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Ground movements caused by TBM tunnelling in the Athens Metro Project

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ABSTRACT: The construction of the Athens Metro has provided extensive experience on soft ground tunnelling in urban environment. The paper reviews the geological and geotechnical conditions (Athens schist formation), the TBM tunnelling practices, the technical complications (mainly due to TBM over-excavations) and the methods used to resolve the construction problems (ground pre-treatment with jet grouting). Measured surface settlements along the treated and untreated zones are presented, compared and evaluated.

1 INTRODUCTION

The Athens Metro project, an important underground project, at present in the final stages of construction, has provided extensive experience on soft ground tunnelling in urban environment. The project consists of two lines (total length 18 km), 21 stations, 29 ventilation shafts and various miscellaneous structures.

Four types of construction methods were used:

i. Two identical TBMs have bored about 11 km of the twin-track, 9.5m diameter, running tunnels, located at a depth of 15-20m below street level (measured at the tunnel crown).
ii. A roadheader open-face shield, commissioned towards the end of tunnelling works, has completed the construction of 0.7 km of running tunnel (March 1999).
iii. Five station caverns, auxiliary tunnels and short galleries were excavated in multiple stages and supported using Sprayed Concrete Liners (SCL).
iv. Fourteen stations, 3.3 km of running tunnels and all vertical shafts were constructed by cut-and-cover methods with struts and/or prestressed anchors used to support the walls of the excavations.

Of particular importance to the progress of the tunnelling operations and the technical complications of the project was the need to sufficiently control roof collapses, large uncontrollable over-excavations (over-breaks), excessive ground settlements and occasionally damage to the structures at ground surface. Such events, in conjunction with the difficult and highly heterogeneous ground conditions have delayed the scheduled completion of the works, required significant modifications in the construction procedures, including equipment changes and the use of various ground improvement methods.

This paper reviews the main geological and geotechnical conditions of the Athens Metro project and presents the adopted TBM tunnelling methods and the associated problems. Finally, the ground improvement methods (jet grouting) are described and their effectiveness in controlling surface settlements and over-excavations (over-break failures) is evaluated.

2 GROUND / GROUNDWATER CONDITIONS

Tunneling for the Athens Metro is performed mostly in the "Athenian schist" a term used to describe an Upper Cretaceous geological formation comprising a variety of low-level metamorphic and sedimentary (non-metamorphic) weak rocks (Sabatakakis, 1991). The Athenian schist is a thick sequence of flysch-type sediments, comprising thinly bedded clayey and calcareous sandstones, alternating with siltstones (greywackes), phyllites, meta-sedimentary shales and, occasionally, with limestones and marls.

The Athenian schist formations were subjected to intense folding, thrusting and extensive faulting, which caused extensional fracturing and widespread weathering and alteration of the deposits. The extent to which the flysch formations responded to the tectonic stresses varied according to their stiffness: clay shales, being more ductile, were intensely folded and developed some schistocity while more brittle rocks like sandstones and limestones were badly sheared and faulted. As a result of the

extensive weathering and tectonism, the Athenian schist is often entailed a clearly visible chaotic structure of isolated blocks of hard rock 'floating' within a soft clayey matrix (Marinos et al. 1997). Furthermore, in many locations the material is completely decomposed and can no longer be characterised as rock but has the mechanical characteristics of an engineering soil, usually with poor cohesion (due to the coarse-grained constituents of the material).

The geotechnical investigation campaigns for the project included large number (600) of boreholes, drilled to depths of 25-35m. It must be noted that despite the recent use of large diameter samplers, it was proved difficult to retrieve representative undisturbed samples of the weak, weathered flysch deposits which are more interesting from the engineering point of view, since they control the mechanical behaviour of the formation. Performed in-situ tests were also influenced by the highly heterogeneous ground characteristics. Menard-type pressuremeter tests and dilatometer tests often failed to provide reliable data (due to poor contact of the probe with the borehole, wall collapses, etc). Furthermore, those tests considered reliable provided erratic modulus profiles, showing very poor correlation with depth, among neighbouring boreholes or between the horizons of the schist.

Systematic measurements of the groundwater table were performed in most boreholes and were used to establish the groundwater regime and its temporal variation. It was concluded that the average (large-scale) permeability of the Athenian schist is very low, due to the prevailing effects of the clayey shales and the results of the intense tectonic activity, which precludes the continuity of the coarse-grained intercalation. Nevertheless, the following exceptions are worth mentioning:

a) Concentrated seepage occurs along more permeable paths, such as highly fractured sandstones or limestones and intensely tectonised zones.
b) Low capacity perched aquifers exist along the interfaces between the more weathered layers and less weathered zones.

Due to the already described difficulties and limitations in undisturbed sampling, the engineering properties of the Athenian schist were mostly assessed on the basis of the so-called Material Rating (MR) classification system (Kavvadas et al. 1996), which is a variance of Bieniawski's 1979 RMR. In rating borehole samples, the MR system makes no use of the adjustment for the discontinuity sets orientation and adopts the value "10" for groundwater conditions (which corresponds to "damp" conditions). The reasoning for these choices is that: (i) in the heavily broken schist, there is very little effect of specific discontinuity orientations at the scale of the tunnel size and (ii) the groundwater conditions cannot be estimated from the borehole cores and additionally their effects are not very important on tunnelling in this type of ground. The MR values measured on the face of the excavations are usually similar to those obtained from rating borehole cores, because the effects of sample disturbance in the boreholes samples were mostly offset by the usually more adverse groundwater conditions encountered during tunnelling.

Despite the widespread scepticism about the applicability of empirical rock-mass classifications in tunnelling through weathered weak rocks, the MR index has proved a very useful tool from the early stages of this specific project. The final outcome of its extensive use in the design and construction phases of the Athens metro was the building up of databases which relate ranges of MR values with geotechnical parameter sets, excavation procedures, support measures, ground improvement techniques and prediction methodologies of the over-break types and risk. Nevertheless, these databases must be considered as tentative and cannot be directly applied to different ground conditions in the absence of the local experience.

3 PROBLEMS DURING TBM TUNNELLING

Two identical TBM machines were used for the excavation of the running tunnels (one for each line). Each machine featured an eight-spoke cutterhead fitted with drag bits, disk cutters and very large muck openings (corresponding to about 30% of the total face) radiating from the centre to the periphery. The cutterhead configuration provided a large flow area in order to accommodate relatively large blocks of competent rock without blocking the machine. In this particular case, however, the machine is designed for open (atmospheric) and not pressurised operation under the protection of a 7.5m long double telescopic shield.

A 350mm thick reinforced concrete eight-piece segmental lining was erected under the protection of the tail-skin of the shield to provide a twin-track tunnel with an internal finished diameter of 8.5 m.

The TBMs were designed to deal with the various facets of the Athens schist formation ranging between relatively sound limestone and hard sandstone up to crushed, practically cohesionless soft rocks and completely weathered black shale (behaving as a cohesive soil). Under normal TBM operations, the ground at the excavated face was stable and excavation was limited to the material dislodged by the cutting action of the cutterhead. In unstable situations (mainly when the ground was characterised by poor cohesion), there was generally no need to actually break or cut the material, as it flowed by gravity into the muck removal openings of the cutterhead, especially around the crown. That

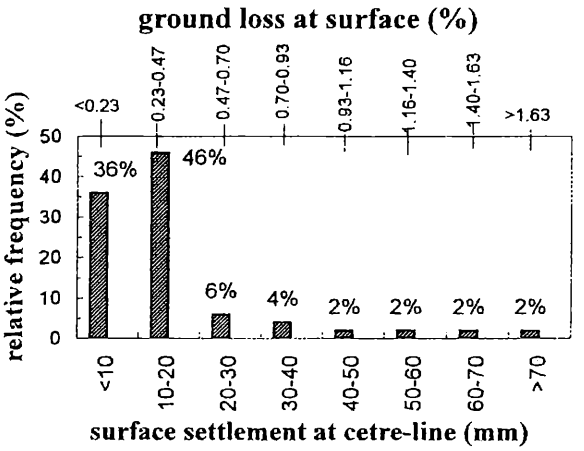

Figure 1. Frequency distribution of the measured maximum surface settlements and ground losses at surface level. No ground pre-treatment (Kavvadas et al. 1996).

material flow continued until natural arching stabilised the ground above the cutterhead, thus resulting to the development of a cavity (called over-excavation or over-break) above the tunnel crown.

When over-breaks did not occur, ground surface settlements were relatively low. Figure 1 shows the frequency distribution of the recorded ground surface settlements above the centreline of the section Larissa - Deligianni of Line 2 TBM tunnel (average MR values are 25–30, without ground pre-treatment). About 80% of the measured settlements were less than 20 mm, corresponding to a ground loss factor less than 0.5%.

Figure 2 presents the surface settlement measurements (normalised with the corresponding maximum surface settlement s_{max} at the tunnel axis) obtained from various monitoring points in the aforesaid section of Line 2 TBM tunnel, as well as the best fitted mathematical curve:

$$s = s_{max} \exp(-x^2/2i^2) \quad (1)$$

In June 1995, the progress of the Line 2 TBM was delayed by about one year due to excessive over-breaks, occasional tunnel roof collapses and finally a major tunnel face instability of chimney type.

These failure incidents, combined to the existing adverse geotechnical conditions (average MR values ranged between 16 – 21) required ground treatment along a 190m field in Agiou Konstaninou street. The type of treatment included successive arrays of jet grouting columns and bored piles constructed from the surface (Fig. 3).

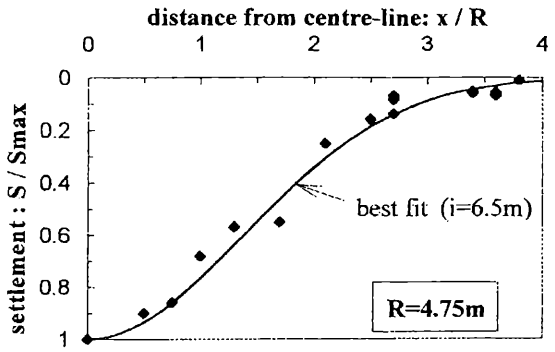

Figure 2: Normalised shape of the surface settlement trough. No ground pre-treatment (after Kavvadas et al. 1996).

4 PRE-TREATMENT BY JET GROUTING

The construction of jet grouting columns aimed at the treatment of the soft, crushed and/or weathered ground, by forming a relatively stiff arch of grouted soil, about 3.0m thick, above the top heading of the tunnel. In this arch, the grout to soil fraction should be 25% to 40%.

The decision about the applicability of jet grouting techniques in the existing ground conditions was made after evaluating the results of performed full-scale trial tests. Double (water cut) jet grouting method, with and without water pre-cutting, was applied, at depths of 9.0m to 12.0m. Moreover, two water pre-cutting techniques were employed: (i) water pre-cutting during drilling, and (ii) water pre-cutting from bottom to top with constant lift rate.

The effectiveness of the applied jetting techniques in the existing highly weathered ground conditions of the area of Aghiou Konstantinou street (MR values < 21) had been evaluated by relating the specific jet grouting energy, E_s, with the finally achieved grouted piles diameter, D. Table 1 summarizes the adopted jetting parameters of some of the trial tests, as well as the achieved diameters of the grouted columns.

The main conclusions from these tests are:

i. The diameter of the constructed grouted columns varied between 60 to 75cm.
ii. The use of water pre-cutting generally produced larger grouted columns, but 25% to 30% more time was needed for the completion of the corresponding tests.
iii. By fixing the specific jet grouting energy of double jet grouting system (water cut) without water pre-cutting at 35MJ/m - 40MJ/m, grouted piles with minimum diameter of 60cm can be produced.

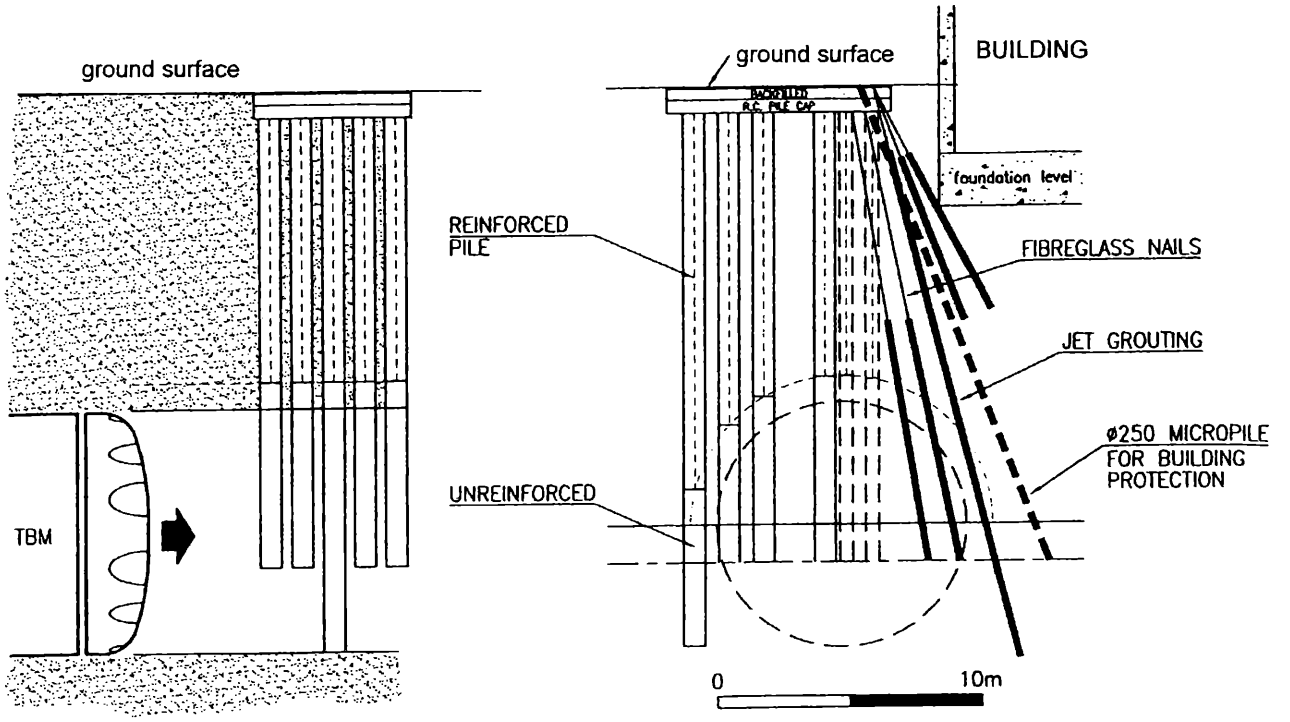

Figure 3. Sections of ground pre-treatment by jet grouted columns and concrete bored piles.

Table 1. Jet Grouting tests in Aghiou Konstantinou.

Name	WC2*	WC4*	JG4
Jetting depth (m)	8.9-12	8.9-12	10 –11.5
Water to grout nozzle (m)	0.75	0.75	0.75
Diam. of water nozzle (mm)	4.0	2.8	2.8
Diam. of grout nozzle (mm)	4.5	4.5	4.5
Lift rate (min/m)	6.2	6.0	6.0
Rotation (rot/min)	10-12	10-12	10-12
Grout flow (l/min)	85	90	90
Grout pressure (bar)	76-88	70-80	80-90
Grout density (KN/m^3)	16-16.5	16-16.5	16.8
Water flow (l/min)	208	100	105
Water pressure (bar)	500	500	500
W/C	0.65	0.65	0.6
Specific Energy E_s (MJ/m)	~69	~36	~34
Average column diam. (m)	~0.70	~0.75	~0.60

*Pre-cutting: bottom to top, pre-cutting water pressure: 300 bars, pre-cutting lift rate: 4min/m.

5 EFFECTIVENESS OF JET GROUTING

The existing ground conditions along Aghiou Konstantinou street – immediately after the exit of Delgianni station towards Omonia station - before the application of the previously described pre-treatment program (Fig. 3) can be described as follows:

i. The overburden layer with thickness between 2m to 6m consists mainly of alluvial deposits and backfill materials of brownish sandy silty clay with fragments of limestone and siltstone.
ii. The first layer of the substratum, with thickness between 4m to 8m approximately, consists of greenish - greyish fractured metamorphic siltstone / sandstone with medium to high degree of weathering.
iii. The second layer of substratum consists of greyish - black slightly weathered metamorphic siltstone / sandstone.

Layers (ii) and (iii) of the bedrock are intensely fractured locally microfolded, with polished planar smooth surfaces of schistosity and slickensides.

Based on the visual examination of core samples the average MR values, above the tunnel's crown, ranged between 16 and 21. Additionally, there was only a small tendency of the MR values to increase with depth, indicating thus that the "deleterious" effects of weathering and tectonism extend over the whole area of interest. Figure 4 shows the distribution of the existing average MR values (above the tunnel's crown) along the part of Aghiou Konstantinou street, which had to be pre-treated.

After the completion of the ground pre-treatment program, the TBM restarted its operations and achieved an average advance rate of approximately 12m/day, with a maximum of 28m on a single day The effect of ground pre-treatment on controlling the occurrence of over-breaks was obvious, since such failure incidents were not observed in the pre-treated zones, while they were quite often in any areas left untreated.

The ground settlements in the pre-treated zones were generally small. More specifically, in area A,

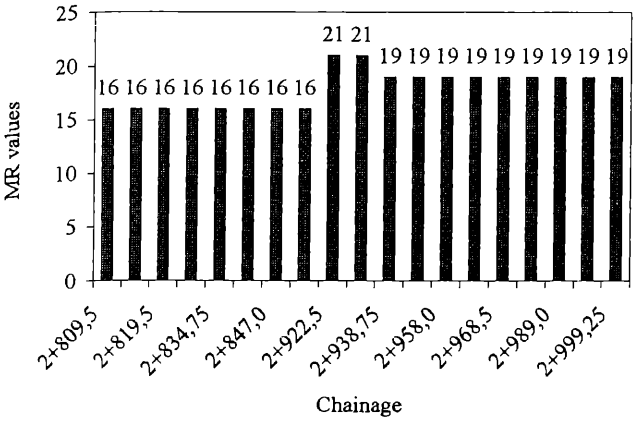

Figure 4. Distribution of MR values along Agiou Konstantinou street.

where jet grouted columns with a soil replacement ratio of 40% were constructed, the maximum measured surface settlement at the tunnel axis did not exceed 11.2mm, while in 84% of the cases, the relative ground loss at the surface was smaller than 0.30%. When compared with the ground loss values in un-treated zones having similar depths of tunnelling (Fig. 1), ground pre-treatment reduced the maximum surface settlements by about 50% and the relative ground loss by about 35%. Consequently, the use of jet grouting improved drastically the strength and deformability properties of the soft ground in Area A.

Figure 5 presents the shape of the surface settlement trough obtained from measurement points offset with respect to the axis of Aghiou Konstantinou tunnel in area A by a distance (x), normalised with the tunnel radius R=4.75m. In this figure the settlements are normalised with the corresponding maximum surface settlement (s_{max}) at the tunnel axis, in order to obtain a unique shape curve. The figure also plots the gaussian settlement curve which gives the best fit of the measured values for i=8.0m, where (i) is the distance from the centreline to the inflection point of the trough curve. The increase of i from 6.5m (in the unimproved area, Fig. 2), to 8.0m (in the jet grouting area A), is directly related to the emerged differences in the reduction of ground settlements and ground loss caused by the use of jet grouting only, since the depth of excavations was unaltered.

In area B, where jet grouting produced grouting columns with a soil replacement ratio 25%, 83% of the measured settlements were less than 30mm corresponding to a ground loss factor less than 0.6%. It must be emphasised that the aforesaid values are very close to the corresponding ones of TBM Line 2 section, where ground pre-treatment was not used (Fig. 1). Consequently, the use of double jet grouting technique with soil replacement 25% created a geotechnical environment in area B which has

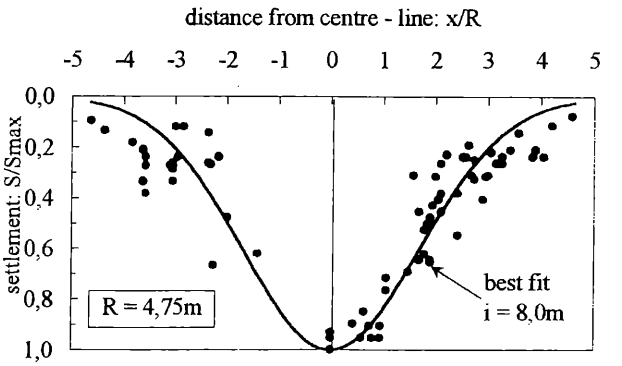

Figure 5. Normalised surface settlement trough in jet grouting area A (Ground replacement: 40%).

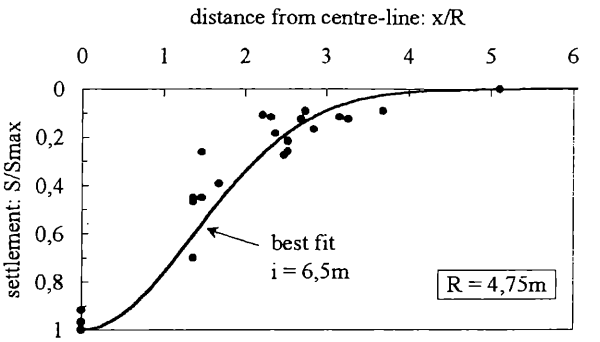

Figure 6. Normalized surface settlement trough in jet grouting area B (Ground replacement ratio: 25%).

similar overall strength and deformation properties with the untreated section of TBM Line 2, since in both areas the depth of tunnelling operations were almost the same.

Figure 6 presents the normalised shape of the surface settlement trough at jet grouting area B of Aghiou Konstantinou street

An overall picture of the distribution of the ground surface settlements at the tunnel axis and relative ground losses along the jet grouting zone (Areas A and B) is given in Figure 7. The appreciable increase of the settlements and the corresponding relative ground loss towards the end of the zone is attributed mainly to the decrease in the grout-to-soil replacement ratio from 40% to 25%.

6 CONCLUSIONS

Significant experience has been gained from the application of jet grouting techniques, aiming to control ground deformations caused by TBM tunneling in the soft ground environment of the Athens Metro project.

More specifically, the construction of grouted

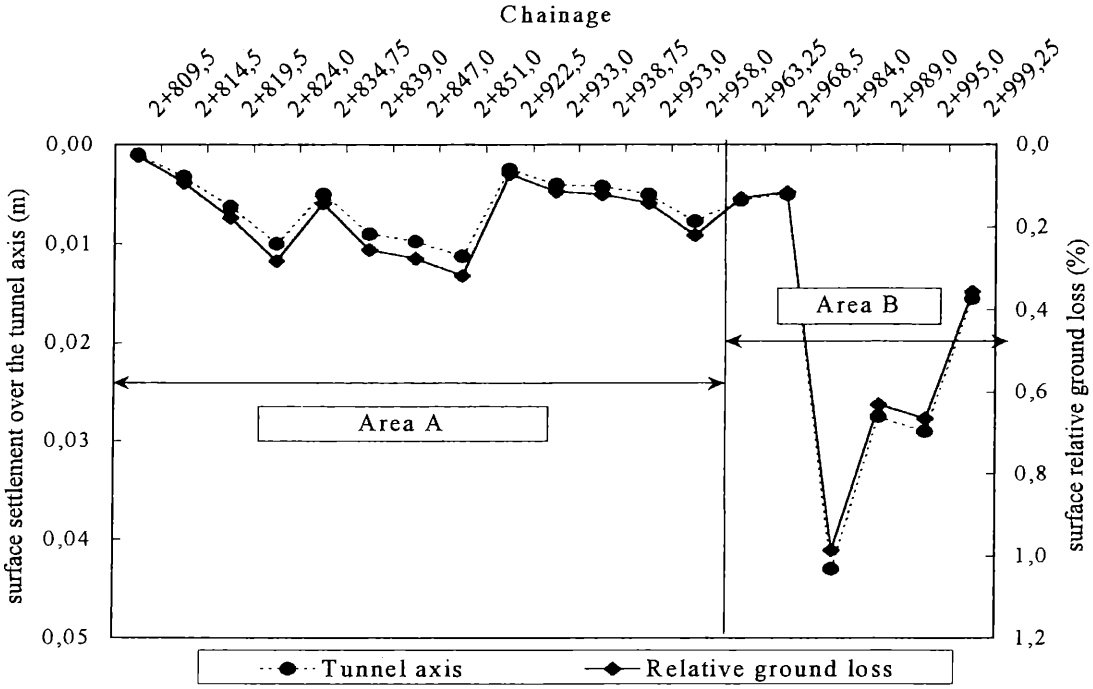

Figure 7. Surface settlement distribution and ground loss along TBM tunnel – Jet Grouting Areas A, B.

columns, 60cm in diameter, with the double (water-cut) jet grouting technique proved extremely efficient in improving the strength and deformability properties of soft, crushed and/or weathered ground. The finally adopted layout of grouted columns formed a relatively stiff arch of grouted soil, about 3.0m thick, above the top heading of the tunnel, where the grout to soil fraction varied between 25% and 40%.

The ground settlements in the pre-treated zones were generally small. More specifically, in areas where jet grouted columns with soil replacement ratio 40% were constructed, the maximum measured surface settlement at the tunnel axis did not exceed 11.2mm, while in 84% of the cases, the relative ground loss at the surface was smaller than 0.30%. Additionally, in areas, where the use of jet grouting produced grouting columns with soil replacement ratio 25%, 83% of the measured settlements were less than 30mm corresponding to a ground loss factor less than 0.6%. Finally, the occurrence of over-breaks; the major cause of delays in the Athens Metro project was sufficiently minimised.

7 REFERENCES

Kavvadas, M. et al. 1996. Experiences from the construction of the Athens Metro, *Proc. Intern. Symp. on the Geotechnical Aspects of Underground Construction in Soft Ground*, City University, London, April 1996.

Marinos, P. et al. 1997. Geological and environmental considerations for selecting an Athens Metro tunnel alignment beneath an important archaeological area. *Proc. IAEG Symposium on Engineering Geology and the Environment*, Balkema, Vol 3, 2777-2784.

Sabatakakis, N. 1991. *Engineering-geological investigation of the Athens Basin*. PhD thesis (in Greek), University of Patras.