Indian Society of Engineering Geology Jour. Engg. Geol., Vol. XXXVII, Nos. 1-4

Applications of Sleeve-Pipe Grouting to Ground Improvement Around Tunnels to Prevent Settlements at Neighbouring Foundations

Carlos Delgado* and Antonio Santos**

Abstract

The tremendous improvements in TBM technology has caused a revolution in tunnel construction. The development in Madrid area, of new subway lines (hundreds of kilometers within the last few years) and large diameter (15m higway tunnels, reaching new records in construction speed, compatible with safety requirements , bear witness to TBM capacities.

Nonetheless, because of changes in ground conditions and building design, it has been necessary, at a number of locations, to cover foundation settlements through compensation grouting operations. These operations may be very expensive and inconvenient in urban areas, as it is necessary to develop a full net of grouting tubes below buildings, install and grout them from large pits reaching the necessary depths that have to be excavated and stabilized before any compendation operations could start. Delayed settlements due to stress changes in the ground, subsequent to the overall excavations, are to be expected anyway, and the need for extra building-uplifting may affect old structures.

The will consider two alternatives for preventing those undesirable settlements, while making unnecessary the recourse to compensation grouting. For ground improvement ahead of tunnel construction, sleeve pipe grouting has considerable advantages. The ground can be improved by sleeve pipe grouting, either around the tunnel to be excavated, or adjacent to the building to be protected. The former will achieve a primary lining adjacent to the future tunnel cross-section, while the latter will offer, with respect to a protective diaphragm or pile wall, the advantage of an increased inertia at arelatively low cost and the possibility of installation even below façade foundations, preventing both horizontal and vertical building movements.

Introduction

Despite considerable progress in TBM technology, including the possibility of pressurizing the face, either as earth pressure balanced Shield or slurry pressurized Shield, the need to oversize the TBM bore to reduce stresses on the Shield and friction force, allowing steering of the machine, will cause a ground loss of about 1% of the tunnel volume.

Long term effects occur, additionally, in clayey soils, in response to a number of causes, such as disturbance of the clay around the bore, stress changes triggering consolidation processes around the shield and behind the lining, and drainage towards the tunnel.

All those processes account for vertical and horizontal displacements that may be detrimental to existing constructions around the tunnel. As a matter of fact, in Madrid, where the use of the most recent generations of closed face type shield machines were used to construct, at record rates, subway and highway tunnels (15m in diameter for the latter), recourse to compensation grouting to recover settlements, at a number of buildings, was necessary as reported by Sola (2003). In Barcelona the use of protective diaphragm walls and pile walls in the vicinity of some buildings showed, even with ground losses of 1%, results not always favourable.

In this paper, after considering the evaluation presented by Cording (2008) of movements

*Professor Politechnical University. Madrid
** Ph.D CEDEX. Madrid

around tunnels and their impact on buildings in their vicinity, applications are proposed of sleeve-pipe grouting to improve the ground ahead of tunnel excavations in order to prevent unacceptable movements to nearby constructions, even when they ask for differential movements not larger than 1/1000.

Evaluation of ground movements around tunnel bores

Volume of ground loss and volume of surface short-term movement

Figures 1 to 3, taken from Cording (2008), relate the so-called volume of surface movement and the volume of ground loss as a tunnel is excavated.

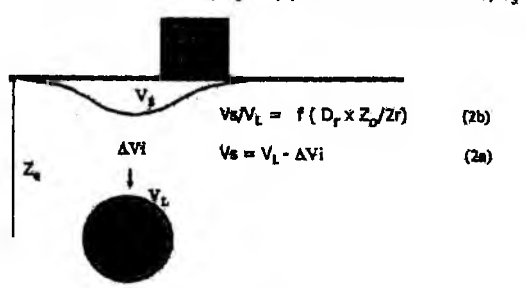


Fig. 1. Relationship betucen volume of surface settlement and volume of ground loss in a tunnel

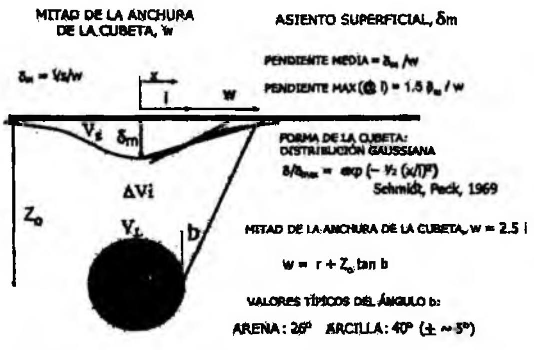


Fig. 2. Estimation of surface over tunnel

A Gaussian distribution is acceptable for surface settlement distribution over the tunnel section, as shown in Fig. 2. By use of the equations shown in Fig. 2, and the typical values adopted for sandy or clayey grounds, the maximum settlement dm can be figured out, along with the average slope dm/w.

Fig. 3 refers to lateral movements at the ground surface. The maximum values of the horizontal (lateral) surface movements occur at the inflexion points of the Gaussian settlement curve, whose abscissas are i = ± 0.4w.

For i </x/< 2,5i the lateral strains are tension strains, and can be evaluated as shown in Fig. 3. The maximum lateral displacement is proportional to the maximum settlement, dm, and increases with the "b" value.

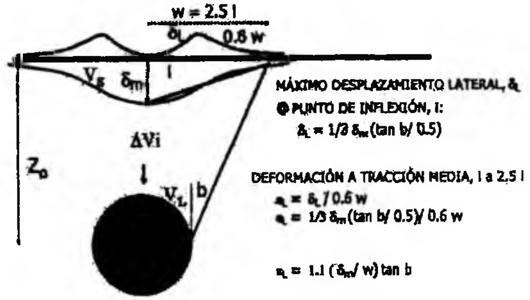


Fig. 3. Estimation of surface lateral movement over a tunnel

As the tunnel is advanced, a "settlement wave" moves ahead of the tunnel face, and for that reason the structures located over the tunnel are subjected to a lengthwise settlement, governed by a "b" angle at the face and showing a slope which depends upon the ground loss distribution along the shield length, but showing, usually, a maximum value approximately equal to the average slope (dm/w) of the settlement distribution at the cross-section. Considering, then, a building located towards the middle point of the settlement trough, where the lateral strains are in compression and the vertical movement corresponds to a settlement (concave settlement), the lengthwise settlement profile, produced by the excavation progress of the tunnel, sill create a "mobile zone" of lateral extension an hogging (convex settlement) below the structure.

Movements in the long range

The long range volume change (consolidation) of a clayey ground around the tunnel is effected by three processes:

1) The disturbance of the clayey material around the tunnel bore;

2) The stress changes occurring around the shield and behind the lining;

3) The drainage towards the tunnel.

In 1939-1941, a tunnel in Chicago in soft to very soft clay, extruded through vents in the shield, caused, through disturbance of the clay, 10cm of lateral displacement, followed by even larger settlements (Terzaghi, 1942a, 1942b).

In 1992, the shield boring of tunnels in Chicago clay caused movements mainly due to the drainage of the ground towards the steel ribs and wooden lagging primary lining. Although the disturbance of the clay only reached a few centimetres around the tunnel, the consolidation process of the medium to low consistent clay reached, laterally, about twice the tunnel diameter from the tunnel axis, as reported by Kawamura and Cording (1999).

Settlements were measured, in the short and the long range, at two sections of a tunnel bored in Chicago in 2000, at a depth of 21m. Around the shield, the behaviour of the clay was essentially undrained, and the volume change during the shield progress and lining installations was very low or almost non-existent. As a result, the volume of surface settlement was almost coincident with the volume of ground loss around the tunnel.

The consolidation settlements caused by drainage towards the tunnel were reduced by using an impervious membrane installed behind the lining, at a rate of 8 to 3 minute lag, every 1.2m of bore progress.

In Table 1, the short and long term settlements (with or without membrane) are shown (Srisirirojanakorin, 2004), along with the degree of short term pore pressure development initially measured.

New criteria to evaluate the relationship between deformations and damages in buildings

It is important to recall (as shown in Fig. 4) the relationship of the damage degrees in buildings with the angular distortion, â, and lateral deformation, $â_L$ established in Fig. 5, as given by Cording (2008). It can be seen that the combination of angular distortion, â, and lateral deformation, $â_L$ controls the degree of damage of buildings. As a matter of fact, a value of $â = 10^{-3}$ may correspond to almost non-existent fissures (as it is accepted), but

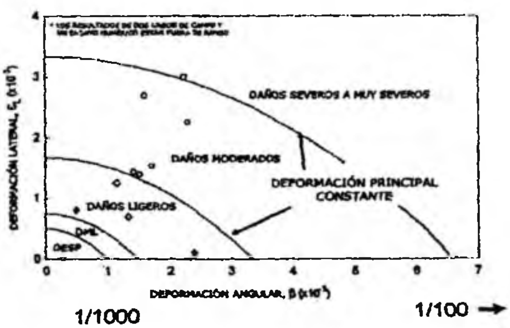


Fig. 4. Degree of damage as a function of angular distorsion and lateral deformation in building

Table 1: Comparison of short and long term, surface settlements in Chicago clays, with or without impervious membrane behind the lining for tunnels in Chicago

Section nº	Volume loss, Vl (on m/m)	Surface settlement volume Vs (on m/m) (short range)	Additional surface settlement volume Vs (on m/m) (long range)	Impervious membrane	Initial degree of pore pressure development
1	0,45	0,58	0,28	Yes	Lower
2	0,44	0,66	0,43	No	
3	0,47	0,61	0,83	No	Higher
4	0,40	0,58	0,40	Yes	

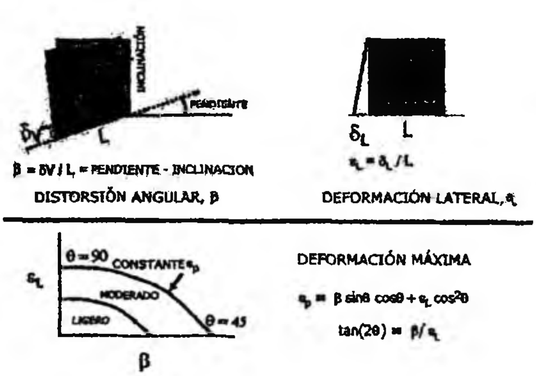


Fig. 5 Deformation conditions at a building section

if the building is affected, at the same time, by lateral deformation, the latter may induce damages of increasing severity in the structure.

Some problems reported in the use of jet-grouting in advance of tunnel excavation and in using pile walls or jet-grouting barriers to protect buildings in the vicinity of urban tunnels

Croce et al. (2004) reported different types of failure mechanisms observed at Les Cretes tunnel in the Northwestern Italian Alps. The longitudinal profile and cross section of the tunnel are shown in Fig. 6. The tunnel was excavated through a soil deposit of glacial origin (moraine), mainly composed of dense sandy gravels and silty sands with erratic rock boulders. The top section of the tunnel was excavated along the entire tunnel length and the bottom was then dug in a subsequent phase. Most of the soil strata were quite pervious, and the water level was highly variable due to sharp seasonal climatic changes.

The jet-grouting treatments were performed by the single fluid system, and some of the jet columns were reinforced by steel tubes (Croce et al., 2004). Provisional lining was provided by steel ribs (IPN 180) placed at one metre span, plus a 20 cm thick fibre-reinforced shotcrete layer.

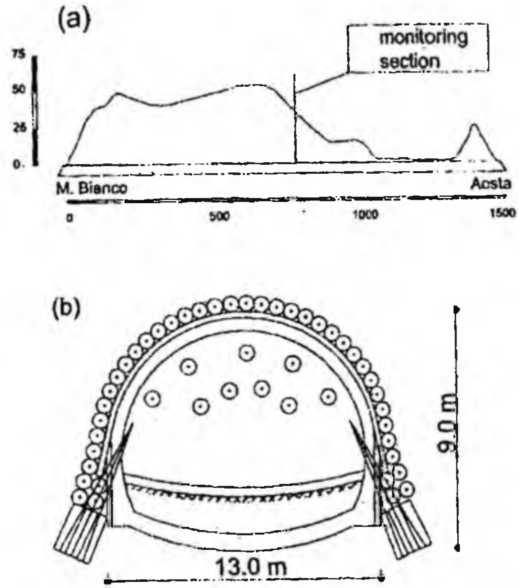


Fig. 6. Longitudinal profile (a) and cross section (b) of Les Cretes tunnel.

The most critical stage was the excavation of the top section, where some unexpected failures occurred at different locations. All failures developed abruptly and caused a large amount of soil to flow into the tunnel. In particular, for each failure, a sinkhole was progressively generated, starting from the tunnel and rapidly developing towards the ground surface.

The observed failure mechanisms could be classified according to three different modes, shown in Fig. 7. Mode (a) (Fig. 7) depicts the soil collapse at the excavation face and did not involve the canopy or the provisional lining; weak layers of soil at the face, not previously improved and possibly affected by piping, may be responsible for the damage. Mode (b) involved the collapse of the canopy tip possibly due to defects of the jet canopy. Mode (c), observed at the tunnel crown, may

Fig. 7 Typical failure mechanism observed on Les Crestes tunnel (Croce et al., 2004)

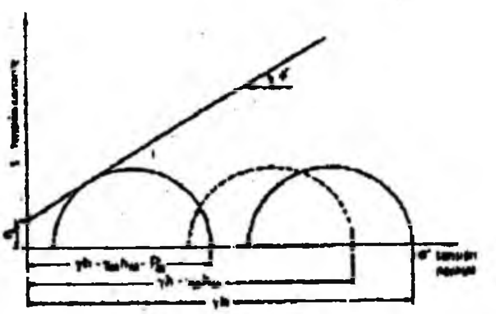
be attributed to local defects of the provisional lining, including the jet canopy, the steel ribs, and the shotcrete layer.

Gens (2008) has reported a behaviour, not always satisfactory, in the use of one-row pile walls or jet grouting barriers to protect buildings existing alongside of urban tunnels in Barcelona. If account is taken of the influence of lateral deformations ($å_L$) in building damages (Fig. 4, Cording et al., 2008), it may be concluded that those barriers may lack enough lateral inertia to effectively protect the buildings.

Some hints on the use of sleeve-pipe grouting for ground improve-ment around tunnels

The sleeve-pipe grouting technique

Santos et al. (2000) have presented the basic concepts, and the progress and possibilities of application and control of using hydraulic fracture grouting of soils through sleeve-pipes, by means of stable cement-water mixes, to obtain predetermined improvements of existing ground, compatible with movements on the order of only a few millimetres in the surrounding constructions.



$$\frac{\sigma_1'+\sigma_3'}{2}\sin\phi' = \frac{\sigma_1'-\sigma_3'}{2} - c\cos\phi'$$

$$p = p_0 + \gamma_w' h_w$$

$$\frac{p}{\gamma h} = 1 + \frac{c'}{\gamma h}\cot\phi'$$

Fig. 8. Relationship between grouting pressure and strength parameters of grouted soil (salos et al 2000)

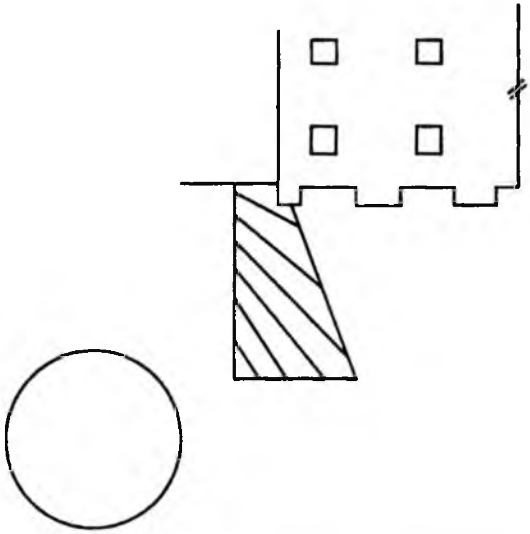


Fig. 9. Sleeve-pipe grouting for building protection of alonguide tunnel excavation (automatic section)

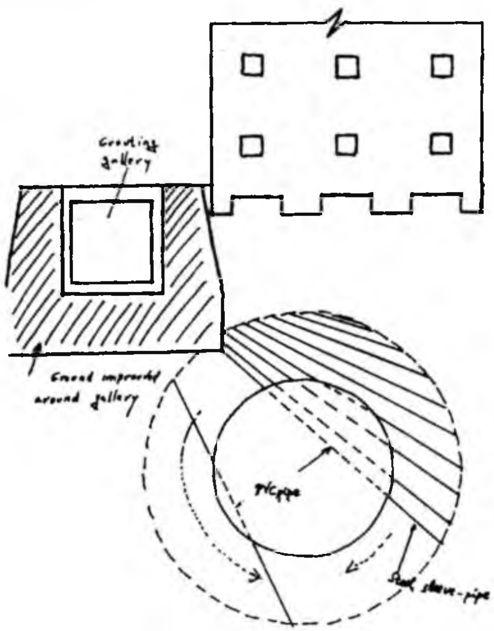


Fig. 10. "Primary lining "of tunnel" by means of ground treated ahead of tunnel excavation (schematic section)

Fig. 8 shows the relationship, that can be established, between the shear strength parameters 'c' and 'ø' of the improved soil surrounding a grouting sleeve (at a maximum distance from the sleeve of some 0.75-1m), and the final grouting pressure p at the end of the grouting of that sleeve.

Santos and Cuéllar (2000) reported the mechanical improvement of argillaceous marl, through cement-based reinforced grouting. Through loading tests on two footings (2mx2m), built at a depth of 1.5m, on treated and untreated marl, it could be established that on untreated marl, the footing showed a settlement of 4.5cm under a unit load of 20 kg/cm² whereas on treated marl, the settlement was of only 3.5mm for the same unit load of 20 kg/cm². In the loading-unloading cycles performed during the tests, most of the untreated marl settlements (75-80%) were permanent, whereas, for the treated marl only 1mm settlement at 20 kg/cm² was permanent.

The use of the MPSP (multiple packers sleeve-pipe) system allows the grouting of fissured rocks through sleeve-pipes. In this case the grouting may proceed by descending steps (the best process in fissured rocks) without any recourse to drilling after each grouting step. Three fundamental characteristics must be distinguished in the sleeve-pipe grouting of ground.

a) The volume of ground to be improved may be geometrically defined and determined beforehand, even when it is to be located under an existing construction.

b) The set of grouting pipes is also defined beforehand, in such a way as to "cover" the volume to be treated, taking into account the spacing of tubes (1-2 m) so that the volume of ground improved around a sleeve properly intercepts the volumes of ground improved around the neighbouring sleeves.

c) Once the sleeve-pipes are installed (a flexible process, since the geometry of the pipes may vary, provided the volume of ground to be treated is properly "covered") the grouting may proceed, with close control of movements all-around, and repeating at each sleeve the number of passes which are necessary to reach the final grouting pressure fixed, beforehand, for that sleeve.

It can be seen, from the description of the method accounted for so far, that a great difference exist, between the jet-grouting technique ("one shot grouting" per boring) and the sleeve-pipe grouting technique, where the number of passes at each sleeve depends upon the nature and condition of the ground surrounding the sleeve.

Improvement of ground around the tunnel to be excavated

The extensive development of large urban tunnels construction in the city of Madrid, both for subway lines and for highway itineraries, during the last decade needed to resort to a peculiar use of sleeve-pipe grouting, different from the improvement technique mentioned so far; the so-called "compensation grouting". This is, in fact, a quite expensive expedient to get across the settlements induced in buildings by underground excavations, through introducing horizontal inclusions of cement-bentonite mix below the construction affected buidlings by means of two "layers" of sleeve-pipes extended to the complete horizontal projection of the building. It is always necessary to build, at least, two large deep wells, external to the building, to allow the drilling equipment to reach the necessary depth of pipe installation. Later on, the settlement volume is compensated by forcing in the ground an equal "heave" volume. Since, as it has been mentioned, delayed settlements are to be expected in clayey ground, the "heave" volume is forced, sometimes, to even twice the settlement volume.

The technique of ground improvement by grouting through sleeve-pipes, as it has been established in 5.1 can solve the problem at a less cost than compensation grouting and without resort to short-term movements of the building structure of different sign, that may be detrimental depending upon the characteristics and condition of that structure. Two different situations will be considered.

a) Ground improvement to protect a building located outside the tunnel horizontal projection, but in its vicinity

Fig. 9 schematically depicts this situation. As it may be seen, by use of sleeve-pipes distributed in fan-like groups, and taking advantage of the possibility of pre-establishing the adequate volume of ground to be treated, "counterforts" of improved ground may be developed adjacent to the different frames that build up the structure of the building. This will abruptly limit both vertical and horizontal movements of the building due to tunnel construction since, as it has been established, both the mechanical properties of the treated ground and the inertia of the treated masses can be decided beforehand. In addition, the grouting control may insure that the ground improvement is reached while keeping differential movements of the building less than $^1/_{2000}$ to $^1/_{1000}$.

b) Ground improvement to build up a "primary lining" around the tunnel, ahead of its construction below a building

Fig. 10 shows this situation schematically. Only shallow galleries are needed to be able to reach the tunnel cross-section location. Ground improvement can be used, if necessary, to excavate the galleries without any problem of instability, or of adequately effecting water control below the water-table.

As it is shown in the Figure, an adequate "primary lining" may be executed in advance to tunnel construction. The sleeve pipes act as steel bolts within the grouted ground, achieving a supplementary "soil nailing". Within the future tunnel excavation p.v.c. or glass-fiber closed pipes may be used to evitate further problems of excavation in the presence of steel pipes or grouted ground.

Conclusions

Although tunnel construction has been considerably enhanced by the progress achieved in TBM technology, changes in stresses and ground losses inevitably produce detrimental movements in neighbouring constructions. In clayey grounds, time effects occur due to pore pressure changes around the shield and behind the lining, fostered by drainage towards the tunnel.

It is important to take into account the relationship of the damage degrees in buildings with the combination of angular distortion and lateral deformation of the structure. On this basis, the inertia of the elements provided for construction protection around tunnels is of paramount importance.

The technique of ground improvement (both soil and rock) through sleeve-pipe grouting (reinforced grouting), making use of controlled hydraulic fracture of the treated materials, may allow to build up either "primary linings" of improved ground around tunnels, ahead of the construction of their sections below buildings, or protective barriers of adequate inertia in the vicinity of neighbouring constructions.

This course of action would make unnecessary the recourse to the expensive, and not always properly justified, compensation grouting.

References

Kawamura, N. and Cording, E. J. (1999): "Long-term behaviour of tunnels in Chicago clay", Proceedings, 3rd National Conference of the Geo-Institute, Geo-engineering for Underground Facilities, Univ. of Illinois, Geotechical Special Publication nº 90, June, pp. 866-878.

Cording, E. J. (2008): Chapter 4 in "Ingeo/túneles, libro 14, Ed. Carlos López Jimeno, E.T.S.I. Minas, Universidad Politécnica de Madrid" (in Spanish).

Croce, P. Modoni, G, and Russo, G. (2004): "Jet-Grouting Performance in Tunneling", A.S.C.E. Geotechinical Special Publication, nº 124, January, pp. 910-922.

Santos, A. and Cuéllar, V. (2000): "Mechanical Improvement of fan Argillaceous Marl through Cement - based Reinforced Grouting". Proceedings of the 4th

International Conference on Ground Improvement and Geosystems, Helsinki, June 7-9.

Santos, A., Martínez, J. M., García, J. L., and Garrido, C. (2000): "Geotecnia en el año 2000", Ministerio de Fomento, CEDEX, y Sociedad Española de Mecánica del Suelo e Ingeniería Geotécnica, pp. 217-223 (in Spanish).

Sola, P. (2003): "Inyecciones de desplazamientos y compensación en Curso sobre Técnicas Generales de Refuerzo y Mejora del Terreno", CEDEX, Madrid, pp. 1-30 (in Spanish).

Srisirirojanakorin, T. (2004): Personal Communications to Prof. Cording.

Terzaghi, K. (1942 a), "Liner Plate Tunnels on the Chicago subway", A.S.C.E., Proceedings, V. 68, Nº. 6.

Terzaghi, K. (1942b): "Shield Tunnels of the Chicago subway", Journal of the Boston Society of Civil Engineers, V. 29, Nº. 3, July.