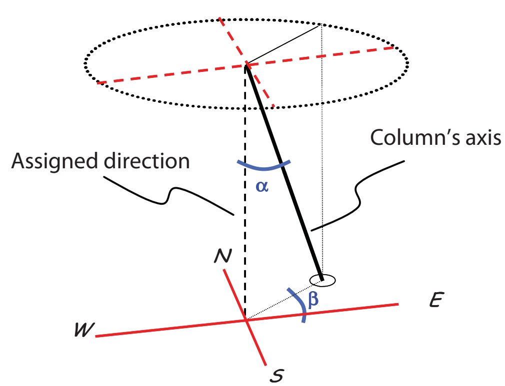

Figure 2. Definition of column deviation from its prescribed direction.

Table 2. Soilcrete uniaxial compressive strength for different treated soils (modified after Bell, 1993).

Uniaxial compressive strength	Clay	Silt	Sand	Gravel
Average value, $\bar{\sigma}_{lim}$ (MPa)	0,5 ÷ 3	5 ÷ 25	4 ÷ 18	5 ÷ 30
Coefficient of variation, CV (σ_{lim})	0,02 ÷ 0,05		0,02 ÷ 0,1	0,05 ÷ 0,15

and focusing only on the random component, a uniform distribution between 0° and 180° and a Gauss probability function around zero can be respectively assumed for the angles β and α. The standard deviation of α does not depend on the soil type, being strongly related to the robustness of drilling equipment and to the operators' ability. Values in the range of 0.5–1° have been typically recorded in monitored systems.

2.2 *Mechanical properties*

Jet grouted soil is generally assumed to behave as a low quality concrete and, similarly to this material, its resistance is defined in terms of uniaxial compressive strength σ_{lim}. Variation of this latter may in principle occur along vertical and radial directions within the column's body. However published data (Croce et al., 2004) have shown that, apart from a slight increase with depth, uniform random scattering is usually observed on σ_{lim} values. The asymmetric frequency distribution derived from statistical analyses of these data suggests, together with the logical consideration that σ_{lim} cannot assume negative values, to simulate variability with a log-normal probability function to (Croce et al. 2004). Parameters of this distribution can be related to the mean and the standard deviation of data and should be again derived from specific field. However, preliminary structural analyses can be performed based on the indicative values given in Table 2. These values show that larger and more variable σ_{lim} must be expected on coarser soils.

3 BIDIMENSIONAL ANALYSES

From a mechanical viewpoint the supporting structures shown in Fig.1 can be imagined as assemblies of interconnected longitudinal (columns) and cross sectional (arches formed by overlapped columns) elements. Under simplified assumptions (linear response of these elements and surrounding soil thrusts independent on deformation, i.e. no soil structure interaction), the distribution of forces between columns and arches can be calculated combining equilibrium and consistence via the well known differential equation:

$$W\frac{d^4v}{dz^4} + K \cdot v = p_e - p_i \qquad (1)$$

where z is the longitudinal coordinate, *v* the displacement in the cross sectional plane, W the flexural stiffness of the columns, K the compressive stiffness of cross sectional arches, p_e and p_i respectively the external and internal stresses given by the soil (the internal ones being progressively removed as the soil is excavated within the shaft). For instance, Figure 3 reports bending moments on columns calculated for the case of a 21 m long vertical shaft (D_{shaft} = 12 m, 63 columns having D_{col} = 0.6 m). The solution has been obtained for an inner excavation of 15 m, considering the two cases of perfect columns, mutually overlapped over the whole length, and of a lack of continuity in the horizontal arch at 15 m depth (obtained by imposing K = 0 for z = 15 m). The difference between the two curves is very large, showing an increase of moments up to 23 times due to the missed overlapping of columns just at one depth.

The example reported in Figure 3 shows the importance of assessing continuity and stress tolerability in the cross sectional elements of curved jet grouted structures. The following paragraphs report two bi-dimensional analyses developed for the supporting structures shown in Figure 1, probabilistically taking into account the defects of columns.

3.1 *Tunnel's canopies*

Jet-grouted canopies (often also called umbrella) are often used for tunnel temporary support. Such

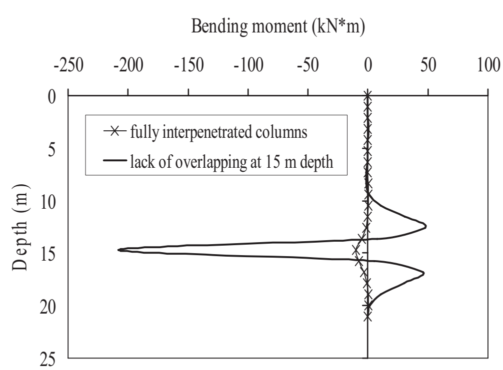

Figure 3. Bending moment profiles on columns for perfect and defective walls.

a jet grouting structure is a sequence of partially overlapped vaults, each having the shape of a frustum of cone with the length and opening angle the operators wish to use.

In the hypothesis that the jet grouted vault has no resistance in the longitudinal direction, the jet grouted umbrella works as far as the single columns are overlapped by a thickness sufficient to ensure arching support. In the ideal situation of perfectly oriented cylindrical columns, such a thickness depends only on columns diameter, soil properties and depth from ground level. In practice, columns overlapping and therefore arch thickness strongly depend on columns defects, and the overall structural performance must be considered by taking into account the possible variations of both diameter and axis inclination.

The combination of these defects gives rise to a much more irregular shape, which by no means is a regular frustum of cone, with cross-sections like the one reported in Figure 4. A random variation of the overlapping thickness is expected, and overlapping decreases along the span more dramatically then it would in the ideal case of columns having no defects. There is a critical length of the span after which structural continuity is difficult to obtain.

Once probabilistic distribution laws of statistical variables (geometrical and mechanical properties of the columns) are given, it is possible to explore different scenarios by Monte Carlo Method simulations (Lignola et al., 2008).

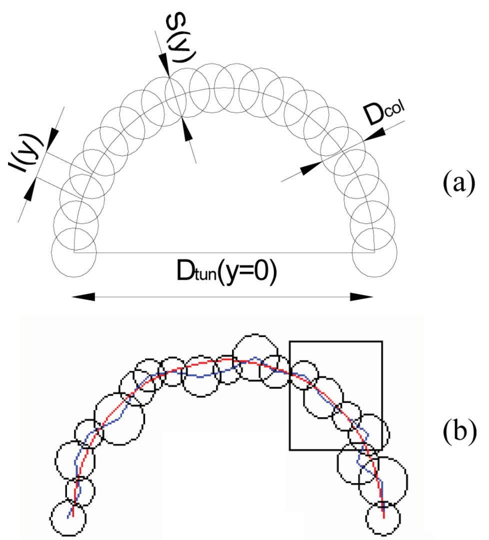

Figure 4. Typical jet-grouted umbrella cross section: a) with cylindrical columns (D_{col} = cost); b) with irregular columns.

In Figure 5 the simple case of an imperfect jet-grouted umbrella (D_{col} = 0.6 m) as a support of a shallow tunnel having D_{tun} (y = 0) = 8 m is reported.

The initial overlapping between adjacent columns (at the beginning of the span y = 0) is 80% of the column diameter. Due to variations in position and diameter of the columns, the geometric shapes generated by Monte Carlo simulations are *imperfect*, and therefore have in each cross section ($0 < y < y_{max}$) neither semi-circular shape nor constant overlapping thickness (S(y) in Fig. 4). In this example, the rather irregular shape is assumed to be represented by an equivalent semi-circular arch having a cross sectional constant thickness $S_{5\%}$ (the value lower than 95% of all obtained thicknesses).

As expected, the lack of overlapping is basically governed by defects in the position of the columns' axis (represented by the standard deviation of angular deviations $\sigma(\alpha)$), while the variation of column diameter (represented by the coefficient of variation of column's diameter CV_d) plays a minor role. This simple approach is attractive and can be easily implemented along with a simple structural model to check arch performance (Flora et al., 2007), in the hypothesis that jet grouted columns have no longitudinal flexural capacity; as a consequence equilibrium in the jet grouted umbrella is possible only if transversal arches are complete and able to carry the design loads. In such a way, a complex 3D problem is converted into a much simpler 2D problem.

Even though this simple approach allows to perform risk evaluations, the structure with defects may have an irregular axis that makes the real structure far from the perfect arch, with the consequence of possible unexpected flexural moments that cannot be considered by the described approach (equivalent ideal arch).

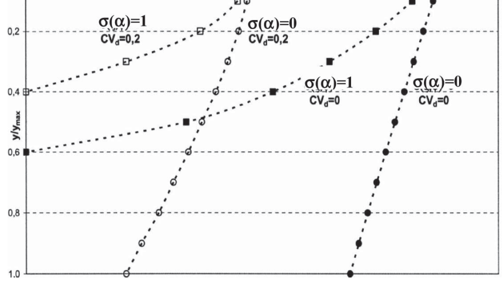

Figure 5. Design charts for sand: the normalized value $S_{5\%}/D_{tun(y)}$, versus the normalized y/y_{max}.

Lignola et al. (2009), therefore, have developed a simple numerical code able to analyse the behaviour of irregular arches taking into account defects both in dimensions and position of each single column, i.e. studying each cross section as it comes out from a random probabilistic generation. Irregular arches may be generated for instance with a Monte Carlo procedure, considering the statistical parameters of defects and modeled as assemblies of mono-dimensional beam elements able to develop bending moments, axial forces, and shear forces. The behavior of individual elements is characterized by the element's stiffness relation with constant cross section having an height equal to the overlapping thickness. Then, the global stiffness matrix, needed to get the exact solution of the structural problem, is obtained by assembling each single element local matrix. This stiffness method allows in fact to account for real structures with defects, far from being a perfect arch. Frictional hinges are considered as external constraints at the base of the curved open structure. External loads can be applied considering any wished stress redistribution caused by the complex 3D effects of tunnel excavation. In the program, vertical loads are introduced as a function of an equivalent depth z, and horizontal loads are considered proportional to the vertical ones via a coefficient K. The results obtained with this code show the significant role played by the irregular shape of cross sectional elements given by defective columns.

Both the proposed approaches allow to plan the number of jet grouted columns to be used and their initial overlapping, also in multilayered layouts to be adopted with a given level of confidence once stability of the jet grouted supporting structure, and the tunnel average diameter is given.

3.2 *Shafts*

The influence of columns defects on circular excavation shafts has been evaluated with a similar probabilistic analysis (Croce et al., 2006, Fusco, 2009). A shaft of diameter D_{shaft} formed by a single crown of identical overlapped columns having diameter D_{col}, mutual span i and uniaxial compressive strength σ_{lim}, can be preliminarly studied as a cylindrical tube inserted into a homogeneous soil. Under these ideal conditions (perfect cylinder, no defects), the limit depth where the soil confining action produces collapse of the cemented soil (z_{lim}), can be easily calculated by the following equation (Croce et al., 2006):

$$z_{lim} = \frac{2\sigma_{lim}\sqrt{D_{col}^{2} - i^{2}}}{K_0 \cdot \gamma \cdot D_{shaft}} \quad (2)$$

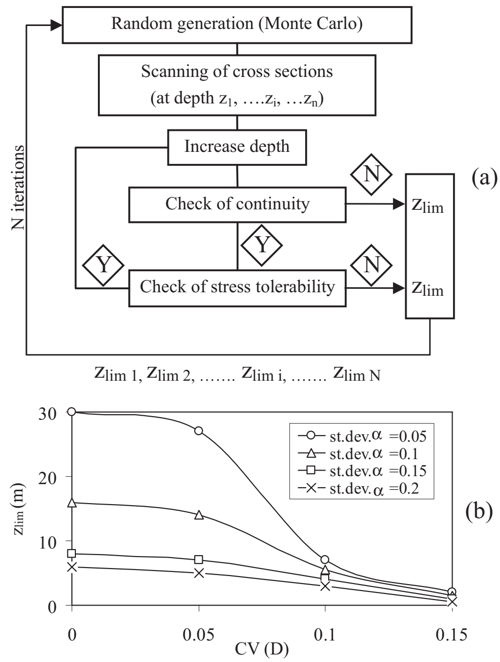

Figure 6. Calculation process for a vertical jet grouted shaft (a) and sample of results with CV(σ_{lim} = 0.2)(b).

By considering defects in both diameter and axis position, a solution can be obtained using the calculation process described in Figure 6.a. A non cylindrical shaft is generated with Monte Carlo simulation technique, where the geometrical and mechanical properties of columns are simulated with the probabilistic models introduced in the second paragraph. z_{lim} is then defined at the first depth where at least one between continuity or stress tolerability conditions is not fulfilled.

The big influence of variability of columns properties can be seen in Figure 6.b, where the limit depth corresponding to 5% accepted probability of failure is calculated (D_{shaft} = 12 m, 63 columns having D_{col} = 0.6 m, γ = 20 kN/m^3, K_o = 0.5, σ_{lim} = 13 MPa).

4 IMPROVEMENTS OF DESIGN METHODS

The results obtained in all the previously described analyses show that, independently on the considered case and regardless of the adopted probabilistic procedure, very large thicknesses are generally required to guarantee integrity of the jet grouted structures; in some case, the values could be too large to be realistic.

This result is significantly affected by the very conservative assumptions made in previous calculations. In particular, collapse of structures has been referred only to continuity or stress tolerability of cross sections, while nil contribution has been considered from the longitudinal flexural resistance of columns. Even assuming nil tensile strength of soilcrete, a significant improvement to the flexural resistance of columns may on the contrary derive from the longitudinal compressive stresses and/or from the possible insertion of reinforcements. Furthermore, nil interaction was assumed between supporting structures and surrounding soil (applied forces independent on displacements), while this effect could in principle produce a reduction on the assumed thrusts. Finally, it is worth considering the fully three dimensional nature of the studied problem, with its implications on the supporting structure and the surrounding soil. In the next paragraphs, the relevance of these factors on the results of calculations is singularly considered.

4.1 *Soil structure interaction*

Soil-structure interaction may influence the stress state in the structure to a great extent, its relevance depending on soil-structure relative stiffness. The use of the stiffness method previously described with reference to tunnels, for instance, allows to simply take into account the interaction between the jet-grouted structure and the surrounding soil through a number of independent Winkler type springs. Then, the stresses acting on the structure change along the loading process because of structure's deformation. Inward movements release the springs and decrease the horizontal stress component (active path), while outward movements have the opposite effect (horizontal stress increase, passive path).

For example, the non dimensional deformed shape $w(\eta)$ in the local coordinate system of an element loaded by a transverse unit displacement is given by:

$$w(\eta) = 2x^3/L^3 - 3x^2/L^2 + 1/w(\eta) \qquad (3)$$

Because of this displacement field, the independent springs load the element with a pressure $p(\eta) = \kappa \cdot w(\eta)$, giving rise to an additional displacement field, $w'(\eta)$, according to equation:

$$w'(\eta) = \frac{\kappa L^4}{EI}\left(\frac{x^7}{420L^7} - \frac{x^6}{120L^6} + \frac{x^4}{24L^4} - \frac{13x^3}{210L^3} + \frac{11x^2}{420L^2}\right) \qquad (4)$$

where κ is the interaction parameter. A possible expression of this parameter is:

$$\kappa = a \cdot S \cdot \left(\frac{E_{soil}}{D_{tun/shaft}}\right) \qquad (5)$$

being S and $D_{tun/shaft}$ respectively the structural thickness and the diameter of either the tunnel or the shaft, and E_{soil} the soil stiffness.

Soil stiffness is a nonlinear function and depends on the sign of the displacement function. To avoid an iterative approach, an elastic formulation can be adopted for the Winkler springs with a constant stiffness κ. In Figure 7, for instance, the results of a calculation carried out with the code developed by Lignola et al. (2009) considering also Soils Structure Interaction (SSI) is reported (assuming a = 2) to show how relevant it can be. Since inward movements reduce the stresses applied on the arch the structure with SSI is in a much safer structural condition.

The subgrade reaction factors κ given by eq. 5 have been compared with those obtained by a linear interpolation of the relations found with two dimensional FEM simulations (Plaxis 2D, Brinkgreve & Vermeer, 2000) between normal stresses and displacements at the contour of a semicircular canopies. To this aim a parametric variation has been assigned to the cover (2.5 ÷ 10 m), the diameters (5 ÷ 10 m) and the wall thicknesses (0.6 ÷ 1 m) of the canopy and to the stiffness of cemented soil (2 ÷ 8 GPa). The non linear soil response has been simulated with an elasto-plastic, double hardening surface model (Schanz, 1998) by considering different stiffness parameters ($E_{50\%} = 40 \div 238$ MPa). The comparison reported in Figure 8.a for two positions A and B (respectively at the top and the base of the crown). on the arch-soil interface is not particularly satisfactory due to the large spread of results,

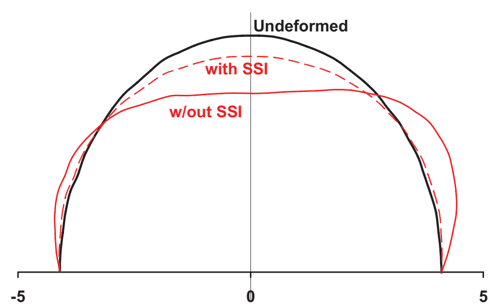

Figure 7. Effect of soil-structure interaction in terms of displacements in the arch (cross section of a jet-grouted canopy (after Lignola et al., 2009).

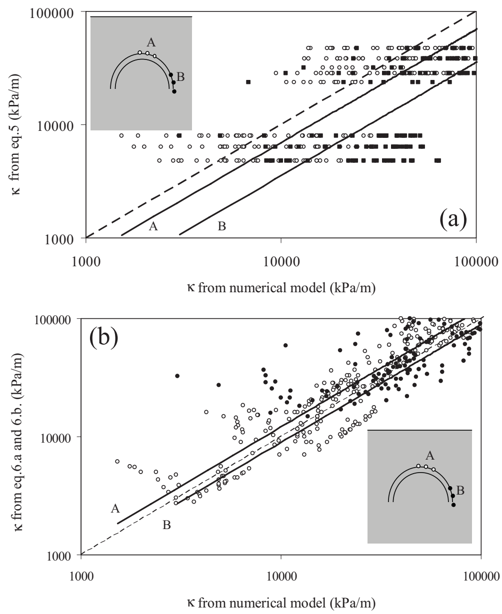

Figure 8. Subgrade reaction factors obtained from simplified relations (a. with eq.5; b. with eqs. 6.a and b) compared with those obtained by the numerical model.

indicating that the value of κ given by eq. (5) may be oversimplified, or at least unable to catch the different soil response for stress release (active) and stress increase (passive) paths.

An improvement (see Fig. 8.b) in the interpretation of numerical results can be obtained separating the two kinds of paths (in this case defined for active and passive points respectively from the results in point A and B) introducing the following two empirical regression curves:

$$\kappa = 0.2\,\frac{\left(E_{jet}\cdot s_{jet}\right)^{0.36}\cdot E_s\cdot z^{0.86}}{D^2} \tag{6.a}$$

$$\kappa = 0.32\,\frac{\left(E_{jet}\cdot s_{jet}\right)^{0.43}\cdot E_s^{\,0.57}\cdot z^{0.5}}{D} \tag{6.b}$$

A positive effect of soil structure interaction on the horizontal displacements and stresses of columns has also been shown on jet-grouted shafts by Fusco (2009) (Fig. 9).

It must be however pointed out that, due to the larger stiffness of closed rings compared with tunnel canopies, the advantage of considering SSI is not particularly relevant. Therefore, in an attempt to reduce complexity of structural analyses, SSI could be conveniently avoided unless very slender

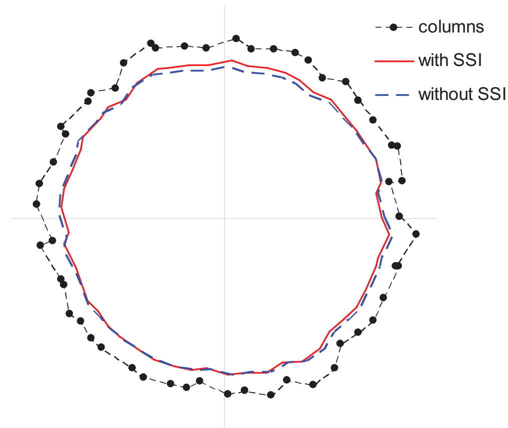

Figure 9. Effect of soil-structure interaction in terms of displacements in the cross section of a jet-grouted shaft: D_{shaft} = 10 m; D_{col} = 1 m; σ_{lim} = 10 MPa (Fusco, 2009).

shaft sections are considered (but this latter case is in contrast with the above discussed need of reducing defects).

4.2 *Three dimensional (3D) response*

By analysing structural performance, it is found for both tunnels and shafts that the lack of overlapping is the most probable failure mechanism. In Figure 10, for example, the results of a case study of jet-grouted canopies are shown (Lignola et al., 2009). In the figure, the upper bar represent the percentage of arches that fail (that is the probability of failure P_f) for the given cross section/arch of the umbrella, while the lower bar represents the percentage of the three expected failure modes (soilcrete failure, stability failure and no columns overlapping). Starting from the 8th arch, P_f reaches 100% and the corresponding most probable failure mechanism is always the lack of overlapping.

This depends on the fact that, in these 2D analyses, the lack of continuity (i.e. no overlapping between at least two adjacent columns) is considered as a condition sufficient to attain arch failure. This is certainly very conservative, as the 3D jet grouted structure (either open or closed) may have the ability to carry soil loads even if in a small portion it is not continuous. The question is: how small should this portion be? How can we take into account the existence of structural discontinuities from a structural viewpoint? The questions are worth being considered and deserve an answer.

From a theoretical point of view, the structural analysis of geometric discontinuities (in the following briefly called 'holes') is very complex. Holes in

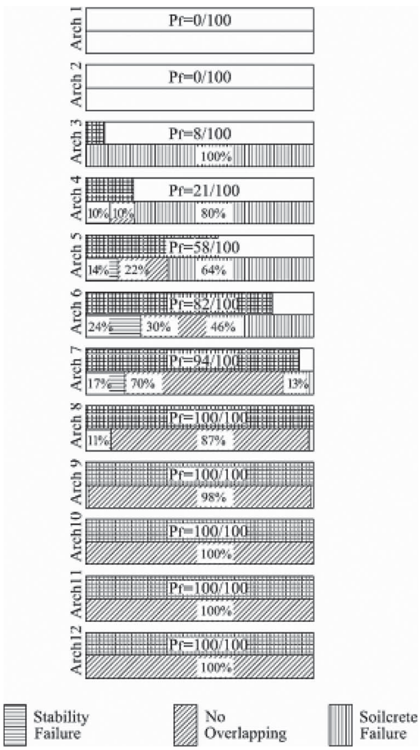

Figure 10. Probability of failure for arches forming an umbrella (D_{tun} = 8 m; D_{col} = 0.6 m) with defects in sand soil with CV_d = 0.10 and $\sigma(\alpha)$ = 0.5. Effect of Soil-Structure Interaction (SSI). (Lignola et al., 2009).

the structure cause a local increase in the intensity of the stresses, depending on the dimension and shape of the hole itself. A proper analysis should include the real geometry of the hole, which the case of defected jet grouted structures is strictly related to the statistical parameters adopted for the analysis.

Figure 11, for instance, shows typical maps of holes on the lateral surface of a shaft, as numerically calculated using two different sets of statistical parameters of the columns geometrical properties (CV_d = 0.1 in both cases; $\sigma(\alpha)$ = 0.5° and 1° respectively) using the extension to shafts of the code developed by Lignola et al. (2009) previously described. These maps show, as expected, that the amount of holes increases with depth, and that most of them are connected. However, some are not, specially in the upper part of the shaft.

To estimate the maximum allowable dimensions of the hole in the case of the shaft, the stress increase within the structure around the hole has been calculated via the simplified analytical

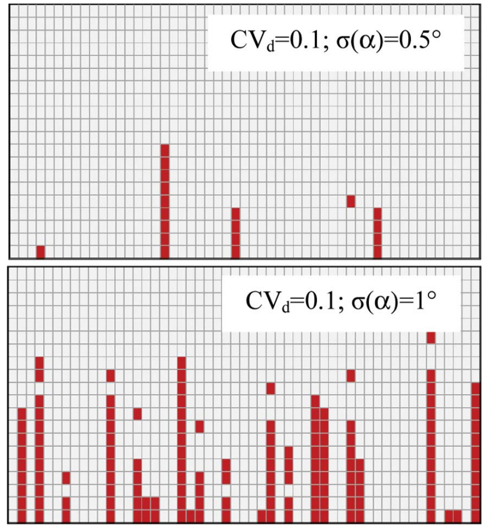

Figure 11. Maps of holes on the lateral surface of a shaft, for different angular deviations (D_{shaft} = 10 m; D_{col} = 1 m; σ_{lim} = 10 MPa).

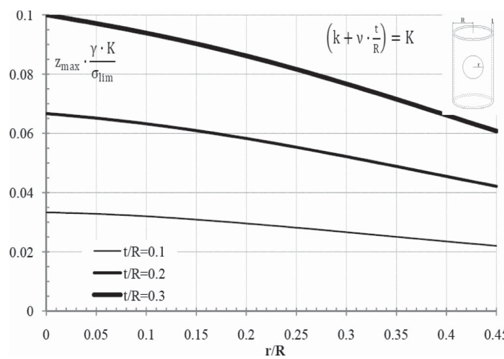

Figure 12. Design chart for maximum radius of critical holes at depth lower than z_{max}.

method suggested by Young and Budynas (2002) (see Appendix A). The structural safety is analysed by verifying that $\sigma_1 K_t \leq \sigma_{lim}$, being σ_1 the maximum compressive stress within the jet grouted structure (see Appendix A). By manipulating this structural condition, a simple relation can be found:

$$z \cdot \frac{\gamma \cdot K}{\sigma_{lim}} \leq \frac{t}{R \cdot K_t} \qquad (7)$$

being $K = k + \nu \cdot t/R$. In this relation, the radius r of the hole is included in the expression of K_t (Appendix A). Eq. (7) allows to plot the design chart shown in Figure 12, in which z_{max} is the

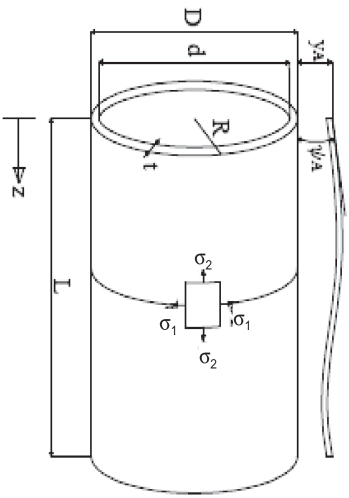

Figure 13. Scheme of a cylindrical shaft.

maximum depth at which a hole having radius r still complies safety conditions. For a given geometry of structure and defects, the deeper is the location or the lower is cemented material strength, the smaller is the maximum hole radius r that complies with structural safety.

By using the chart reported in Figure 12 it can be easily seen that, if the jet grouted soil has fair strength, holes of dimensions of a meter or so do not necessarily imply structural failure, even at considerable depths. Even though the chart refers to circular holes, it suggests that the assumption that arches (for tunnels) and rings (for shafts) have to be continuous in the cross section to avoid failure may be too strong. Further research is needed and is currently under course to extend and confirm this result.

5 CONCLUSIONS

Jet grouted supporting structures are unavoidably affected by defects. By using a simple probabilistic or semi probabilistic approach, structural performance can be assessed with a given level of confidence. This probabilistic approach is rational and cost effective if compared with a deterministic one. Yet, the approaches suggested by the authors in the past, briefly recalled in the paper, may still result into massive structures with large thicknesses under typical soil loads. In this paper, it is argued that the reason why of this conservativeness in results is the inability of the original approach to take into account some relevant aspects, namely Soil-Structure Interaction (SSI) and the truly 3D behaviour of tunnel canopies and shafts.

By introducing SSI into a numerical code developed by some of the authors (Lignola et al., 2009) it was shown that the stresses within the jet grouted structure strongly reduce, and a less conservative design can be obtained. A simplified approach is also suggested to take into account the existence of structural discontinuities ('holes') without necessarily implying structural failure. So doing, the three dimensional ability of the structure to carry loads can be considered, and less conservative design attempted.

APPENDIX A

Young and Budynas (2002) propose a formula to evaluate the increase of stresses around a circular hole of radius r on the wall of a cylindrical shaft (having thickness t and external radius *R*, Fig. 13) via the use of a stress multiplier, called stress concentration factor K_t.

The formula can be applied if $t/R > 0.1$ and $r/R < 0.45$. The intensity factor is then calculated as:

$$K_t = C_1 + C_2\left(\frac{r}{R}\right) + C_3\left(\frac{r}{R}\right)^2 + C_4\left(\frac{r}{R}\right)^3 \tag{8}$$

where the parameters C1, C2, C3 and C4 are:

$$C_1 = 3.000$$

$$C_2 = 2.773 + 1.529\left(1-\frac{t}{R}\right) - 4.379\left(1-\frac{t}{R}\right)^2$$

$$C_3 = -0.421 - 12.782\left(1-\frac{t}{R}\right) + 22.781\left(1-\frac{t}{R}\right)^2$$

$$C_4 = 16.841 + 16.678\left(1-\frac{t}{R}\right) - 40.007\left(1-\frac{t}{R}\right)^2$$

In the case of loads linearly increasing with depth z, the vertical and horizontal normal stresses (σ_1 and σ_2 in Fig. 13) within the jet grouted structure can be calculated as:

$$\sigma_2 = \gamma \cdot z \tag{9}$$

$$\sigma_1 = \gamma \cdot z \cdot \left(\frac{K_0 \cdot R}{t} + \nu\right) \tag{10}$$

where the horizontal stress in practical cases is always larger than the vertical one.

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