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Pre - Supported Soft Ground Tunnels

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ABSTRACT

The use of pre - support in soft ground tunnels is increasing in urban regions, with the purpose of improving excavation stability and reducing settlements induced by tunnelling. Pre - support design is reviewed in this paper, and the main factors controlling it's behaviour are analyzed. A dimensionless parameter refiecting the efficiency of pre support is proposed. A general methodology for the design of tunnel pre - support is presented, based upon relationships between ground treatment efficiency and dimensionless parameters. Hence the performance of some pre - support techniques can be assessed, allowing the comparison of alternative designs. Predicted and observed behaviour of pre - supported soft ground tunnels recently built in Brazil are presented. It is concluded that reasonable estimates of pre - support efficiency (and of settlements induced by the excavation) can be provided, in cases where good ground control conditions exist during tunnel construction.

RÉSUMÉ

Dans le régions urbaines, le traitment des sols est de plus en plus utilisé lors du percement d'un tunnel en sols mous, soit pour assurer Ia stabilité d'une excavation, ou pour réduire le tassement que cause la construction du tunnel. La théorie pour l'utilisation des traitement des sols est brievement révisée, et les principaux facteurs qui in.fluencent le comportment de ce8 tunnels sont analysés. La méthodologie de Ia conception de tels tunnels est aussi presentée. Une foi8 que le sol en question est modeler par éléments finis, les relations entre l'éfficacité du traitment du sol et des certains paramétres sans dimensions peuvent être établies. La prédiction de l'éfficacité des differentes techniques de traitment des sols peuvent être analysée, permettant ainsi la comparaison de ces méthodes d'éxecution. On peut raisonnablement prédire l'éfficacité du traitment (et aussi du tassement causé par l'excavatíon) dans le cas ou les conditions du sol sont bien controlées durant Ia construction du tunnel. Des résu1tats estimés et observés par instrumentatíon pour des tunnels en sols mous récemment contruits au Brézil sont présentés.

INTRODUCTION

A large increase in the use of shallow tunnels in soft ground has been observed, mainly in urban regions, during the last few years. These tunnels have been built for a variety of purposes, such as transportation, water supply and as part of sewerage systems.

Although shield tunnelling machines have been widely used, an increasing trend towards the use of staged excavation and shotcrete support has been be observed, associated with ground treatment where necessary. The staged excavation alternative usually results in lower initial investments with equipments, and greater construction flexibility when compared with tunnel boring machines (TBM). The staged excavation method, however, is usually slower. Pre support has also been used (e.g.) jet grouting) for shaft construction in soft ground (Bell et. al., 1991).

Main concerns regarding soft ground tunnelling in urban regions are face stability and ground movements induced by excavation. As safety and settlement requirements become more rigorous, the use of pre - support for soft ground tunnels becomes more feasible. In this paper, pre - support means any ground treatment or ground modification technique) executed before tunnel excavation, to improve stability and to reduce settlements (soil injections with cement or resins; steel forepoling; grouted forepoling; jet grouting; pre - cutting; and soil freezing). Thus (in this paper) pre - support and ground treatment have the same meaning as regards soft ground tunnelling) and both will be used here indistinctly.

Conventional pre - support design relies on empirical criteria) thus often leading to conservative thicknesses of ground treatment. Consistent design criteria should ideally take into account the interaction between ground mass and pre - support) and should be amenable to validation by back analysis of monitored excavations.

This paper reviews cases where pre - support (horizontal and vertical jet grouting columns) was used for soft ground tunnels. Pre - support behaviour is also analyzed, using the concept of ground treatment efficiency. A general methodology for tunnel pre - support design (applicable to jet - grouting columns) horizontal or vertical; as well as cement grouting, silicate grouting, structural or grouted forepoling) is presented. Upon modeling the treated ground by finite elements, relationships between ground treatment efficiency and dimensionless parameters can be established, allowing efficiency prediction of distinct pre - support techniques, comparison and optimization of ground treatment alternatives.

Validation of the presented methodology is verified comparing predicted and observed instrumentation results for pre - supported soft ground tunnels recently built in Brazil.

Reasonable estimates of pre - support efficiency (and of settlements induced by the excavation) can be made, in cases where good ground control conditions exist during tunnel construction.

PRE - SUPPORT FOR SOFT GROUND TUNNELS

Pre - support design should ideally aim at providing adequate stability at the working face, and minimizing ground displacements due to the excavation. lining. During the last few years, jet grouting has been extensively used throughout the world for achieving this purpose, first in granular soils and, more recently, in cohesive soils as well.

Jet grouting applied to tunnel pre support is a relatively new technique. It was developed in Japan during the late 1960's and 1970's. Since then, it has been increasingly adopted in Europe (mainly Italy and West Germany), as well as in South America (Brazil and Argentina). It's main advantage over chemical grouting lies in the absence of environmental risk, fast execution, flexibility of use (either from the surface or from inside the tunnel), and high efficiency compared to other ground treatment methods.

Jet grouting also offers the advantage of being applicable to any soil permeability, as opposed to permeation grouting. Three jet grouting systems are commonly available in Europe, Japan and South America :

a) CCP (Cement Churning Pile) : a single jet is used to erode the ground mass under high pressure, and place cement grout;
b) Jumbo Grout : a double jet (one for cement grout and the other for compressed air) is used to enhance the ground erosion effect;
c) Column Jet : a triple jet is used, comprising a high pressure water jet to induce hydraulic fracturing of the ground, followed by compressed air and cement grout, as in the Jumbo Grout system.

Experience shows that jet grouting columns present large variability in : mechanical and strength properties, column diameters attained in the field and structural integrity (column continuity). Traditional design methods are based on empirical criteria, thus often leading to treatment thicknesses larger than needed, with unknown safety margins. Experience indicates that, in order to achieve a reliable execution, it is necessary to perform pilot columns in the field, before the tunnel pre - support construction. Monitoring execution parameters, and measuring column diameters obtained in the field, allows fine tuning execution procedures and adaptations to local subsoil conditions. Consequently, an increased quality level can be obtained for the tunnel pre - support (Humes & Kochen, 1991).

Ground treatment techniques (including chemical grouting, and specially designed grout mixes, as used in the Channel Tunnel - Gouvenot, 1990), for tunnel pre - support are also often designed based on empirical rules. Empirical design procedures do not allow comparisons to be made between several pre - support alternatives. Optimization of the adopted alternative, as regards pre - support thickness and its strength, is not possible either. Previous attempts for establishing more adequate procedures for the design of tunnel pre - support have been presented by Gartung et. al. (1979), and Tan & Clough (1980). The methods, however, are limited to specific conditions. Thus the use of the empirical design rules cited before continued.

GROUND TREATMENT EFFICIENCY

In order to move towards a general methodology for tunnel pre support design, the efficiency of ground treatment systems has to be considered. Efficiency, in the context of this paper, is a function of the ground losses induced by tunnel excavation. Ground loss is, as defined by Cording & Hansmire (1975), the soil volume crossing the excavation perimeter. A 100 % efficiency corresponds to null ground losses, and a 0 % efficiency corresponds to zero reduction of ground losses. Pre support efficiency can be defined by Equation 1 bellow :

$E = (1 - V_1 / V_2) \times 100$ ....(1)

where E is pre support efficiency (in the range of 0% to 100%), V_1 represents ground loss for the treated soil mass, and V_2 is the ground loss for the untreated ground. Soils exhibiting volume reduction during deformation can generate surface settlements even with null ground losses, as the settlement volume can be greater than zero due to consolidation of the soil mass (resulting from drainage effects). For this reason, efficiency is preferably defined as a function of ground losses instead of settlement volume.

Gartullg et. al. (1979) and Tan & Clough (1980) have shown that circular or semi circular shapes of treatment are the most efficient ones. These results were confirmed by a research sponsored by São Paulo's Subway Company (Negro, 1988), assessing the efficiency of circular and slab ground treatment shapes, both done with the same volume of treated ground. Back analysis of pre - supported tunnels with finite element models showed that the circular shaped pre - support had, for a large tunnel being analyzed, an efficiency of 60% ,while the slab shaped treatment above the tunnel crown presented a lower efficiency value (30%). For the same double line subway tunnel, grouted forepoling showed an efficiency of only 9% . Although grouted forepoling, for this tunnel, was executed with a circular shaped geometrical configuration, it 's thickness was small (about 0.05 of the tunnel radius), and it's flexibility was high, resulting in a low overall treatment efficiency.

METHODOLOGY FOR GROUND TREATMENT DESIGN

To the author's knowledge, the only methodology applicable to specific Cases of pre support design of tunnels is the one presented by Tan & Clough (1980). However, the parameters used by these authors were not dimensionless, making difficult to use this method in engineering practice. Kochen (1991) presented an alternative methodology for soft ground tunnels, based on dimensionless parameters and ground treatment efficiency, as defined by Equation 1. It's main goals were aimed at :

a) identifying behaviour mechanisms of treated ground; b) identifying key parameters to evaluate efficiency;
c) establishing a design method for optimization of thickness and deformability of treated ground.

These objectives led to a design methodology both simple and easy to use in practice.
It's main parameters are those represented in Figure 1, as follows : R- tunnel radius; H - axis depth; Em- natural ground elasticity modulus; K- ratio of horizontal to vertical stress; t - ground treatment thickness; Et - elasticity modulus of treated ground; and Eb - bench material elasticity modulus. Main hypothesis of this methodology have been explained in detail elsewhere (Kochen, 1991), and they will not be repeated here.

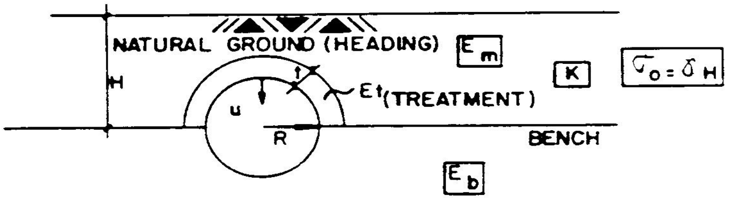

Figure 1 - Modeling of Pre Support for Soft Ground Tunnels

Based on simplifying assumptions, it is possible to group the parameters governing the tunnel's roof displacement into the dimensionless factor U, as defined by Einstein & Schwarz (1979). For a fixed t/R ratio, the dimensionless displacement U becomes a function of the relative stiffness between treated and natural ground (Et/Em). Numerical values of U were computed for usual ranges, observed in practice, of parameters H/R, t/R, and Et/Em. The first two parameters are a function of the geometry of the treatment, geometry of the tunnel and its depth. As regards Et/Em, experience shows that this parameter varies between 20 and 120 for jet grouting treatment, for execution conditions observed in tunnels recently built in São Paulo State, Brazil.

Figures 2 to 5 shows dimensionless parameter U as a function of Et/Em, for H/R in the range of 3.0 to 1.50 . In each figure, four curves are represented (for t/R in the range of 0.05 to 0.40). Although U is a non - linear function of H/R and t/R, for pratical application purposes an interpolation can be used for values of these parameters inside the ranges given in figures 2 to 5.

Efficiency, as defined by equation 1, corresponds to linear elastic soil behaviour. Pre supported tunnels, even shallow ones, usually behave in an elastic manner, due to the fact that ground treatment significantly increases soil strength and stiffness. For untreated ground with low strength and stiffness, ground behaviour can be highly non linear, due to the spread of plastic regions into the soil mass. In these cases, even ground treatments with low strength and stiffness (like, for instance, grouted forepoling) can be highly efficient, if the treatment stiffness is large enough to keep soil deformation limited to the elastic range.

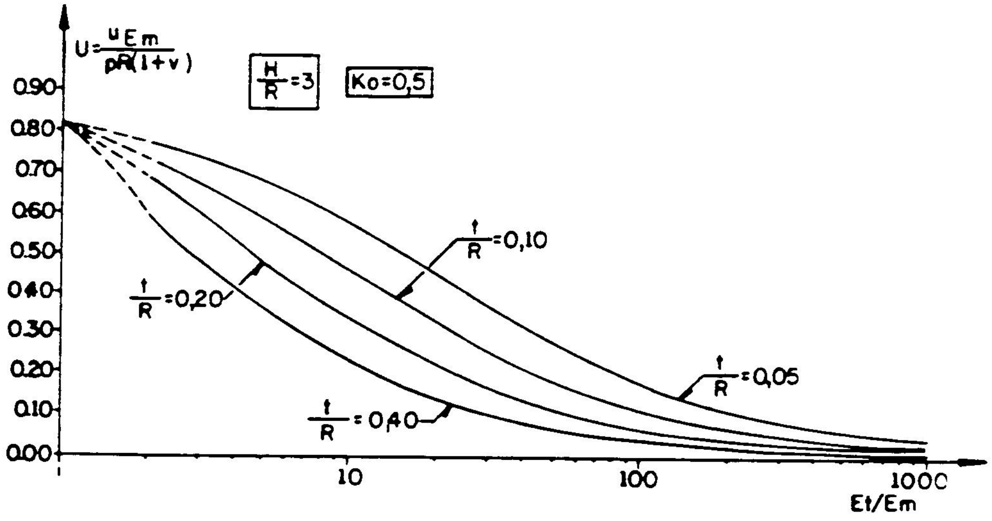

Figure 2 - Parameter U as a Function of Et/Em (H/R = 3.00)

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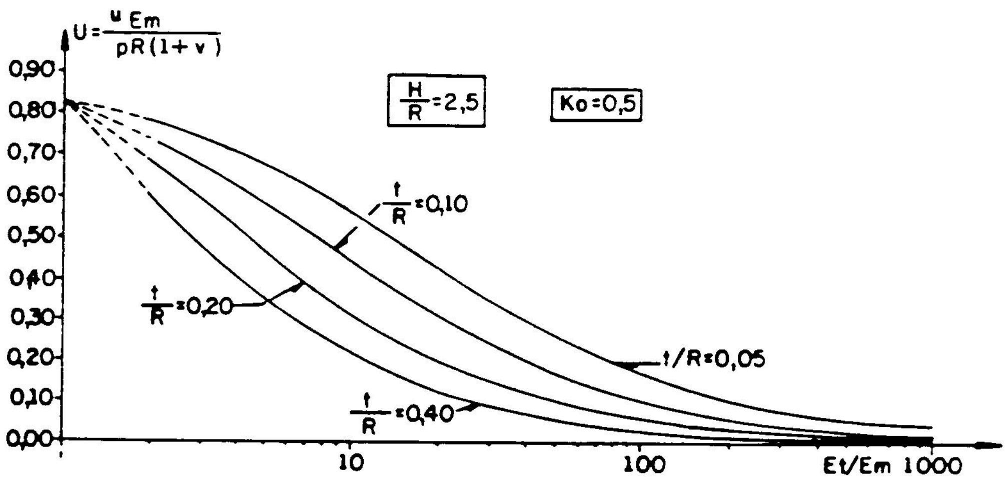

Figure 3 - Parameter U as a Function of Et/Em (H/R = 2.50)

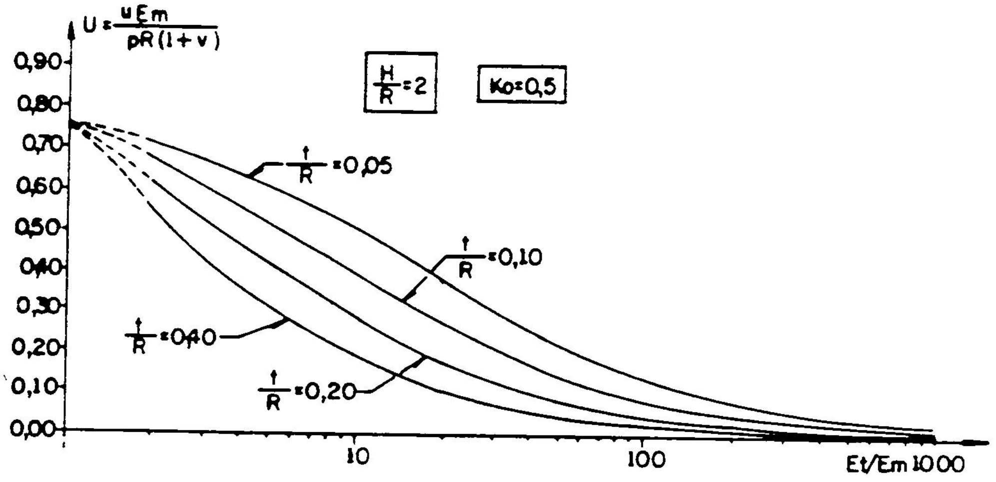

Figure 4 - Parameter U as a Function of Et/Em (H/R = 2.0)

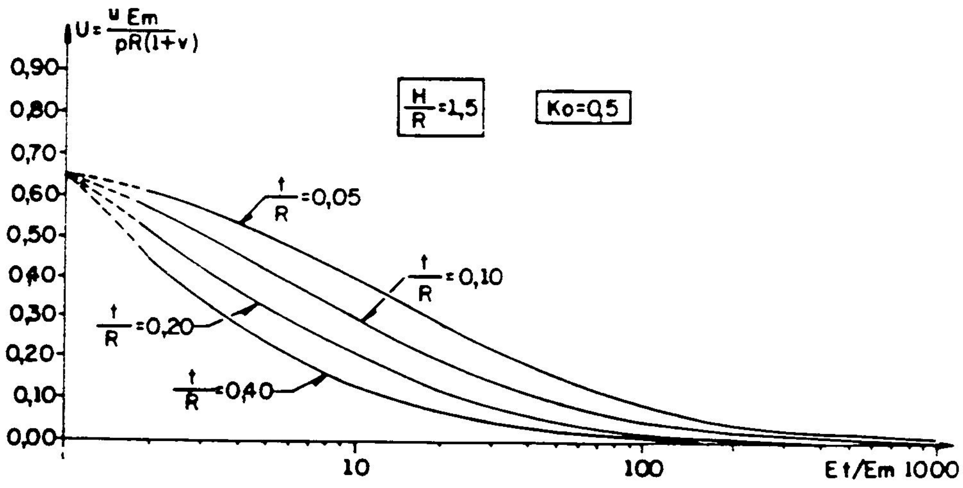

Figure 5 - Parameter U as a Function of Et/Em (H/R = 1.50)

Results presented in figures 2 to 5 are valid for bench material stiffness significantly higher than natural ground sti.ffness at the heading (Figure 1). A low stiffness relation Eb/Em results in the occurrence of additional displacements at the crown, induced by bench's deformation, thereby reducing pre support efficiency. Figure 6 presents the dimensionless displacement Ub as a function of Eb/Em (being Eb the bench 's material elasticity modulus). For relative stiffness Eb/Em higher than 30, bench displacements are negligible, and can be omitted on computing treatment's efficiency.

Results presented in figures 2 to 6 can be organized into a design methodology (Kochen, 1991), comprising ofthe assessment ofthe tunnel and treatment geometry (H, R and t);
of the initial vertical stress p at the tunnel centre; and the elastic modulus of the heading, bench and treatment materials (Em, Eb, and Et). The dimensionless displacement of the tunnel crown can be obtained through figures 2 to 5, for treated and untreated ground (Uo and U1, respectively). Where the bench material is deformable compared to the soil mass, the dimensionless displacement of the treatment - bench contact can be obtained from figure 6 (U2). The pre - support efficiency can therefore be assessed with equation 2 :

E= 11 - (Ul + U2) / Uo J x 100 ....(2)

If the ground treatment efficiency is lower than required, ground treatment features can be modified to improve efficiency (for instance, by increasing t or Et) . If efficiency is higher than necessary, then ground treatment cost can be reduced by optimizing t and Et.

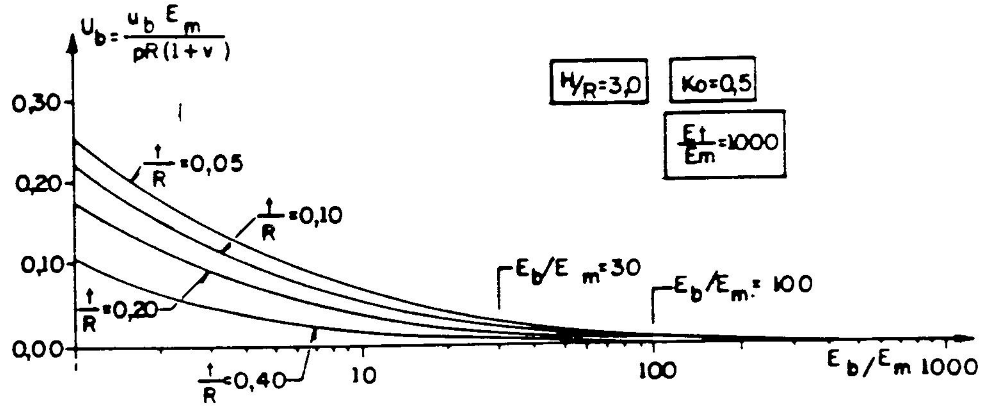

Figure 6 - Dimensionless Displacement Ub as a Function of Eb/Em

TIETE SEWER TUNNEL

Figure 7 shows a longitudinal section of the Tiete tunnel, part of São Paulo's City sewerage system. This tunnel was excavated using an open face shield machine. The geological profi1e along the tunnel's alignment contained a soft clay layer with low undrained strength (SPT blow counts between 2 and 5). Ground treatment (CCP columns), was adopted in order to improve face stability and make tunnelling with the open face TBM feasible. More details on this sewer tunnel can be found in Pan & Oliveira (1983).

Figure 8 shows two typical treatment sections : on the first one, treatment was done at the roof and sidewalls of the tunnel; on the second one, the floor was also supported with CCP columns. Treatment thickness on the tunnel crown is 3.00 m, which results in a thickness - radius ratio (t/R) equal to 1.20 . Based on laboratory tests made on samples extracted from soil - cement columns, and on empirical correlations, elasticity modulus for the CCP columns and for the soil mass were estimated.

Pre - support design for this tunnel could be carried out by evaluating the treatment thickne8S necessary to obtain a specified efficiency value. In this example, a minimum efficiency value of 80 % is adopted. For a pre support thickness of 1 (one) meter, one obtains the following efficiency values for the sewer tunnel :

- Section I: Et /Em = 20

Uo = 0.80; U1 = 0.13; U2 = 0.00 .... E= 84 %

- Section II: Et /Em = 75

Uo = 0.80; U1 = 0.05; U2 = 0.00 .... E= 94 %

Results above show that a pre - support thickness of 1 (one) meter would have been enough to obtain an efficiency value, for this tunnel, higher than the minimum value adopted.

CAMPINAS CITY ROADW AY TUNNELS

Figure 9 shows the transverse cros - section of one of the parallel roadway tunnels built in Campinas, a city of 1.5 million inhabitants located 100 km west of São Paulo. These parallel tunnels, with an extension of 400 meters each, were excavated in downtown Campinas, under several settlement sensitive buildings and active railway lines. They were designed to contain three traffic lanes each, within a large excavation cross 8ection (125 sq.m. each), having a width of 14 m and height of 11 m, approximately. The soil profile, at the tunnels heading, contained mainly medium loose sand. The water table was near the tunnel crown in 60 % of the extension, and 2 m bellow the tunnel crown in the remaining part.

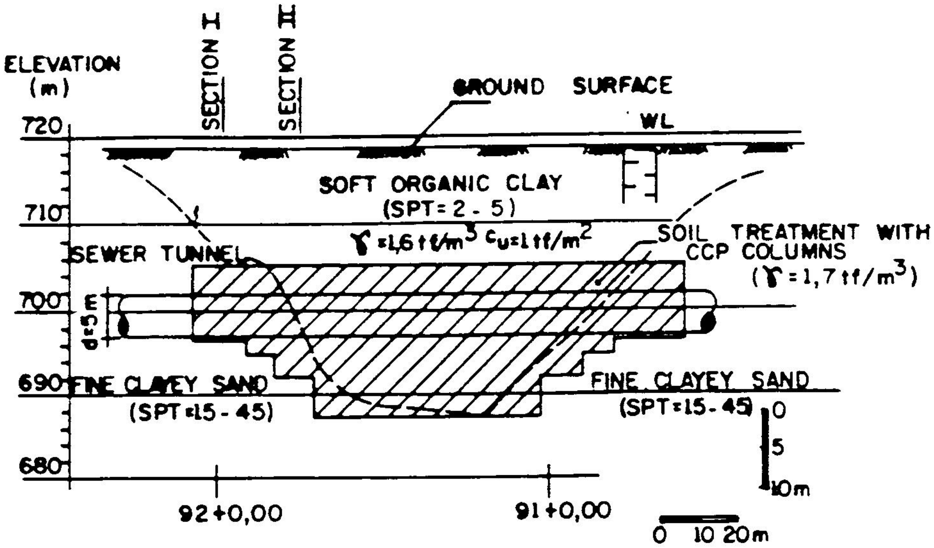

Figure 7 - Longitudinal Section of Tiete Tunnel (São Paulo)

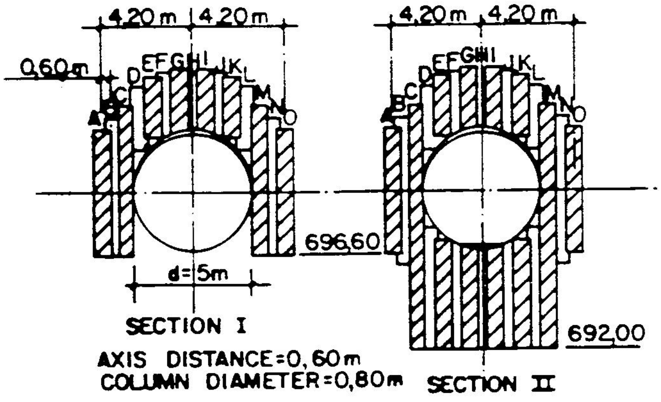

Figure 8 - Tiete Tunnel Typical Pre Support Geometry

The tunnel execution started at the South Portal, following the installation of vertical Jumbo Grout coiumns. The crown cover was small at this portal (4 meters). Execution sequence comprised of excavation of the heading; installation of the primary lining (steel sets and shotcrete); bench excavation (performed in dense sand and sandstone);
installation of the bench primary lining; and finallining (casi-in-place concrete). The central part of these tunnels was pre - supported with horizontal jet grouting columns1 executed from inside the heading in a single line layout with 0.60 thickness. At the North Portal, heading excavation had to pass under an operating railway line, with a crown cover of 3.50 meters, and having to comply with very small settlement limits. Excavation was successfully completed using pre support with horizontal jet grouting columns, executed in a double line layout1 with a thickness of 1.20 meters.
The proposed methodology allows estimation of the dimensionless displacement U, and of the crown displacement (if elasticity modulus of the natural ~round, of the ground treatment and of the bench material are known). Surface settlements can be obtained though extrapolation of the crown displacements using empirical correlations. A settlement prediction was made for the deepest section excavated, under a soil cover of 17 meters. The subsoil profi1e at this section is represented in Figure 10. Geometry and stiffness dimensionless parameters for this section were as follows :

- $H/R = 2.0$; $t/R = 0.05$; $Et/Em = 14$; $Eb/Em = 4$.

Roof displacement can be computed using equation 3 :
$U\ roof = (U1 + U2) . p . R(1 + v) / Em$ ....(3)

Sudace settlement was estimated through extrapolation of the displacement at the crown, using Atkinson & Potts empirical correlation1 with the alpha parameter being equal to 0.13, as proposed by Eisenstein & Negro (1985) for tropical residual soils. Predicted settlement was 5.5 cm, which agrees reasonably well with the monitored value of 6.3 cm. Other predictions, performed for different sections of these tunnels1 yielded settlement values 10 % to 30 % lower than the observed ones. The underpredicted settlements are believed to be

partly due to the fact that ground control during excavation was not good1 and the ground response deviated from linear elastic behaviour .
Additional ground losses (which were added to those generated by pre support elastic deformation) occurred, as a consequence of the heading being excavated in a loose sandy soil, under water table, and with a very flexible pre support system (horizontal jet grouting columns forming a treated ground arch 60 cm thick). Better predictions were obtained for sections containing a higher proportion of clayey soils in the heading.
In clayey soils1 the volume of water seeping through pre support voids (carrying soil particles and increasing ground losses) were low or null, and the heading excavation was performed in the elastic range.

Applications of the methodology for settlement prediction yields lower bound values, corresponding to the elastic range of behaviour for the tunnel excavation. Therefore, these applications can perform well in practice, if based in sound engineering judgment.

LARGE CROSS SECTION ROADWAY TUNNELS (SÃO PAULO)

São Paulo, the largest Brazilian city with 15 million inhabitants, has a strong need for expanding it's transportation systems. As a consequence, several tunnels have been built since 1985 as part of subway lines and traffic roadways. The large cross section roadway tunnels analyzed here were built to connect two major freeways (Anchieta and Imigrantes), located in the outskirts of the city. Each of the parallel tunnels is 740 meters long, with triple traffic lanes, and a large cross section with an excavation area of 125 sq.m. Geometry of these tunnels is the same as the Campinas tunnels referred before, with height of 11 m and width of 14 m, approximately. The distance between tunnel axis is 28 m.
The construction started at Anchieta Portal, following pre - support of the ground with vertical Jumbo Grout columns, with a crown cover of 4 meters. The tunnels were mined through saturated loose sandy soils. Execution sequence began with excavation of a pilot tunnel in the lower region of the bench, followed by the excavation of the headingi installation of the primary lining (steel sets and shotcrete)i bench excavationi installation of the bench primary lining and final lining (cast-in-place concrete). Excavation of the heading was preceeded by pre support execution. The initial 30 meters of tunnel used vertical jet grouting columns as pre support, following a geometrical configuration similar to the Campinas tunnels (as depicted in fig. 9). Then, heading excavation continued using pre support formed by the execution of horizontal jet grouting columns (from inside the tunnel), in a single line layout, with a thickness of 0.60 meters. A typical cross section of this tunnels geometry is represented in figure 11.
Pilot tunnels had a cross section of 10 sq.m. (3 m of width and 3.5 meters of height, approximately), and were built with the purpose of : confirming the geological assessment based on widely spaced boreholes (due to lack of access from surface, as this urban region is densely occupied with buildings)i performing vertical boreholes from inside the pilot tunnels (to gather precise soil strata information)i drain the sandy soil layers at the elevation heading of the tunnelsi and allow treatment of sandy soil layers by chemical grouting (in case drainage proved to be ineffective).

Monitoring was carried out with the purpose of measuring settlements induced by the execution of the horizontal jet grouting columns, and asymmetries generated in the settlement profile, due to the execution sequence of the columns.

Figure 12 shows execution sequence of horizontal jet grouting columns, and surface settlements observed. The pre - support arch was executed in 6 steps, with settlement monitored in each of these steps. The maximum settlement monitored was 5 mm, and the maximum settlement observed for this section after excavation of the heading was 50 mm. Settlements induced by pre support execution (in this case, horizontal jet grouting columns) were about 10 % of total settlement induced by tunnelling excavation.

The settlement profile is asymmetric, with larger settlements being observed for the right side of the curve. The left side treatment was built first, hence the right side columns were executed in a soil mass already disturbed and softened. Also, execution steps 5 and 6 caused the highest settlement increases, due to the fact that they contained a number of columns larger than in the previous steps (6 columns executed in steps 5 and 6,4 columns in steps 2 and 4,3 columns in steps 1 and 3). For the remaining part of the tunnels, settlements induced by the execution of the jet grouting columns were further reduced by adopting a symmetric execution sequence.

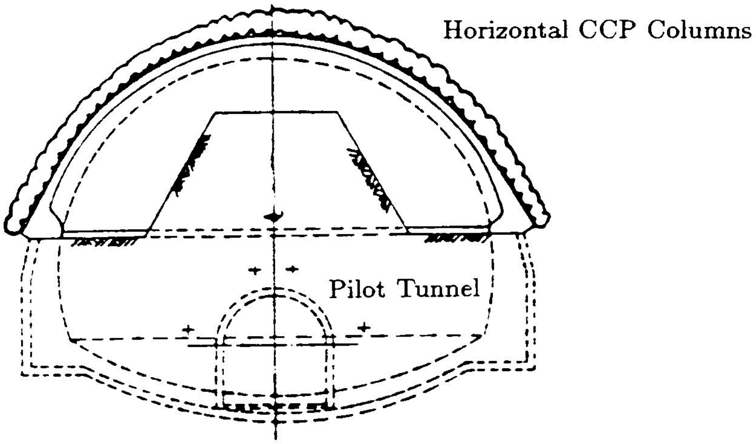

Figure 11 - Horizontal Jet Grouting Pre Supported Section, with Pilot Tunnel Excavated Bellow Heading (São Paulo Roadway Tunnels)

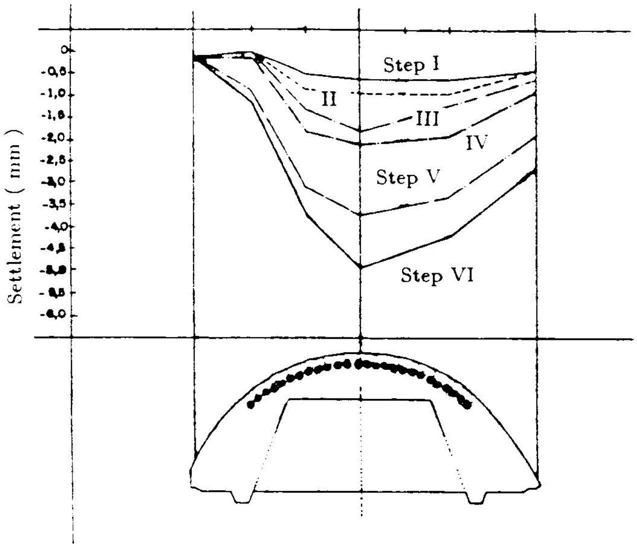

Figure 12 - Execution Steps and Monitored Surface Settlements (Horizontal Jet Grouting Pre Supported Section)

SUMMARY AND CONCLUSIONS

This paper reviewed pre - support design for soft ground tunnels, and presented a brief analysis of the main factors controlling its behaviour . Pre - support has been defined, in this paper, as the use of ground improvement or soil reinforcement techniques (such as cement or silicate grouting, jet grouting, structural or grouted forepoling, and pre cutting, among others) to improve soil mass stiffness and strength, and to improve stability during construction of the tunnel. The most relevant factor regarding pre support behaviour (settlements induced by the excavation) have been analyzed using the concept of ground treatment efficiency.

Finite element modelling was used to relate pre - support efficiency to dimensionless parameters. This procedure allowed the establishment of a simple methodology to estimate ground treatment efficiency and settlements associated with tunnel excavation.

Efficiency prediction of distinct pre support techniques could be assessed, allowing the comparison of different alternative designs. Kochen (1989) showed that there is an optimum treatment thickness for each value of relative stiffness Et/Em. Thicknesses larger than the optimum value increase ground treatment cost without increasing it 's efficiency. Reasonable estimates of pre - support efficiency and of settlements induced by the excavation could be provided, if ground losses during tunnel excavation are controlled and kept small.

Analysis of the Tiete sewer tunnel showed that a smaller pre support thickness would have been adequate to assure an acceptable efficiency value for the ground treatment. Campinas large cross section roadway tunnels were analyzed, and settlement predictions presented a good agreement with observed values in sections where the heading's soil layer presented a high clay content. For sandy soils, predictions yielded settlements lower than observed, as the tunnels' construction deviated from elastic behaviour due to additional ground losses caused by difficult soil conditions. Monitoring of São Paulo's roadway tunnels 8howed that settlements induced by pre - support execution are usually low, and can be further minimized by carefully planning ground treatment execution sequence.

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REFERENCES

- Bell, A.L.; Crockford, P.M. & Manley, G.D. (1991) : "Soilcrete Jet Grouting in Tunnel Construction in Cohesive Soils at Burnham-on-Sea, Somerset, England " , Tunnelling 91, Instnt. Min. Metall., London.

- Campanhã, C.A.; Kochen, R.; Margarido, A. & Kosh1ma, A. (1990) : "Monitoring of Execution Effects for Sâo Paulo's Parallel Roadway Tunnels", 6th. Brazilian Conference on Soil Mechanics and Foundation Engineering, Salva.dor, Brazi1 (in Portuguese).

- Cording, E.J. & Hansmire, W .H. (1975) : "Displacements around Soft Ground Tunnels", 5th PCSMFE, Buenos Aires, Argentina, Vol. 4, pp. 571- 633.

- Eisenstein, Z. & Negro, A. (1985) : "Comprehensive Method for Shallow Tunnels", Proc., Conf. on Underground Structures in Urban Areas, Prague, Czecho8lova.kia, Vol. 1, pp. 375- 391.

- Einstein, H.H. & Schwarz, C. W . (1979) : "Simplified Analysis for Tunnel Supports'l, JGED, ASCE, Vol. 105, no. GT4, pp. 499 - 518.

- Gartung, E.; Dubois, J. & Bauerfeind, P. (1979) : "Viscoplastic Finite Element Analysis of Tunnel Sections in Grouted Sands", 3rd Int. Conf. on Num. Meth. in Geomech., Aachen, Germany.

- Gouvenot, D. (1990) : "Les Nouvelles Techniques de Reconaissance et de Traitment des Sols", Franchissements Souterrains pour l'Europe, Legrand (ed.), Balkema, Rotterdam.

- Humes, C. & Kochen, R. (1991) : "Optimization of Execution Parameters for Jet Grouting Columns based on Field Tests", 2nd Special Foundation's Engineering Seminar, Sâo Paulo, Brazil (in Portuguese).

- Kochen, R. (1989) : "Contribution to Pre Support Design of Shallow Tunnels in Soil", Doctoral Thesis, Escola Politécnica, University of Sâo Paulo (in Portuguese).

- **Kochen, R. (1991) :** 'IPre Support Design for Shallow Tunnels", 9th PCSMFE, Vol. III, pp. 1363 - 1376, Vina Del Mar, Chile.

- **Negro Jr., A. (1988) :** "Design of Shallow Thnnels in Soft Groundl', Ph. D. Thesis, Department of Civil Engineering, University of Alberta.

- **Pan, Y.E. & Oliveira, H.G. (1983) :** I!Relevant Geotechnical Aspects of a 12 km Intercepting Sewer Tunnel in Sâo Paulo, Brazil", 7th PCSMFE, Vancouver, Canada, pp. 269- 279.

- **Tan, P.V. & Clough, G.W. (1980) :** "Ground Control for Shallow Tunnels by Soil Grouting", JGED, ASCE, Vol. 106, no. GT9.