Δελτίο της Ελληνικής Γεωλογικής Εταιρίας τομ. XXXII/4, 167-177, 1998
Πρακτικά 8ου Διεθνούς Συνεδρίου, Πάτρα Μάιος 1998

Bulletin of the Geological Society of Greece vol. XXXII/4, 167-177, 1998
Proceedings of the 8th International Congress, Patras, May 1998

CHARACTERISATION OF THE "ATHENS SCHIST" FOR TBM EXCAVATION OF THE ATHENS METRO TUNNELS; A GEOLOGICAL ASSESSMENT FOR ENGINEERING PURPOSES

P.G.MARINOS[1], J.A. BLANKE[2], M.D.BENISSI[3], G.D. ROVOLIS[3], M.G. NOVACK[3], I.S. PAPADATOS[4], A.A. ANTONIOU[1] & K.I. ANGELIDAKI[5]

ABSTRACT

An engineering geological assessment with respect to the TBM excavation, within a highly heterogeneous system of formations known as the "Athens Schist" is presented. The method considers mainly the rock mass competence on the basis of criteria related to lithology, tectonic deformation (fracturation-folding-shearing), weathering and rock mass quality as well as geometrical-structural and groundwater criteria. Hence it calibrates the rock mass interaction during excavation using the specific TBM of the Athens Metro project, with an emphasis to potential face failure and overbreaks. It is based on a statistical-minded extrapolation of factors that govern the behaviour of the ground, when subjected to mechanised boring. The final objective is to identify which tunnel sections exhibit *'friendly'*, *'moderate'* or *'adverse'* tunnelling conditions with respect to overbreak development and propagation and to provide a basis for the selection of appropriate treatment and/or alternative excavation methods.

KEY WORDS: Engineering geology, Athens' Schist, Tunnel Boring Machine (TBM), Athens' Metro, Greece.

1. GENERAL

The first two fully-underground lines of the Athens Metropolitan Railway are under construction since November 1991. These lines comprise 18km of tunnels, 21 stations, 29 ventilation shafts and various miscellaneous structures. Two 9.5m diameter TBMs, one for each line, were employed in order to bore the twin-track running tunnels which are generally located at a depth of 10-20m (measured at the crown). At the time of writing this paper, all the stations are excavated, as well as the tunnels from *Pentagono* to *Syntagma* and from *Sepolia* to *Olympion*.

The objective of this independent tunnelling assessment is to evaluate whether the tunnelling conditions along the Athens Metro interstations are *'friendly'*, *moderate* or *adverse* for excavation with the tunnel boring machines (TBM) of the specific project.

The methodology of this analysis has been put into practise especially for the assessment of the Athens Metro interstations and has provided successful predictions of the ground conditions. This methodology is continuously developing (see also Marinos, P. et al, 1997), as the experience gained from the works underway lead to particular adjustments in its approach, through a better understanding of the engineering behaviour of the rock mass.

[1] National Technical University, Civil Engineering Dept., Athens, Greece
[2] Bechtel Int. & Attiko Metro S.A., Mesogeion 191-193, GR-11525, Athens, Greece
[3] Attiko Metro S.A., Mesogeion 191-193, GR-11525, Athens, Greece
[4] Athens, Greece
[5] University of Athens, Geology Dept, Athens, Greece

2. GROUND CONDITIONS

The geological substratum of the city of Athens consists, within the depth range of the Metro works, of a series of formations known as the system of the "Athens Schist".

The 'Athenian Schist' is a term used to describe a sequence of Upper Cretaceous flysch-like sediments (Marinos, G. *et al*, 1971). The system includes clayey and calcareous sandstones, greywackes, siltstones and shales as well as limestones and marls, exhibiting a low degree metamorphosis that has transformed them to metasandstones, metasiltstones, shales. Igneous activity has locally introduced peridotitic and diabasic bodies causing lithologic transformation and significant deformation of the pre-existing members. During the Eocene the 'Athenian Schist' formations were subjected to intense folding and thrusting. Later extensive faulting caused extensional fracturing. Widespread weathering and alteration of the deposits are additional controlling factors of the rock mass quality .

The resulting rock mass is highly heterogeneous and anisotropic not only in the macroscopic-geotectonic scale of the Athens basin, but mainly in the mesoscopic scale of the tunnel works. This inherent heterogeneity of the "Athenian Schist" rock masses is a key-factor for the generation of overbreak developing conditions during TBM excavation.

In practice, the heterogeneity of the 'Athenian Schist' is proved by the uncertainty for correlating adjacent boreholes, a fact which makes the drawing of reliable geological sections more difficult. In the methodology described herein, a 'statistical-minded' extrapolation of the borehole data is employed, instead of compilation of classic geological sections.

3. POSSIBLE CONSEQUENCES OF TBM BORING

The tunnels of the two new Athens Metro Lines are being excavated with two identical Tunnel Boring Machines, one per each line. The 9.5m-diameter TBMs are of the shielded type with a cutterhead equipped with disc cutters and drag bits (Figure 1). The uncontrolled muck discharge openings represent about 30% of the total cutterhead area while a series of belt conveyors are used to transport the muck at the back and load it to trains.

In principle the Athens Metro TBMs were designed to deal with various constellations of rock and soil, and their behaviour was indeed very good in excavating a major part of the Athenian substratum. However TBM excavation cannot always avoid collapses of the surrounding material. Ground failures may initiate either from the face, or, in minor extend, from the very restricted section of the crown that is temporarily left unsupported at the upper front part of the TBM, as the machine advances.

Indeed, certain ground conditions can easily induce such collapses, by 'ravelling' of loose fine-grained material or by 'flowing' of soil or crushed rock, or by slippage of 'flakes' of tectonically disturbed phyllite (weak black shale). In other words, the aforementioned phenomena are favoured by 'passages' with low modulus of deformation (E), or in presheared formations of low strength with closely spaced foliation.

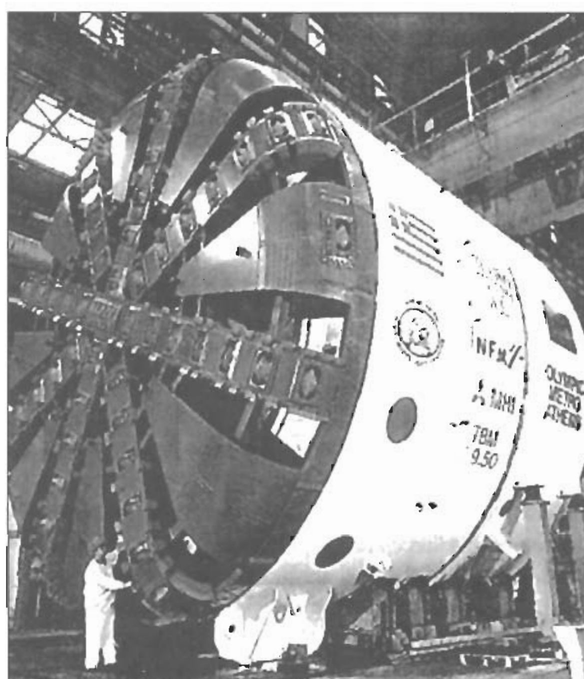


Fig. 1: The Athens Metro open cutterhead shielded TBM

Overbreak developing conditions are further aggravated by the presence of water. During tunnelling with a TBM, the unlined part of the tunnel constitutes a medium of infinite permeability. In general, vertical drainage towards the tunnel cannot be intense due to the overall moderate to low permeability of the 'Athenian Schist' rock masses and therefore overbreak due to internal erosion is not a typical mode of failure. However, the schist rock mass, with its very low permeability, becomes softer and weaker when saturated with water, and the discontinuities condition is radically downgraded, especially in the case of completely weathered or presheared formations (persistence of shale) with clayey infillings of low friction. Special significance is thus attributed to the groundwater presence at the level of the tunnel crown: water-induced unstable conditions may develop in zones of presheared 'flaky' material with soap-like schistosity surfaces that can slip away.

At this point it should be stressed that the encounter of ancient (empty or backfilled) wells and cisterns, may constitute an imponderable failure factor at the tunnel face and cover zone. Aside from the uncontrolled flow of water and mud from the well itself, the surrounding rock mass tends to be softened and disturbed and is generally liable to collapse from the rapid drawdown. Weakening may also occur due to leakages from overlying sewage pipes.

4. GEOLOGICAL INFORMATION

A solid basis of all necessary geological and geotechnical information is first compiled, in the form of *'geological sections for engineering purposes'* on which the key parameters for the evaluation of the ground conditions are depicted.

Detailed logs of both recent and older boreholes are prepared, following careful inspection of the cores. The geological material is described and classified into distinct *engineering geological formations*, not according to strict classic petrographical criteria but combining basic engineering geological data such as:

- the type of tectonic deformation, i.e. brecciation, intense fracturing, compact endogenetic breccias,
- the type of infilling material of the discontinuities, i.e. soap-like clayey coatings or thick compressible gouge infillings of low friction angle,
- the presence or absence of slickensides (lines or striations) along the discontinuity surfaces and susceptibility of the formations to shear failure,
- the degree of participation of loose rock material and susceptibility of the formations to ravelling failure,
- the degree of participation of engineering soil material, which may occur in the forms of completely weathered rock (residual soil) or discontinuity infilling material or fill material in the voids or mylonitic clay along zones of intense tectonic shearing,
- the presence of blocks of very hard rock within a very weak, sheared and laminated mass that exhibit differential behaviour during excavation (incapability of the cutters to break the floating blocks),
- the presence of groundwater which downgrades the condition of discontinuities.

It should be stressed though, that high quality coring is required in order to acurately perform the aforementioned engineering geological descriptions.

5. HYDROGEOLOGICAL INFORMATION

All the available information, such as the water level drawdown during drilling, the ground water piezometric data, the in situ permeability tests, the hydrographic info on watercourses or preferential surface runoff in the broader area of the alignment, etc., are compiled on distinct hydrogeological profiles along the drive.

These allow the evaluation of the hydrogeological conditions of the overburden deposits and of the Athenian Schist bedrock. In the former case, the presence of alluvia or of deep buried channels that could approach the tunnel or tunnel crown elevation, are of major significance. In the latter case, particular importance is attributed to perched water tables above the tunnel or to sections with enhanced permeability that could induce increased water inflow. The presence of water in poor quality formations is responsible for a further degradation of the ground.

6. ROCK MASS CLASSIFICATION

In the Athens Metro Project the "Athenian Schist" geological formations are being rated according to a Mass Rating system (MR), a modification of the RMR classification of Bieniawski (which, in simple terms, subdivides the *R.Q.D* and *discontinuity spacing* ratings and does not account for the effect of the discontinuities orientation).

Since the Athenian Schist rock masses, in several cases, exhibit an engineering soil behaviour, the present assessment does not rely upon the rock mass classification ratings to deduce its stability versus TBM excavation. It is possible that the same MR rating is attributed to formations with totally different behaviour during TBM excavation (e.g. cohesionless soil-like material with frictional characteristics, as opposed to laminated presheared shales of poor quality) or response to strengthening measures ("groutable" or "non-groutable" ground). Nevertheless, the MR-ratings are coevaluated with all other controlling geological parameters of the tunnel's cover zone and face. On the *engineering geological profile* the MR-values are shown in distinct columns adjacent to the boreholes, thus allowing the facile identification of areas where blocks or lenses of hard rock 'float' within a predominantly weak-rock or engineering soil environment of low MR. This is important in the case of TBM cutting processes in areas where there are distinct and persistent layers of rock, not blocks or lenses surrounded by weak material.

7. PILOT TUNNEL INFORMATION

Pilot tunnels, when constructed (usually of ∅=3.0m and located 1.5m below the TBM crown), have been proved to be valuable sources of information, since, apart from the accessibility for undergroung treatment of the rock mass (if necessary), they allow:

a) compilation of a continuous geologic section along the area of the tunnel,
b) encounter of wells and other pre-existing voids that intersect the tunnel,
c) unveiling of underground water routes in the vicinity of the tunnel,
d) observation of the rock mass behaviour during excavation and identification of potential causes for failures.

The above four categories of pilot tunnel information are added to the drawing of the engineering geological section in the form of 'bars' (Figure 2) that enable the quick visualisation of hazardous zones along the pilot.

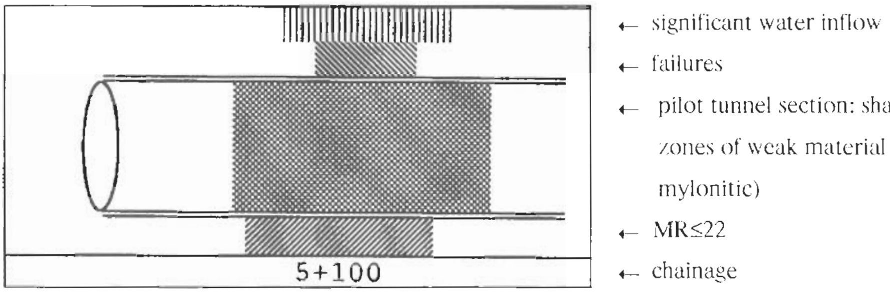


Fig. 2: Pilot tunnel information on the hazardous zones

8. ASSESSMENT OF GEOLOGIC CONDITIONS FOR TBM EXCAVATION

An analysis is made hereafter, of the factors which are appropriate for examining the tunnel stability as to the occurrence of overbreak developing conditions and, generally, of the factors that govern the behaviour of the ground when subjected to mechanised boring.

Of great importance is the proportional participation and the geometrical structure of the '*competent*' (rock-like) and '*non- competent*' (weak rock or soil-like) ground materials, both in the cover zone and the tunnel face. The relevant information originates from the cores of the boreholes which are close to the tunnel axis. The rock mass classification ratings of the core and the hydrogeological measurements and test results are also taken into account, while the overall assessment is counterbalanced with an empirical estimation of the behaviour of similar rockmasses, as witnessed during inspection of both TBM and conventional excavations in the completed tunnels of the project.

8.1 Cover zone

Of interest here are the following parameters:

1) The depth of the tunnel crown.

2) The *participation of the various weak materials*, (as seen in the borehole cores) i.e. alluvium, backfill, mylonitic material, brecciated rock, loose rock fragments in a matrix of soil, black shale and any other type of geological material that simulates to soil (*engineering soil*). The individual percentages of the various categories of weak material are calculated and then added together, to give the overall proportion of the weak material in the cover zone.

3) The *participation of rock-like materials* in a 6-metre zone immediately above the tunnel crown. This 'factor' is considered as indicative of the capability of the cover zone to bridge over a progressive overbreak and prevent its propagation towards the surface.

4) The *hydrogeological conditions* in the zone of the overburden; the permeability values of the formations, either of the entire cover zone, or mainly, of a critical 3m-zone above the crown, indicate the likely water influx in the tunnel and the potential for water-induced overbreak.

5) The *presence of natural or man-made voids* within the cover zone.

8.2 Tunnel face

As regards the tunnel face, the rock mass is assessed in terms of differential behaviour as of its hardness and in terms of potential slippages or ravelling behaviour. The latter may cause problems at the face, with a risk of propagation to the cover zone right above the crown. The parameters which are examined are (Figure 3):

BOREHOLES	AKS 102	AKS 103	SYO 409
Chainage (m)	4216	4231	5445
Distance from TBM tunnel axis (m)	5.5	20	5.6
Tunnel crown depth (m)	15.8	15.8	19.8
Alluvium - Fill(%)	8.9	10.1	17
Completely Weathered Rock/ Engineering Soil (%)	3.8	6.3	19
Sericitic schist with black shale(%)	0	0	0
Breccia (%)	0	26.6	32
Black Shale(%)	0	0	15
void (%)	-	-	-
Total cummulative percentage of weak material in the cover zone, alluvium excluded (%)	3.8	32.9	66
Total cummulative percentage of weak material in the cover zone (%)	12.7	43	83

BOREHOLES	AKS 102	AKS 103	SYO 409
Percentage of soil-like material in the 6-m zone above the tunnel crown (%)	3	35	73
Full face:			
Soil-like material (%)	10.4	28.1	68
Upper half of face:			
Soil-like material (%)	0	29.2	48
ASSESSMENT FOR TBM EXCAVATION	F	M	A

Fig. 3: Engineering geological assessment of borehole cores for TBM excavation. Typical cases of boreholes for which the material both of the cover zone and of the tunnel face are characterised as F: friendly, M: moderate, A: adverse for TBM excavation. In those cases where a different characterisation is assigned to the cover zone and to the face material, the final assessment is a matter of judgement.

1) The participation of *rock-like against soil-like material*, at the *full section* of the tunnel.

The *rock-like* material at the face may represent distinct layers with sufficient thickness and lateral persistence in the scale of the tunnel. In case such rock layers prevail within the section of the tunnel face, the conditions of excavability are favourable with minimum or total absence of overbreak. In the sections where the tunnel is driven through members of the lower "Athens Schist" unit, only the sandstone members can be regarded as rock-like geological material for the TBM. Nevertheless, at the scale of the tunnel face, this formation may not always occur in distinct benches but in lense-like blocks inside the phyllitic mass that have been subjected to shearing and fracturing due to differential behaviour during their tectonic co-deformation. As a result, fractured sandstone blocks may 'float' within a surrounding soil-like mass of soft and sheared black phyllite. This is a typical unfavourable condition for excavation with the specific TBM, since, in a case of profound geomechanical difference between the strong blocks and the sheared phylilite or shale, gripping and cutting of the rock blocks may not be achieved. As a consequence, the harder blocks are displaced and ripped rather than cut by the TBM, hence extending the cut line beyond the tunnel section.

The *soil-like* material at the face is mainly represented by the black presheared phyllite of the lower unit. Horizons of highly fractured and loose rock, or mylonitized or highly weathered rock in the upper unit, are also considered as soil-like material.

2) The participation of *rock-like against soil-like* materials in the *upper half* of the tunnel face, since this very part is the most prone to face-collapse initiation. The dominance of soil-like materials at the upper-half of the tunnel face is regarded as a serious warning for the expectation of *adverse* conditions for TBM excavation.

3) The *geometrical distribution and structure* of the various materials at the face, as concluded from the aforementioned evaluation. The simultaneous presence of 'competent' and 'non competent' members is responsible for the differentiality of the rock engineering behaviour of the face.

8.3 Ratings

The parameters discussed in the previous sections of this chapter are co-evaluated, in order to provide an assessment of the expected engineering geological conditions for TBM excavation. Such an assessment is of practical value if it identifies distinct areas along the drive and suggests the likely precautions to be taken before, or during, the passage of the TBM. These precautions will be first aimed at eliminating any possible risk of damage to the urban environment, such as surface collapses, settlements and associated damages. Additionally, they will be aimed towards guiding an efficient, trouble-free and thus rapid excavation procedure.

Individual ratings (in the form of symbols **A** for adverse, **M** for moderate and **F** for friendly) are assigned at each borehole, based on the cover zone quality, the face quality and the MR values (Figures 4, 5). As a rule, the meaning of these ratings is the following:

Friendly:

No significant overbreaks are expected due to the good quality of the rock mass.

Moderate:

Case 1: Incompetent rock may exist at the tunnel face, but the quality of the cover zone obstructs the upwards propagation of extensive overbreaks.

Case 2: The face consists of competent materials but the cover zone is partly intensely broken (brecciated etc.). In this case it is difficult to have initiation of extended overbreaks by a face instability. If, however, an overbreak occurs, then the cover zone may in principle have some ability of bridging, since it does not consist of the black shale ravelling flakes, but of angular portions of fractured or brecciated layers.

Adverse:

Predominance of the black shale or of very weak material at the face, associated with material of similar weakness at the cover zone, over a significant height above the tunnel crown. The latter material might be very weathered or intensely brecciated rock of the upper unit, or transitional material from the upper to the lower unit. The enhanced presence of groundwater dramatically downgrades the condition of the discontinuities, which generally bear clayey coatings, and as a rule contributes to *adverse* conditions. Overbreaks may easily initiate from the tunnel face and propagate towards the surface.

The presented geologic assessment was proven to be in good agreement with the performance of the TBM; as a rule, in areas where the borehole information indicate the extended development of soil-like materials, overbreaks or frontbreaks have appeared. Events of ground failure were much less, or totally absent, in areas where rock-like material prevails (Figure 4). However, the geology is sometimes not the

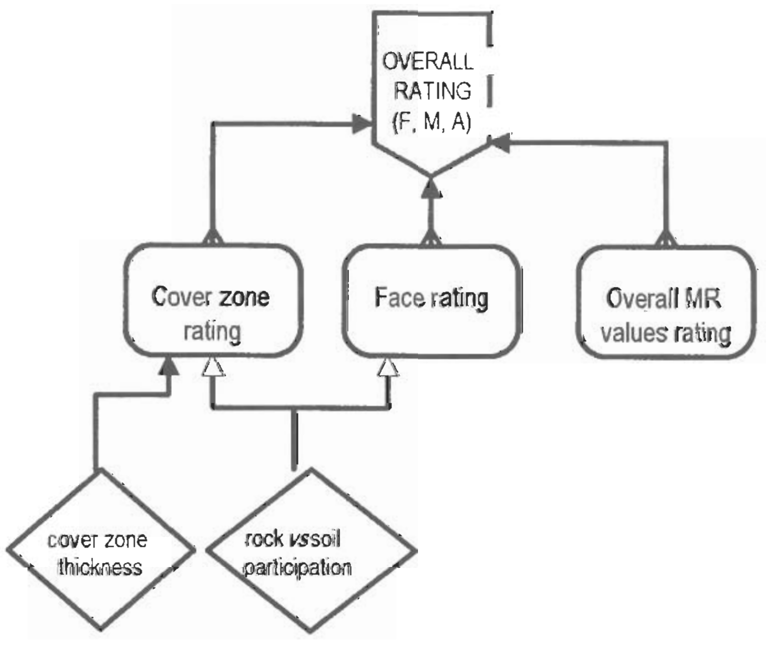


Fig. 4: Ratings of borehole cores for the assessment of the geological/geotechnical conditions for TBM excavation.

sole reason for ground failures; indeed, a number of failures are caused by other reasons, such as the encounter of leaking sewers or aqueducts associated with TBM stoppages and provoking internal erosion of the ground.

8.4 Effect of voids and/or buried disturbing features

It is common knowledge that as the TBM is driving through the substratum of the city of Athens there is an inherent high risk of encountering pre-existing voids and/or other buried structures, either empty or filled with loose material. Among buried features and voids of the modern times (known or unknown utilities' networks, one could indicatively mention the ancient hydraulic structures (wells, shafts, aqueducts and galleries either isolated or in complex systems) or the fortification wall of Athens (moat, trenches and galleries).

In the presented assessment method the geotechnical conditions for TBM excavation are deduced purely on the basis of the coevaluation of the rock mass characteristics and their interaction with the engineering structure. However the presence of buried natural or man-made disturbing features in the cover zone and/or the tunnel face, constitutes a highly influential parameter which can downgrade or in the worst case reverse the geotechnical assessment.

More specifically, the presence of wells may not prove to be sufficient to induce dangerous overbreak, where the wells are found 'isolated' in a '*friendly*' environment of good rock. On the other hand, the same ground response cannot be anticipated in the case of *moderate* or adverse *conditions*. If however these voids do not represent individual 'isolated' features but rather they form part of a combined system of wells, aqueducts or galleries, the danger of extensive overbreak exists irrespective of the nominal geotechnical conditions for TBM excavation.

9. FINAL ASSESSMENT: 'FRIENDLY', 'MODERATE' & 'ADVERSE' CONDITIONS FOR THE TBM

The final assessment results from the co-evaluation of the borehole core ratings along with the Fig. 5: available pilot tunnel information, the hydrogeological information, the presence of buried disturbing structures and the overall sensitivity of the area (buildings, important city activity and archaeological/ historic monuments). The geotechnical conditions for TBM excavation are again assigned the characterisations '*friendly*' *(low risk)*, '*moderate*' *(medium risk)* and '*adverse*' *(high risk)*. These characterisations are an index of geotechnical hazards and consequent overbreak risk, now in conjuction also with the vulnerability of the area (sensitivity of buildings, presence of ancient structures, wells & underground chambers, sewers, utilities, etc.)

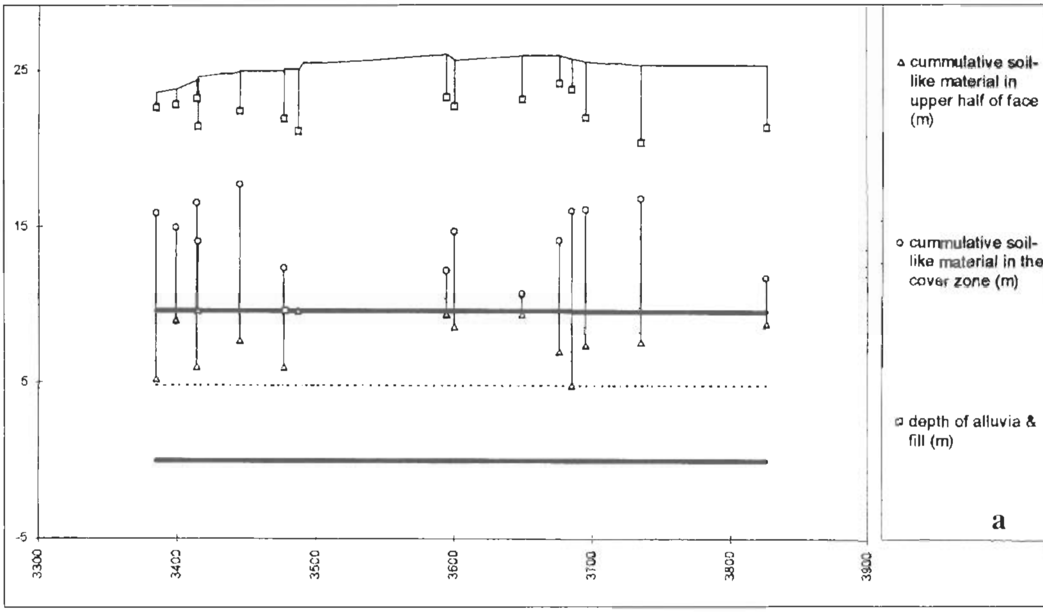
10. FACING THE ADVERSE CONDITIONS

An early assessment of the tunnelling conditions to be encountered during TBM excavation allows the contemplation of appropriate remedial measures and alternative engineering solutions, particularly since face treatment facilities cannot easily be implemented through the specific TBMs.

Adverse conditions for TBM excavation denote the inability of the machine to excavate through these ground conditions, without inducing extensive overbreak that could possibly propagate to surface collapse. The range of solutions are then levelled as follows:

1. If adverse conditions prevail over significant lengths of a tunnel drive, or if significant structures are to be underpassed by the TBM, then the *realignment of the tunnel*, where feasible, is a way of bypassing the problem. This was the case with the realignment of the Metro tunnel beneath the Archaeological Site of Keramikos (P. Marinos et al., 1997).
2. If the tunnel alignment cannot be modified, then treatment will be required (Figure 6).

2. a . In this case *pilot tunnels* driven ahead of the TBM are considered highly beneficial, because:



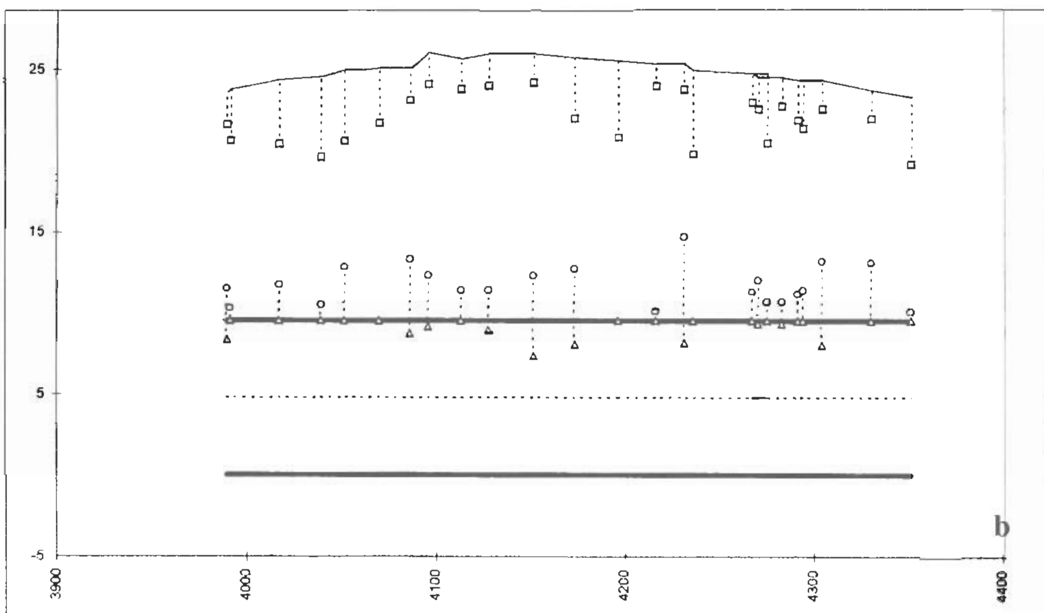


Fig.5: Assessment of borehole materials for TBM excavation, in terms of the cummulative percentage of soil-like materials. a) Interstation where major & minor overbreaks have occured, b) interstation with no overbreak occurrence. Notable is the very limited presence of weak black shales at the tunnel face in case b.

- they permit the implementation of rock mass strengthening techniques (e.g. grouted fiberglass nails) ahead of the TBM, (that is where the rock mass is susceptible to treatment),
- they allow the detection and filling of pre-existing voids (wells, galleries, e.t.c.) which are often the basic imponderable factor for high risk of failures
- by means of the strengthening measures for their own temporary support (e.g. shotcreting), pilot tunnels reduce th

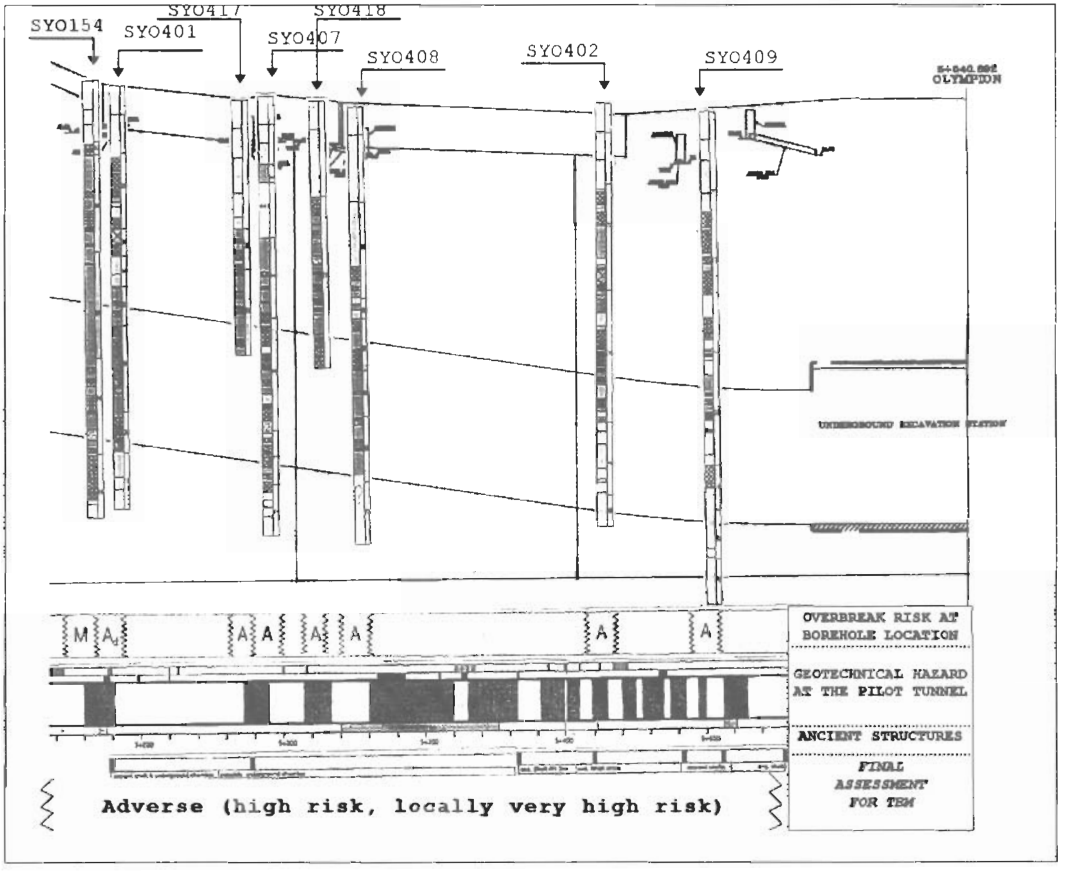


Fig. 6: Engineering geological section, part of Plaka area, central Athens (part of SYO interstation, line 2, see also fig. 8). The area was characterised as "adverse" and the cover zone was reinforced through the pilot tunnel with grouted anchors, prior to the TBM advance.

3.b . If the rock mass cannot be treated (or if treatment is uneconomical) through a pilot tunnel, then ground treatment implementation from the surface should be considered (grouting, jet grouting, nailing, e.t.c.)

4. All the aforementioned solutions are aimed at ensuring safe TBM boring by preconditioning the ground. However, if none of them is feasible (i.e. due to the underpassing of buildings or to the predominance of non-treatable ground in the pilots), then a change of method has to be seriously considered. Alternative methods may include the use of an open shield machine or ultimately conventional tunnelling (forepolling or NATM).

11. CONCLUSIONS

The assessment presented in this paper is based on an engineering geological classification of a complex geologic formation, that takes into account the particularities of the behaviour of the specific boring machine for the construction of the Athens Metro. This classification distinguishes the various members of the Athenian Schist by means of strength, tectonic fatigue, weathering and groundwater conditions and assumes their behaviour (rock-like or soil-like) during excavation with the TBM. The final risk evaluation takes into account man-made particularities of each area and may be supported by information from pilot tunnel. This method is intented for the works of Athens Metro; however, the same principles of assessment can also be applied to other projects and different ground types, given that the sensitive parameters for a particular method of excavation are properly recognised.

ACKNOWLEDGEMENTS

We acknowledge the support of Attiko Metro S.A. for the publication of this paper.

REFERENCES

MARINOS, G., KATSIKATSOS, G., GEORGIADOU-DIKEOULIA, E. & MIRKOU, R. 1971. The Athens' schist formation. I. Stratigraphy and structure. Ann. Geol. Pays Hell., XXIII: 183-216 (in Greek).

MARINOS, P., BLANKE, J., NOVACK, M., BENISSI, M., ROVOLIS, G. 1997. Geological and environmental considerations for selecting an Athens Metro tunnel alignment beneath an important archaelogical area, Proc. IAEG Symp. Eng. Geology and the Environment, Balkema, Vol.3 (2777-2784).

MARINOS, P., BLANKE, J., M., BENISSI, M., NOVACK, M., ROVOLIS, G. 1997. Engineering geological assessment of the "Athens Schist" for TBM excavation of the Athens Metro, Proc. Geology for Engineering, Urban Planning & the Environment South African Inst. Eng. Geol., Gauteng.