TUNNELLING CONSTRUCTION CHALLENGES IN ATHENS METRO PROJECT

1. General

In the following paragraphs two tunnelling cases of Athens Metro [1], [2] are presented in detail. Both of them are considered that they have provided useful experiences for the successful applications of innovative tunnelling construction technologies in challenging weak rock conditions.

2. Microtunnelling application for Athens Metro

A microtunneling application was attempted for the construction needs of Monastiraki underground station complex of Athens Metro.

Monastiraki is a very densely populated area at the historical centre of Athens, downhill of Acropolis ancient monument.

The general dimensions of the station are: (a) length = 180m, (b) underground cavern diameter = 16.20m. The depth of the excavations from the ground surface was 18m approximately.

Except of the underground cavern, the complete realisation of the station complex included a number of excavations, related to an access shaft, a cross – over and the stairway galleries.

The geotechnical conditions in the area of Monastiraki station were evaluated as very adverse, where highly weathered graphitic and chloritic phyllites, alternating with meta-sedimentary shales, dominate. These geo - materials have usually a dark grey to green-grey color ("black Athenian schist") and are characterized by very low shear strength and deformability parameters.

The criticality of the situation became very obvious immediately after the completion of the excavations of the vertical access shaft, as the surface settlements exceeded 80mm, by creating a great deal of skepticism about the safe supporting methodology to be applied in the next construction stages.

The microtunnelling, aiming to the construction of 22 steel pipes of 1.2m diameter, along the outer periphery of the main cavern, was decided as the proper method, which could create the necessary stiff crown support, prior to the continuation of the underground excavations (Figure 1). The design of the microtunnelling was based on the application of sophisticated 3-D finite element software (Figure 2).

The whole application was successful and the scope of controlling the ground movements, during the excavations, to acceptable serviceability limits for the existing superstructures was finally achieved.

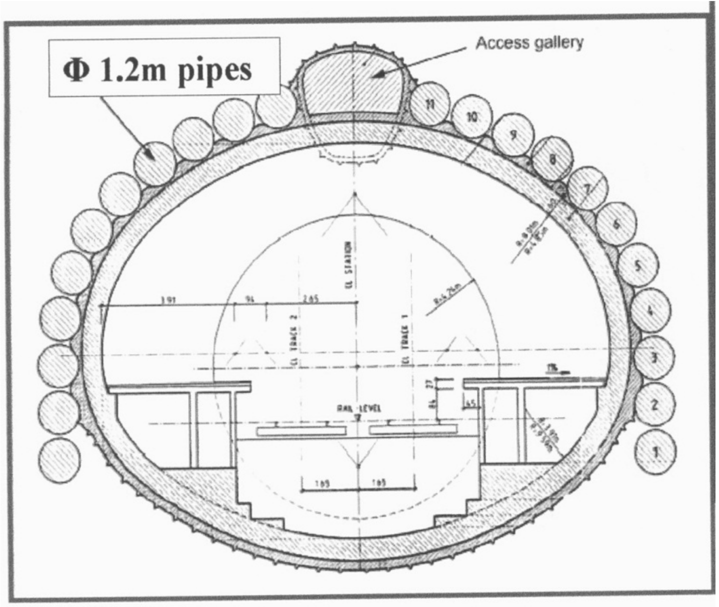

Figure 1. Microtunnelling application in Monastiraki, for the pre-support of the main station cavern.

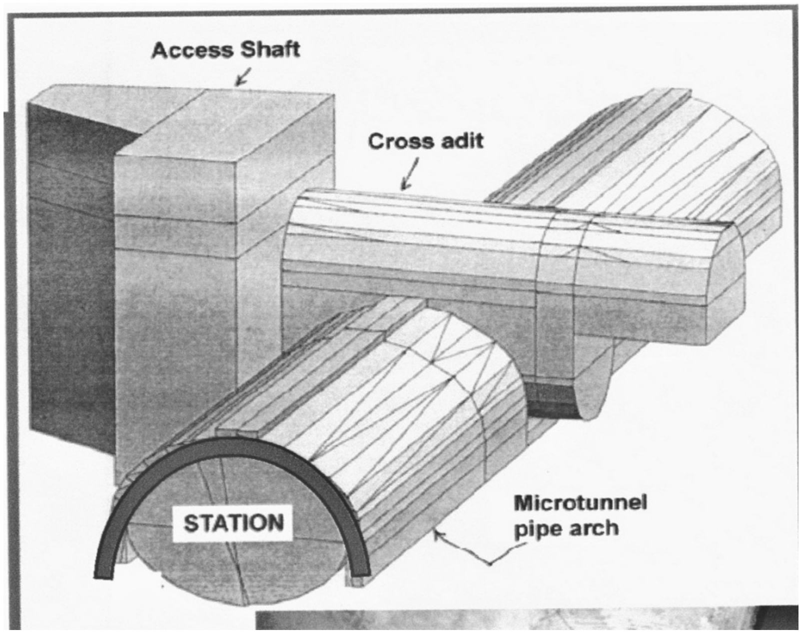

Figure 2. 3-D finite element model for the numerical simulation of the microtunnelling in Monastiraki.

3. *Jet grouting application in weak rock conditions for Athens Metro*

Jet grouting techniques were extensively applied in one location of the Athens Metro project with poor sub-ground conditions; the tunnel stretch along the alignment of Aghiou Konstantinou street in the historic centre of Athens. This case has been extensively presented by Mihalis et al [2]. At this particular site, TBM was operating with an extremely poor performance, resulting to an overall advance rate less than 2.0m/day. This was due to the occurring large, occasionally uncontrollable, over-break failures (Figure 3), which caused major delays, while freeing the TBM and grouting the cavities.

Figure 3. Significant over-break failure at Aghiou Konstantinou street. Athens Metro project.

The main reasons for the observed ravelling tendency of the ground strata, (above the TBM cutterhead), were attributed mainly to the insufficient cohesion, along the locally existing highly weathered and intensely tectonised zones, in conjunction with the large muck openings of the TBM cutter head, which could not control the muck-flow.

According to the findings of the performed geotechnical investigation, the existing ground conditions at Aghiou Konstantinou area are summarized as follows:

- The overburden layer, which varies between 2 and 6m in thickness, mainly consists of alluvial deposits and backfill materials of brownish sandy silty clay with fragments of limestone and siltstone.
- The first layer of the substratum, with thickness between 4 to 8m approximately, consists of greenish - greyish fractured weak metasiltstone with medium to high degree of weathering.
- The second layer of the substratum consists of greyish - black highly weathered, very weak phyllite and fractured very weak metasiltstone.

Figure 4 presents the results of Menard type pressuremeter tests, performed in the jet grouting area for the purposes of the ground investigation. According to Figure 4 there is a clear tendency of the Menard modulus E_M (in MPa) to increase with depth. The average values of the Menard modulus in the zone of influence above the tunnel crown is E_M=40MPa, while those at the tunnel's excavation limits are somewhat higher, with average value E_M=70MPa.

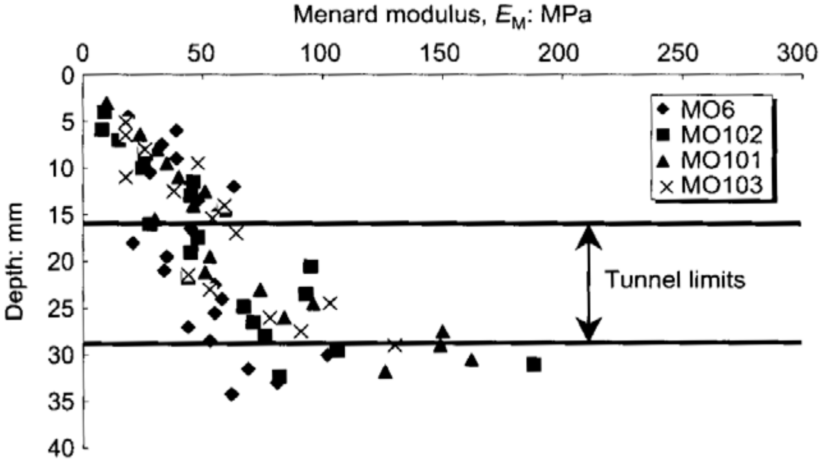

Figure 4. Athens Metro. Distributon of measured Menard moduli E_M with depth

Considering the fact that only minor alignment changes of the running tunnel could be implemented and future TBM tunnelling operations had to proceed for a length of 180m approximately, in close proximity and below buildings at very shallow depths (13m approximately), the implementation of certain ground improvement measures for the efficient control of the existing high risk of the over-break failure incidents was of crucial importance for the safety of the existing superstructures. Under these circumstances, the construction of a dense pattern (~ 1.10m x 2.0m) of jet grout columns, in producing a 3.0m thick, relatively stiff arch of grouted soil (with grout to soil fraction 25% - 40%), above the top heading of the tunnel (Figure 5), was considered as the most efficient solution for: (i) controlling the risk of the over - break failures, (ii) minimizing the ground losses at the surface and (iii) accelerating the TBM advance rates.

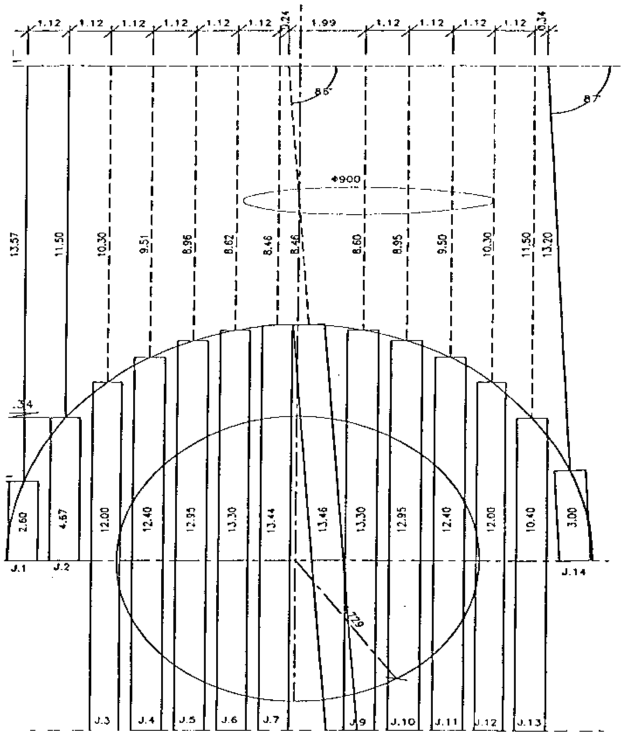

Figure 5. Athens Metro. Jet grouting application

The applicability of the various jet grouting techniques in the geotechnical conditions of the previously mentioned tunnel stretch was decided upon the evaluation of results from extended full-scale trial testing programs, including:

- Vertical and horizontal single jet grouting tests
- Vertical and horizontal double (water-cut) jet grouting tests with and without water pre-cutting,
- Vertical triple jet grouting tests with water pre-cutting.

The evaluation of the performed trial test results was made by correlating the applied specific jet grouting energy values E_s with the achieved grouted columns diameter D. It is explained that for a unit length of a column, the specific jet grouting energy E_s (MJ/m) depends mainly on the: (i) grout pressure P (MPa), (ii) grout flow rate Q (m^3/hr), and (iii) withdrawal speed V_t (m/hr) and is mathematically expressed by the equation (1):

$$E_s = {PQ}/{V_t} \tag{1}$$

The derived relationship between the achieved grouted columns diameter, D (cm) and the specific jet grouting energy, E_s (MJ/m) is remarkably fitted with the curve of Figure 6. This curve is mathematically expressed by equation (2) [2] :

$$E_s = 0.0101 \times D^{2.02} \tag{2}$$

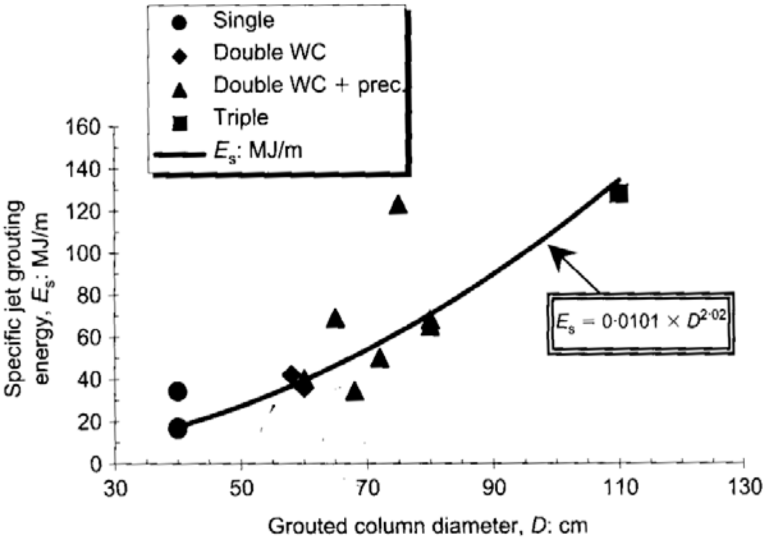

Figure 6. Athens Metro. Specific Jet grouting energy Es versus grouted column diameter D

According to Figure 6, the successful execution of the various jet grouting techniques can be related to the different ranges of the applied specific jet grouting energy, but always it is related to the encountered geotechnical conditions. More specifically, for the aforesaid weak rock conditions of the jet grouting application area of the Athens Metro project, the following conclusions can be safely drawn:

- Single jet grouting can be executed with specific energy levels between 17MJ/m - 30MJ/m. Grouted columns with diameter of 40cm approximately can be successfully achieved.
- The successful application of double jet grouting needs specific energy levels ranging between 40MJ/m to 80MJ/m. Especially, if the specific jet grouting energy of double jet grouting system (water-cut) without water pre-cutting is at 40MJ/m - 45MJ/m, grouted columns with diameter of 60cm can be successfully produced.
- Triple jet grouting can be executed with energy not in exceed of 130MJ/m approximately. In this type of jet grouting application, grouted columns with diameter of 100cm are expected to be finally achieved.

The finally adopted jet grouting system for the needs of ground pre-treatment program along the Aghiou Konstantinou TBM tunnel section was the one of the double water-cut system without water pre-cutting. It is noted, that this technique was proved that can produce faster and more economically grouted columns of satisfactory dimensions (approximate diameter D=0.6m).

After the completion of the ground pre-treatment program, TBM restarted its operations and achieved an average advance rate of approximately 12m/day, with a maximum of 28m in a single day. The effect of ground treatment on controlling the occurrence of over-breaks was obvious, since large scale failure incidents were eliminated.

A clear overall picture of the distribution of the maximum surface settlements and the relative ground losses along the aforesaid jet grouting zone is given in Figure 7 [3]. The maximum observed settlement did not exceed 43mm and the corresponding relative ground loss was equal to 1% approximately. The appreciable increase of the settlements and the corresponding amounts of relative ground loss, towards the end of the jet grouting pre-treated area, is attributed mainly to the decrease of the grout-to-soil replacement ratio from 40% to 25%.

Figures 8 and 9 present the evaluated shapes of the normalized surface settlement troughs obtained from measurement points offset with respect to the axis of Aghiou Konstantinou tunnel, in the areas where the grout – to – soil replacement ratio was 40% and 25% respectively. The decrease of the distance i from 8.0m (in the area with replacement ratio 40%) to 6.5m (in the area with replacement ratio of 25%)

could be directly related to the emerged reductions of relative ground losses (as these are shown in Figure 7), since the depth of TBM operations was unaltered. In addition, the application of the following approximate linear expression (3) between the best fit values i and the depth of the tunnel axis H for both pre-treated areas:

$$i = kH \qquad (3)$$

indicates k values equal to 0.37 (for soil replacement ratio 25%) and 0.45 (for soil replacement ratio 40%).

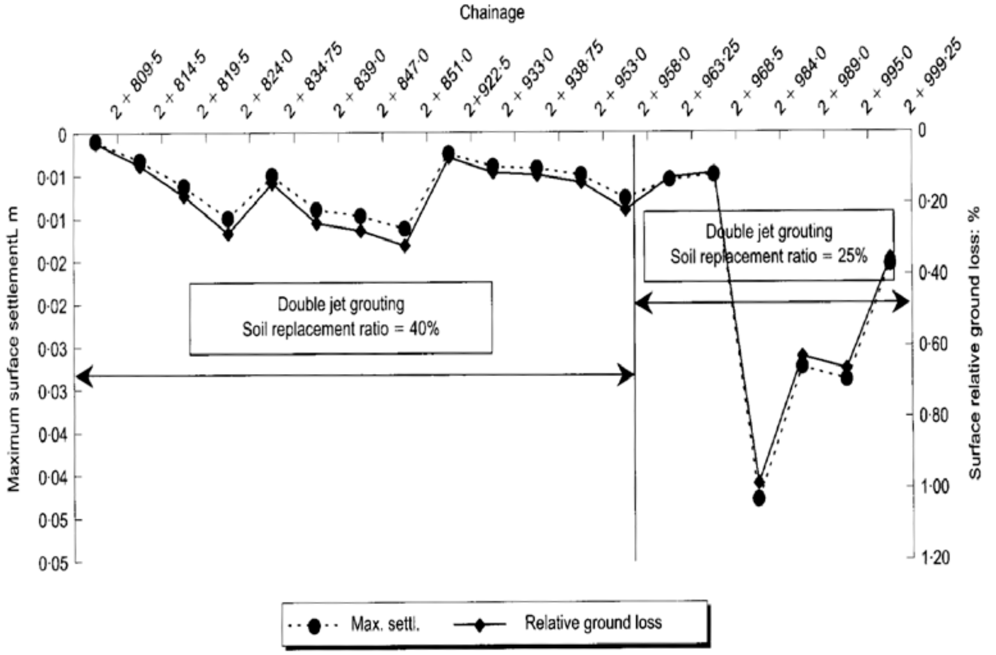

Figure 7. Surface settlement and ground loss distributions along jet grouting zone.

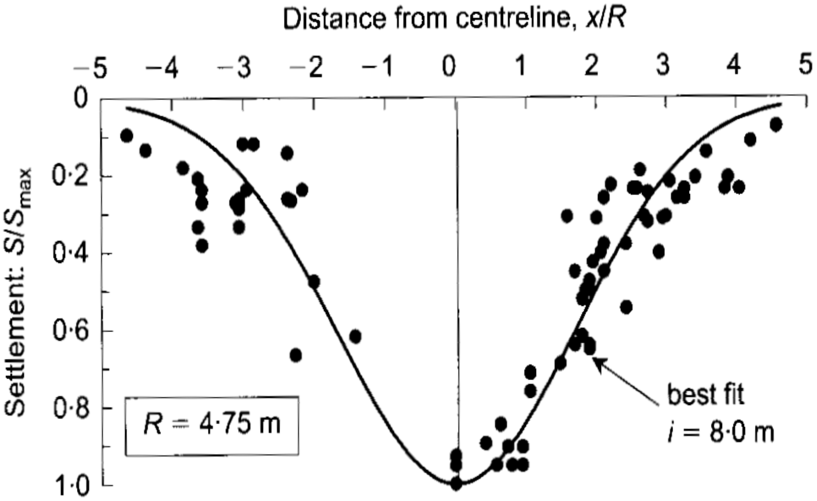

Figure 8. Normalized surface settlement trough in jet grouting

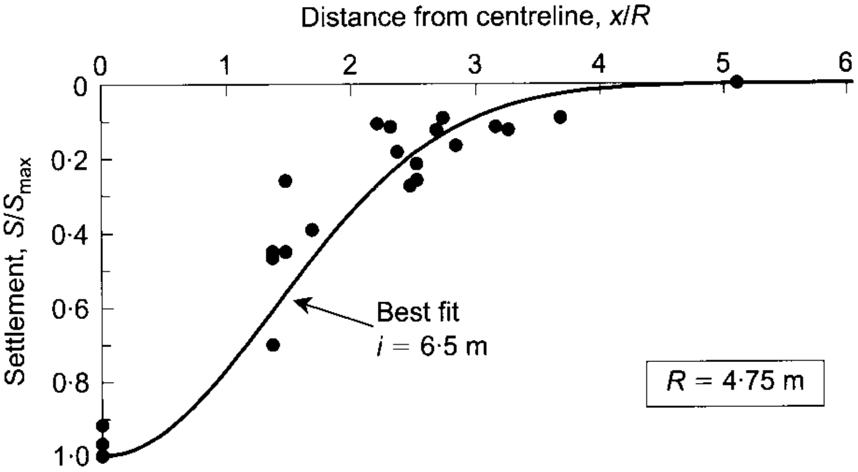

Figure 9. Normalized surface settlement trough in jet grouting area with ground improvement ration 25%.

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Ilias K. Michalis, is an internationally acclaimed tunnel expert, who has considerable experience working with tunnel projects across the world. (e.g. Athens Metro, railway tunnels, motorway tunnels and hydraulic tunnels). He currently works with Qatar Rail and is involved in their underground tunnel infrastructure. Michalis is one of the prominent speakers at the 3rd Annual Underground Infrastructure and Deep Foundations Qatar, where he will be providing insight on jet grouting applications in weak rock conditions.

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