Assessment of Ground Conditions with Respect to Mechanised Tunnelling for the Construction of the Extension of the Athens Metro to the City of Piraeus

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ABSTRACT

This paper refers to the new planned Western Extension of the Athens Metro to Piraeus city. The railway consists of a 9.45m diameter and 8.2 km length tunnel and 7 stations. Tunnelling works are expected to be undertaken within a variety of lithological formations ranging from very strong alpine limestones to recent soft littoral deposits. The tunnel alignment was divided in thirteen areas, with respect to the geological and geotechnical conditions that may be encountered during construction. In many of these zones, the geotechnical conditions in conjunction with the presence of sensitive surface and/or subsurface structures led to the selection of a closed-face TBM (EPBM or Slurry TBM) as the appropriate tunnelling technique. The Piraeus extension is a project where both types of commonly used closed-face tunnelling machines will encounter 'text book' application areas yet not always. The applicability of each type of TBM is discussed using the available data obtained from an extensive site investigation campaign.

1. INTRODUCTION

This paper refers to the new planned western Extension of Line 3 of the Athens Metro, which extends from Haidari city to Evangelistria area in Piraeus city and has a total length of ~8.2 km. The double track tunnel will be bored by means of mechanised tunnelling techniques and will comprise 7 stations. The paper focuses on the methodology of classification and grouping geological and geotechnical data for engineering purposes and with respect to mechanised tunnelling.

2. GEOLOGY

The deepest formations of the project area are the limestones ('Karavas limestones'), the ophiolites, mainly serpentinites and the 'Athens Schist', a tectonic nappe over previous formations. The 'Athens Schist' is a flysch like diaplasis, comprising a variety of slightly metamorphosed formations in two 'units' (Fig. 1). The 'Upper Unit' consists of alternations of metasandstones, metasiltstones and calcareous schists. In the 'Lower Unit', weak materials persist, mainly black shales.
The aforementioned formations are overlaid by neogene and quaternary deposits. The neogene deposits comprise mainly lagoonal ('Marly deposits') and marine marls ('Piraeus marl'). The 'marly deposits' comprise marls, siltstones, marly limestones, claystones and conglomerates. 'Piraeus marl', sequence consists of marls, marly limestones, sandstones, claystones, siltstones and conglomerates. The quaternary formations are recent littoral deposits, marsh deposits, scree, alluvia and fill material.

The recent littoral deposits mainly comprise silts (sandy), sands (silty), sandstones (silty) and siltstones (sandy). The marsh deposits, with very soft clays or silts and clayey silty sands, are found overlaying the recent littoral deposits at the Piraeus port area and overlaying the 'Piraeus marl' formations at the end of the tunnel route.

3. ENGINEERING GEOLOGICAL ZONATION ALONG THE TUNNEL DRIVE

Analysis of the information and data from 125 sampling boreholes led to the consideration that the tunnel alignment can be divided in thirteen areas, with respect to the geological and geotechnical conditions that may be encountered during construction (Fig. 1). Mixed conditions can also be found around these limits however we consider that the presented zonation has a high level of reliability. These zones are:

- <u>From 'Haidari' forestation (ch.~1+418) to 'Aghia Varvara' station (ch.~2+150):</u>
  At the tunnel profile, the lower unit of the 'Athens Schist' prevails whilst the overburden zone is dominated by the presence of upper unit formations. In some areas mixed ground conditions may occur at the tunnel face. This section is characterised by weak to very weak rock masses and in terms of mechanised method of construction, a face support is required.

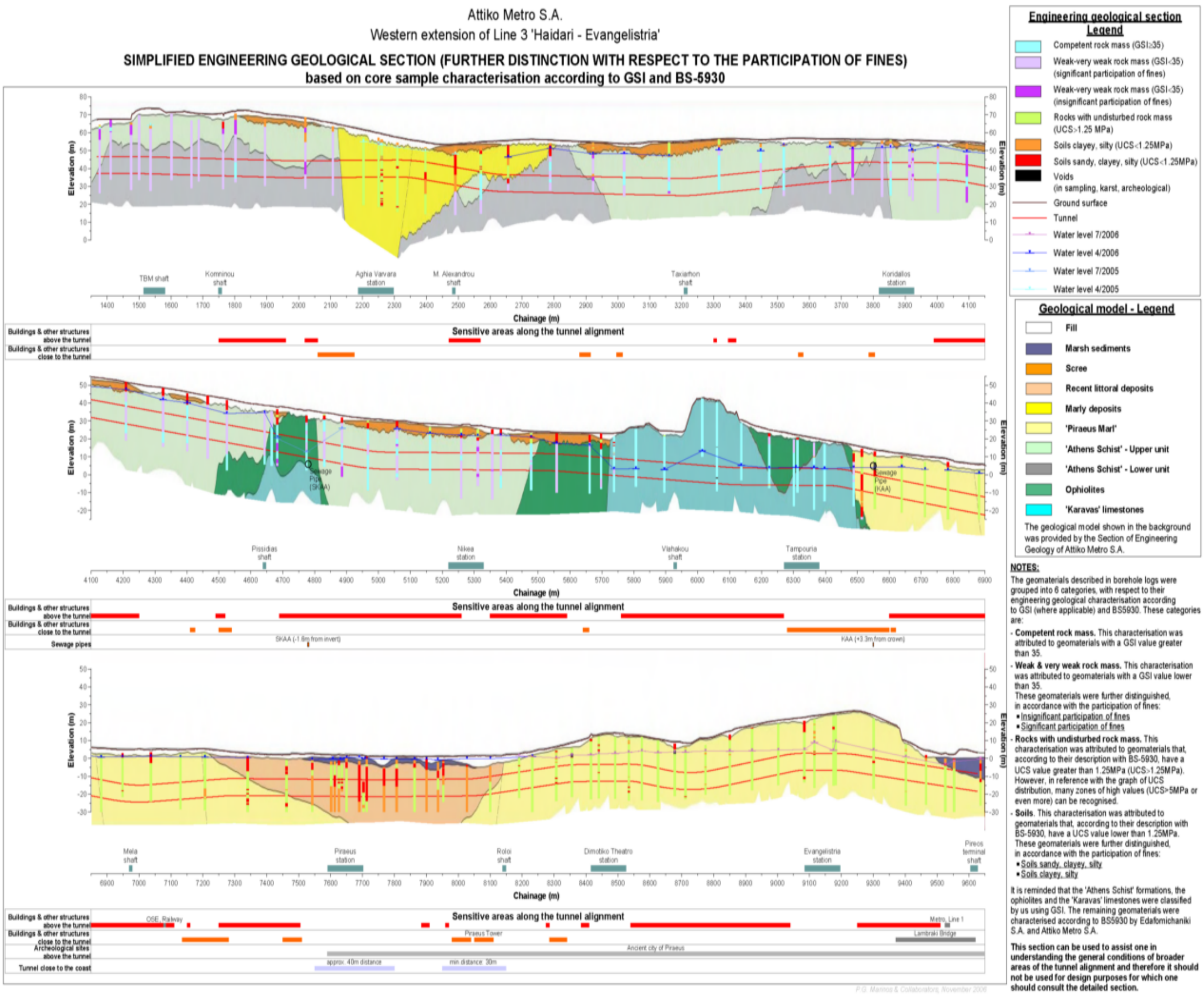


Fig. 1. Simplified engineering geological section.

- From 'Aghia Varvara' station (ch.~2+150) to 'Megalou Alexadrou' shaft (ch.~2+500):
  This section of the tunnel will be driven within the marly deposits. The overburden zone comprises marly deposits and scree. Overall, this section is better than the previous one in terms of the rock mass quality. However, due to the high fracturing mainly in the overburden, as shown by the RQD values (Fig. 2), relaxation of the face should be kept under control which means that face support will probably be needed.
- From 'Megalou Alexadrou' shaft (ch.~2+500) to ch.~2+700:
  This section is characterised by mixed face conditions combining the 'Athens Schist' and the overlying marly deposits. Overall, the formations appear controversial in terms of engineering geology since the rock mass has been characterised both very weak and competent and the marly deposits appear both rock-like and soil-like. This tunnel drive due to the weak overall appearance and the mixed face conditions will need a face support during boring.
- From ch.~2+700 to 'Pissidias' shaft (ch.~4+650):
  The tunnel in this section will be driven within 'Athens Schist' formations. In some areas mixed face conditions and transitions of the upper and lower unit formations are expected. Overall, this section is characterised by the presence of weak to very weak rock mass in the ground profile, where a proper face support should be applied.
- From 'Pissidias' shaft (ch.~4+650) to ch.~4+800:
  Ophiolites dominate both the tunnel excavation profile and the overburden zone whilst, below the tunnel invert, limestone appears. The formations are generally of high GSI values. The overall conditions of the rock mass are fairly good.
- From ch.~4+800 to 'Nikea' station (ch.~5+450):
  The upper unit of the 'Athens Schist' prevails in both the tunnel and the cover although scree have a significant superficial longitudinal extent. Overall, this section is mainly characterised by the presence of weak to very weak rock mass in the excavation and overburden profile, except some areas where good quality 'Athens Schist' is present. However, given the random appearance of sheared zones inside the good quality 'Athens Schist', we consider the whole section as a stretch where a proper face support should be applied.
- From 'Nikea' station (ch.~5+450) to ch.~5+725:
  The tunnel will be driven within ophiolites. Information from boreholes indicated weak to very weak rock mass at the initial part of this tunnel route and competent rock mass at the final part. The overburden zone is of the same manner. In this short tunnel drive, there will be sections, mainly in the initial part, where the stability of the face should be enhanced.
- From ch.~5+725 to 'Tampouria' station (ch.~6+200):
  The ground profile is dominated by the presence of competent limestones. The overburden thickness is the highest of the whole project reaching 37 m. This section will provide stable face during boring.
- From 'Tampouria' station (ch.~6+200) to ch.~6+500:
  Mixed ground conditions are present. The tunnel excavation profile changes from limestone (bottom) - ophiolite (top) to only ophiolite, then to limestone - ophiolite again and only limestone at the final part. The same transitions also apply for the overburden zone with the appearance of ophiolites at the final part of the section. Overall, the rock mass is competent. Poor engineering geological conditions are expected at the final part of this tunnel drive due to the presence of a near-vertical fault zone that delineates the alpine formations from the adjacent neogene marls. With the exception of the final part, the overall quality of this section is good despite the fact that mixed face conditions are present.
- From ch.~6+500 to ch.~7+350:
  The greatest part is dominated by the presence of the 'Piraeus marl'. The formations appear disturbed and soil-like at the initial parts, probably due to fault zone. Farther, 'Piraeus marl' is of a rock-like nature. At the final part of this section mixed ground conditions need to be considered since less competent littoral deposits appear in the overburden zone. In this section the 'Piraeus Marl' is disturbed and exhibits a permeability that should be considered in terms of inflows (Fig. 6). Thus the stability of the face must be secured.

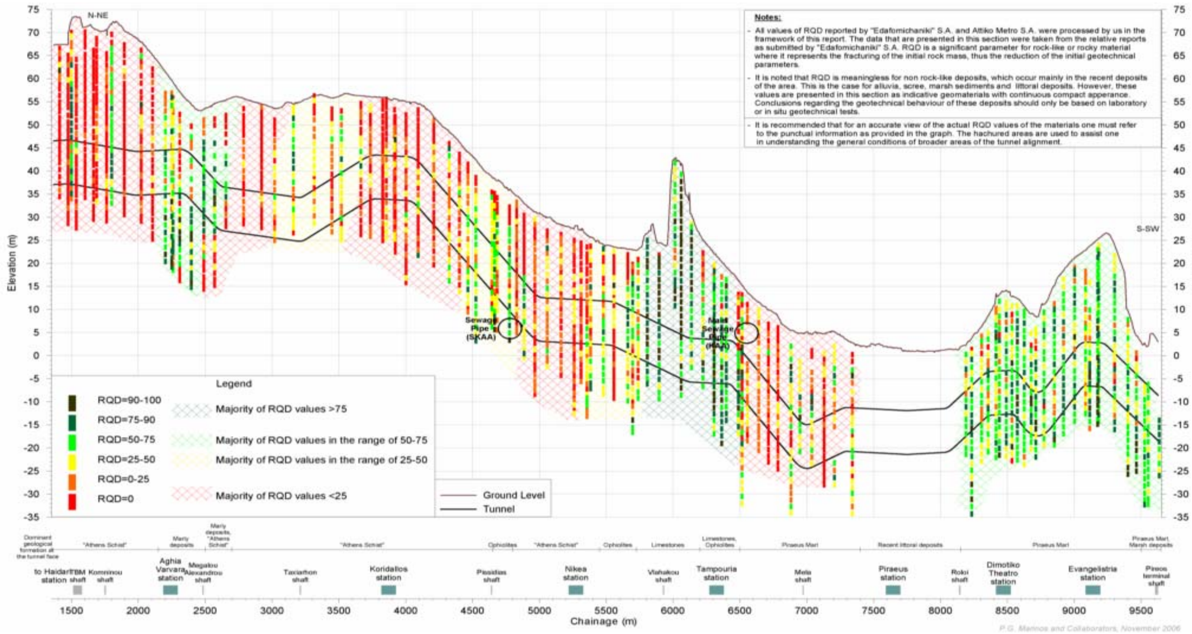


Fig. 2. RQD distribution graph along the area of the alignment.

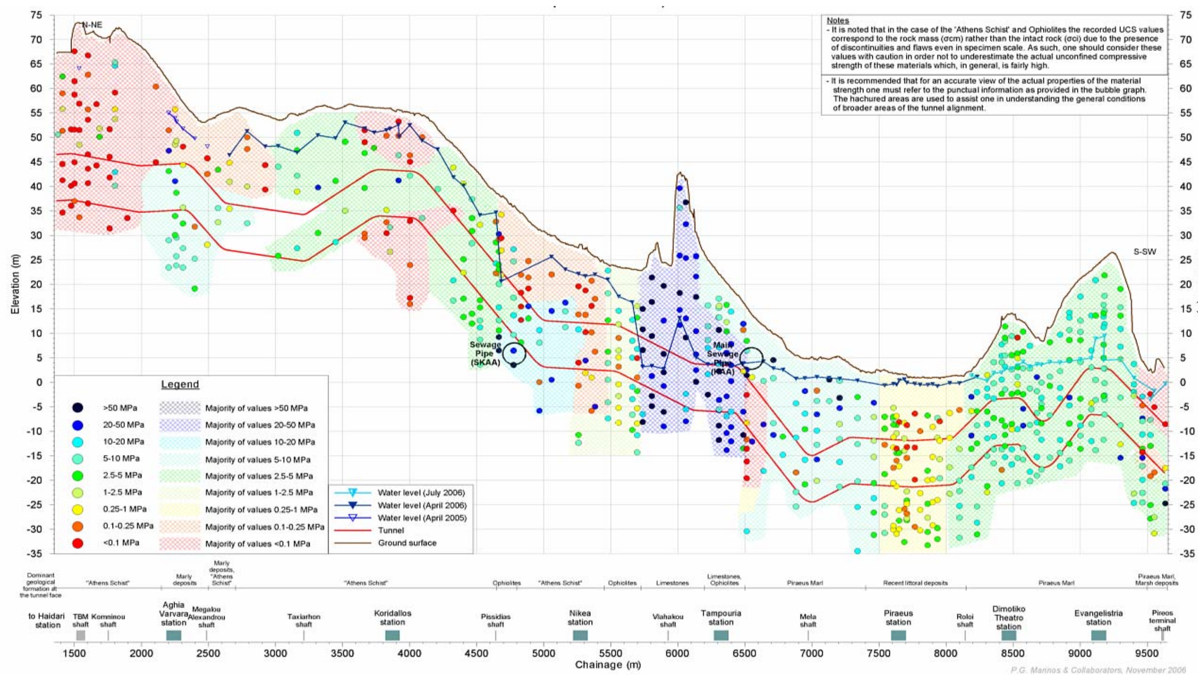


Fig. 3. UCS values distribution graph along the area of the alignment, based on laboratory tests results.

- <u>From ch.~7+350 to ‘Roloi’ shaft (ch.~8+150):</u>
  This section comprises soils of various degrees of diagenesis in both the tunnel and the cover zone. The profile consists of recent littoral deposits that mostly appear as fine grained soils with low UCS values (Fig. 3). Zones of rock-like recent littoral deposits are present yet one must consider that there is an uncertainty with respect to the lateral and vertical extent of these more competent zones, which are in the vicinity of and in communication with the sea. Additionally, marsh deposits of very poor quality and thickness that reaches 4 m are present at the upper parts of the overburden zone. Given the presence of relatively weak soil materials below the water table and the vicinity of the tunnel with the sea, a pressurised face should be applied during boring.
- <u>From ‘Roloi’ shaft (ch.~8+150) to before ‘Pireos’ terminal shaft (ch.~9+500):</u>
  ‘Piraeus marl’ dominates in the whole ground profile. The formations are generally competent

with sporadic and isolated soil-like materials. They exhibit an overall good quality rock. In principle, no face stability problems should occur and ground water can be controlled by traditional methods. The consolidation risks do not seem to be an issue but this should be a subject of consideration during design.

4. CONSIDERATIONS ON TBM SELECTION

4.1 Ground conditions – Basic criteria for fundamental selection

Fig. 4 illustrates in a user-friendly way the expected ground conditions not only at the tunnel face but also in the overburden zone. Additionally, the graph illustrates the zones of the cumulative presence of weak zones in both the tunnel profile and the cover zone. GSI was used to demonstrate the quality of the jointed and tectonised rock masses whereas the classification in accordance with BS5930, as allocated on borehole cores, was used to describe the quality of all other formations.

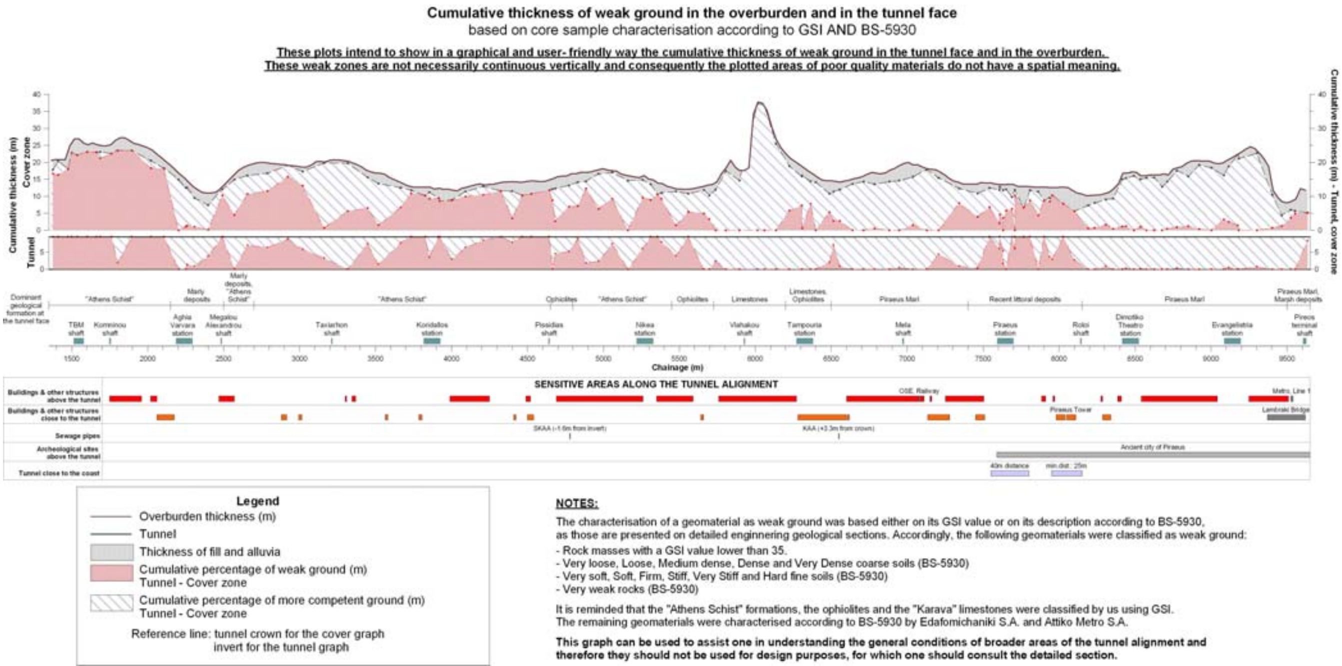


Fig. 4. Cumulative percentage of weak ground in the overburden and in the tunnel face.

From this procedure, weak zones were distinguished along the tunnel alignment. The term ‘weak zone’ is associated with the behaviour of the respective ground against tunnelling with conventional means of excavation. This applies not only to the low stand-up time of the excavated space and overexcavations but also to the stability of the face itself. Additionally, in the overburden zone, weak zones would most probably exhibit increased settlements if a heavy and stiff support of the excavation is not applied and the face is not well supported to prevent its relaxation.

These weak zones occupy a significant length of the tunnel alignment, in many cases with questionable face stability. Any TBM used for the project should not only be shielded but also it should apply face support in order to prevent failures and control settlements due to face relaxation. Such control can be achieved either by an appropriate configuration of the cutterhead to apply support or by a pressurised closed face. We do not believe that the former can face all the cases of the ‘Athens Schist’ stretch, given our knowledge on the tunnelling behaviour of the black clayey shale of the ‘Athens Schist’ (Marinos et al., 1998). Besides that, in all cases, it cannot cope with the littoral deposits materials at the area of Piraeus port. A TBM with a closed pressurised face is thus recommended. This is the case of either an EPBM or a Slurry TBM. Such a TBM must be appropriately equipped in order to be able to operate efficiently with a non-pressurised face since a

number of sections of the whole project can provide stable conditions. Non-pressurised operation reduces wear of cutting tools and cost and increases advance rates. However, the decision of changing the mode of operation must be based on thorough assessment of the conditions ahead of the face based on the investigation data, already existing or acquired during construction. Probing ahead may be necessary in order to assist the decision of shifting the mode.
In the next paragraphs, selection criteria between the two types of closed-face TBM are discussed.

4.2 Discussion between EPBM and Slurry TBM

Given the data presented in this paper, both machines can be considered. Each of them has its pros and cons but if appropriately operated they can perform effectively.

4.2.1. Particle size distribution

The primary and probably most important aspect in the TBM selection process is the grading envelope of the geomaterials. Generally speaking, EPBMs perform better on clayey and/or silty ground conditions while Slurry machines in loose coarse grained soils.
As far as it concerns Slurry machines, British Tunneling Society (BTS) and the Institution of Civil Engineers (ICE) (Anonymous, 2005) mention that if the fine fraction (particles smaller than 60μm or able to pass through the sieve No200) is greater than 20% then "the use of a Slurry machine becomes questionable although it is not ruled out". Main impact of fine-grained soils on the operation of Slurry machines is the difficulty in the separation process of the bentonite support fluid from the fine fraction. As far as it concerns EPB machines, BTS and ICE mention that "a fines content of below 10% may be unfavourable for application of EPBMs". Low fines percentage has an effect on the earth paste that is required to maintain face support pressure. As such, increased conditioning may be required to achieve the appropriate earth paste parameters when fine percentage is low.
The percentage of fines of the formations that will be encountered within the tunnel excavation profile varies (Fig. 5). In most cases, the average grading envelopes suggest that a fine content higher than 20% applies for all the formations within which, weak zones have been identified. However, an average close to 20% obviously suggests that in many areas the presence of fines will be lower and, as has been identified, strata with extremely low fine content and increased presence of coarse fragments will be encountered. These strata are mainly expected within the formations of the upper unit of the 'Athens Schist'. Today, experience has shown that the grain size distribution spectrum for both machines has been astonishingly broadened.

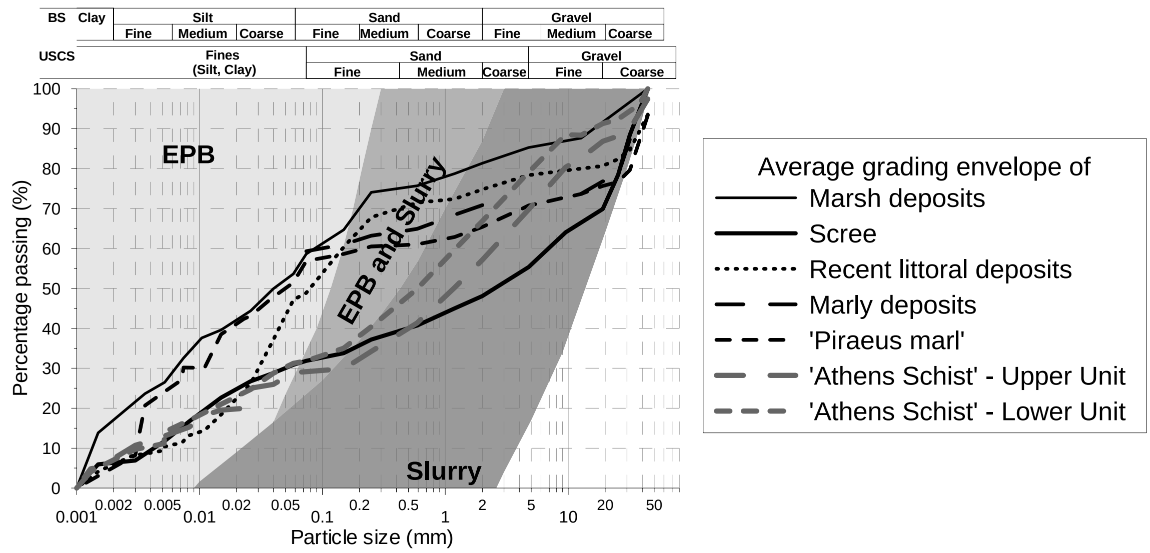


Fig. 5. Average grading envelope of geomaterials of the Piraeus extension and EPB or Slurry suitability limits (suitability limits from Langmaack, 2002).

4.2.2. Permeability

In terms of permeability, BTS and ICE (Anonymous, 2005) indicate as "the point of selection" between EPBMs and Slurry TBMs, a ground permeability of $1x10^{-5}$ m/sec with the Slurry TBMs being more suitable for higher values and accordingly EPBMs for lower.

Overall, 134 falling head and 353 packer in situ permeability tests were undertaken in the project area. The results indicated that for the largest section of the tunnel drive, the permeability values are lower than $1x10^{-5}$m/s (Fig. 6). There are however, tunnel sections of higher permeability in the formations of the 'Piraeus Marl' and in the recent littoral sediments. The presence of these zones does not rule out the selection of an EPBM and not only because their extents are restricted. Indeed, in the case of the recent littoral deposits, these zones are limited in the overburden in less clayey/silty strata while at tunnel level, the increased participation of fines guarantees the formation of an adequate plug in the screw conveyor. In the case of the 'Piraeus marl' the higher values of permeability are due to the presence of fractures whereas the formation is clay/silt dominated and no significant difficulties in achieving water-tight conditions are expected. In terms of sudden loss of pressure, the Additional Face Support (AFS) system, with an automatic slurry participation in the conditioning system, assists the effective EPB operation (Babendererde et al., 2004).

4.2.3. Hydrostatic head

The water table level along the whole alignment is usually 5 to 10 m above the tunnel crown (Fig. 6). In all cases, no high hydrostatic heads are expected and therefore this is not a selection criterion.

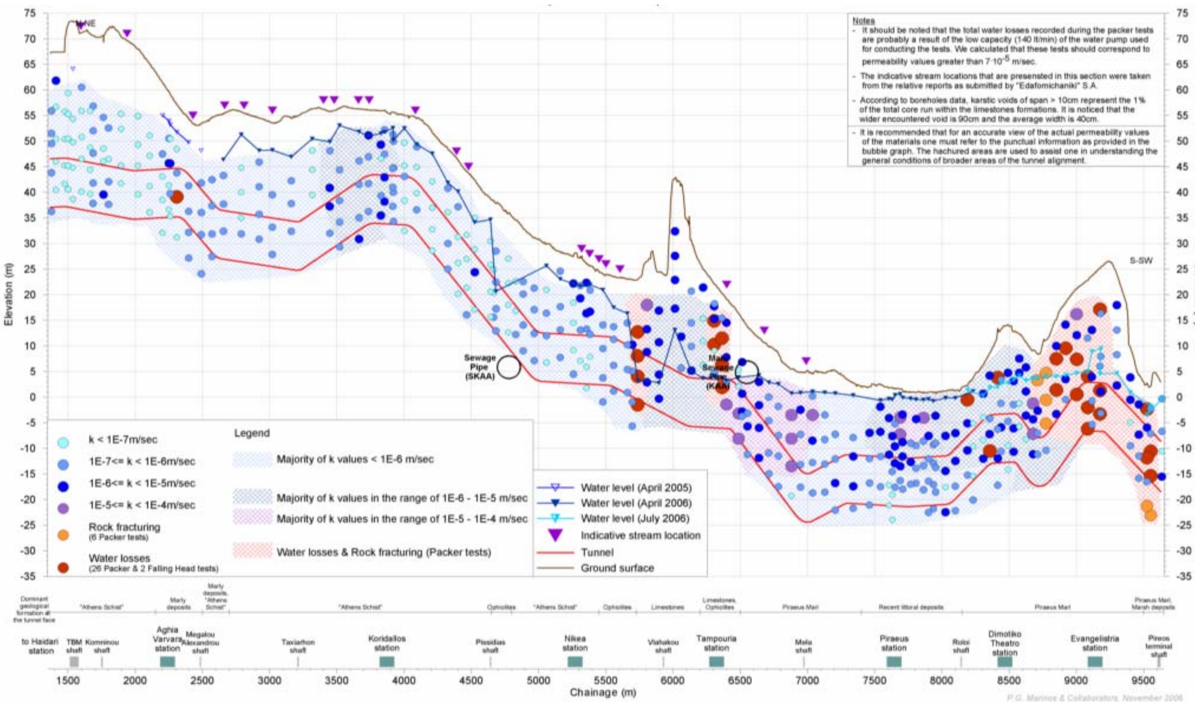


Fig. 6. Permeability distribution graph along the area of the alignment.

4.2.4. Mixed ground conditions

Difficult conditions for TBM tunnelling occur when mixed ground is present within the same excavation profile and especially when less competent formations overlay hard ground. Indicatively, mixed face conditions across the tunnel drive are shown in Fig. 7. In these cases, loss of pressure during operation has to be prevented. Slurry machines can easily handle these cases. In an EPB the AFS system (Automatic Face Support) is greatly contributing.

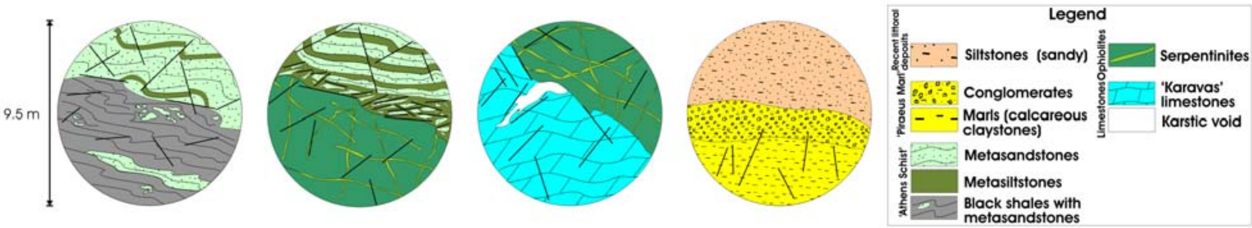
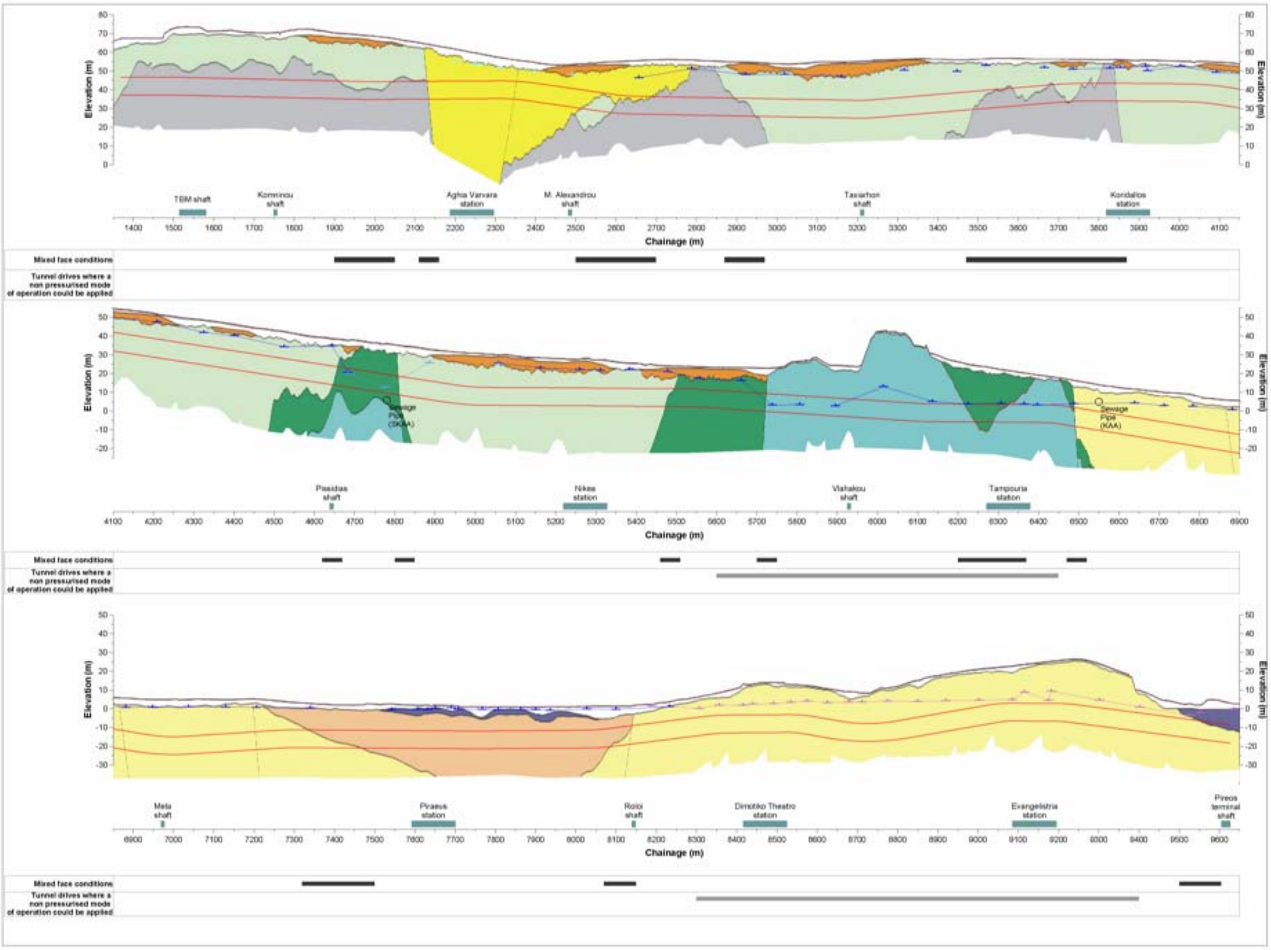


Fig. 7. Schematic mixed face conditions to be encountered.



Notes:
- The lengths and the positioning of the bars should be considered as indicative, since they depend on the type of the machine and the additional investigation results.
- Stretches where an open mode could be applied also exist in the 'Athens Schist' but they cannot be identified either now or during operation as changes are abrupt and frequent.

Fig. 8. Tunnel stretches where a non-pressurised mode of operation may be applied.

4.3 Open mode operation

Although safety issues require a pressurised face for most of the tunnel drive, there are areas where a non-pressurised mode could be applied. Fig. 8 demonstrates these areas. For instance, the tunnel drive within the competent limestones and ophiolites between (ch.~5+600-6+450) is a section where a non-pressurised mode of operation should normally be selected. The strength of these materials is significant and since in terms of structure no instability is expected, tunnelling could take place with no face support pressure in order to “avoid over stressing the machine’s mechanical functions” (BTS & ICE, 2005). The tunnel section between ch. ~8+300 and ~9+400, which will be driven within the highly cohesive ‘Piraeus marl’ formations, is an area where a non-pressurised mode of operation could most probably be applied.

4.4 Abrasiveness

Abrasive ground conditions can cause wear on several parts of the TBM during its operation. In order to assess the abrasivity of the formations a series of C.E.R.CHAR. laboratory tests were performed. Most acknowledged literature suggest the use of a hardened steel needle with a Rockwell Hardness HRC of 54-56 and as such a series of C.E.R.CHAR. tests (40 tests) were performed with this standard needle. As can be seen on Fig. 9, the tested specimens fall into the categories of 'abrasive' and 'very high abrasive' rocks (characterisation in terms of abrasivity of the rock specimens according to the abrasivity scale proposed by the Ecole Polytechnique Fédérale de Lausanne, Anonymous 2004).

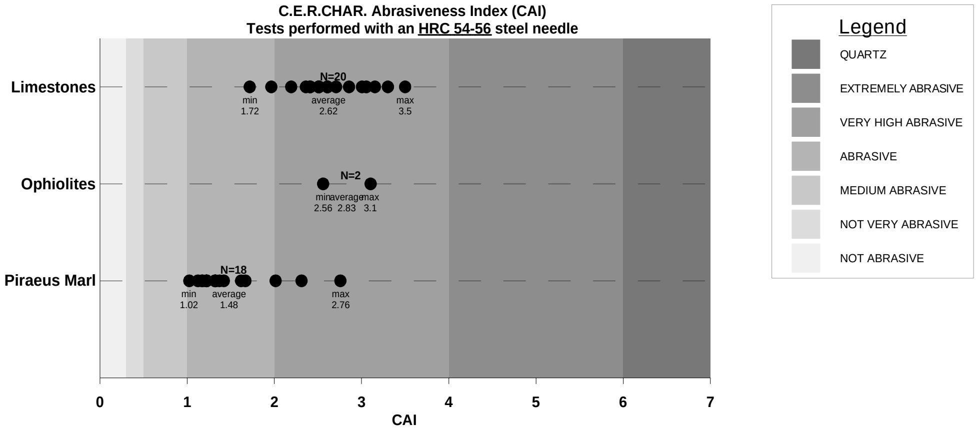


Fig. 9. The results of the second series of C.E.R.CHAR. tests.

4.5 Sticky behaviour – Clogging risk

Some types of geomaterials, especially those consisting of highly plastic clays, have the tendency to develop sticky behaviour (adhesion of clay particles to metal surfaces and/or to stick to each other). This tendency may lead during the operation of EPB machines to clogging in the cutter head, working chamber and screw conveyor or obstruct the shield advance due to friction. For Slurry machines, geomaterials of higher plasticity can lead to 'balling' problems and increased problems at the separation plant.
Geodata – Torino (Anonymous, 1995) proposed the criteria and conditions shown in Fig. 10. This diagram shows the relationship between the ratio of natural moisture content to plastic limit, the plasticity index and the categories for clogging risk. The data points suggest that the majority (89%) of the geomaterials tested have low tendency to 'sticky behaviour'.
Thewes and Burger (2004) proposed three categories of clogging potential. The diagram in Fig. 11 shows the relationship between the consistency and plasticity indices and the categories for clogging potential. This approach is less optimistic than the Geodata-Torino assessment, indicating low to medium tendency to 'sticky behaviour' but again not high.

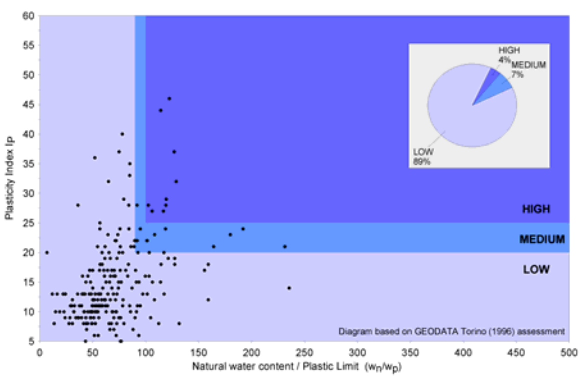


Fig. 10. Sticky behaviour of geomaterials.

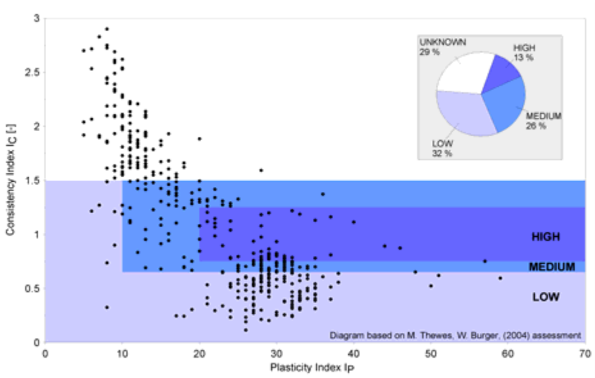


Fig. 11. Clogging risk of geomaterials.

5.CONCLUSIONS

The present paper is the product of an extensive and rigorous elaboration of all the available data from the ground investigation surveys that were undertaken in the Piraeus extension of the Metro of Athens. Considering the geological model of the project area and the findings of the assessment of all in situ and laboratory tests, the formations were assigned in groups of units with respect to their expected behaviour against tunnelling. Extended zones of weak ground conditions were that led to the conclusion that tunnelling should be undertaken with the utilisation of a closed-face tunnelling machine rather than a TBM with only mechanical support against the excavation face. Accordingly, either an EPBM or a Slurry TBM should be selected in order to prevent failures at the face and control settlement at the surface.

The Piraeus extension is a project where both types of machines will encounter 'text book' application areas yet not always. EPBMs are expected to perform better in the clayey shales of the 'Athens Schist' and the recent littoral deposits due to the high fines content of these formations whereas a better control of the applied pressure should be considered during their application in other areas. Slurry TBMs will be more efficient in the upper unit formations of the 'Athens Schist', in the altered-foliated ophiolites and in mixed faces. Marly deposits and 'Piraeus marl' should pose no significant difficulties on any of the TBMs whereas the non-altered/non-foliated ophiolites and the 'Karavas limestones' are areas where a non-pressurised mode of operation could be applied. Although both types can be used in the Piraeus extension, the risk-free operation of a pressurised face machine requires the appropriate operation, independently of the selected type.

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REFERENCES

Anonymous, 1995. Review of alternative construction methods and feasibility of proposed methods for constructing Attiko Metro Extension of Line 3 to Egaleo. Attiko Metro S.A., Greece. Geodata S.p.A.

Anonymous, 2004. Rock Abrasivity. http://lmrwww.epfl.ch. Ecole Polytechnique Fédérale de Lausanne, Laboratoire de mécanique des roches

Anonymous, 2005. Closed Face Tunnelling Machines and Ground Stability, A guideline for best practice. British Tunnelling Society - Institution of Civil Engineers. Thomas Telford Publishing.

Babendererde, S., Hoek, E., Marinos, P., Cardoso, A.S., 2004. Geological risk in the use of TBMs in heterogeneous rock masses - The case of "Metro do Porto" and the measures adopted. Workshop in Aveiro, Portugal (in print).

Langmaack, L., 2002. Soil conditioning for TBM-Chances and limits: Journées d'études internationales de Toulouse-Underground works: Living structures, AFTES.

Marinos, P., Antoniou, A., Novack, M., Benissi, M., Rovolis, G., Papadatos, I. Agelidaki, K., 1998. TBM excavation in weak and heterogeneous rock masses for the Athens Metro. Proc. of the 8th Int. Congress of IAEG, Balkema publ., ed: D. Moore et al., 3513-3522, Vancouver, Canada.

Papanikolaou, D., Marinos, P., 2002. Geological and Geotechnical study of the Athens basin (in Greek). Research Programme. National and Kapodistrian University of Athens. National Technical University of Athens and Earthquake Planning and Protection Organisation.

Thewes, M., Burger, W., 2004. Clogging risks for TBM drives in clay. Tunnels & Tunnelling International, June 2004, pp. 28-31.