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Engineering geological investigations of mechanized tunneling in soft ground: A case study, East–West lot of line 7, Tehran Metro, Iran

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ABSTRACT

The essential requirements of a successful TBM tunneling operation are the complete characterization of the ground and the thorough identification of geological and geotechnical risks. These besides other information are needed for selecting the right TBM and determining its technical specifications for proper soil conditioning and for achieving the optimum TBM performance. This paper concentrates on a methodology for engineering geological investigations and geotechnical ground characterization, which is important for successful application of mechanized tunneling methods in soft alluvial sediments along the East–West section of line 7 of the Tehran Metro. Geotechnical considerations related to tunneling with a soft ground TBM are described in detail, including the site investigation program, project-specific soil grouping system, distribution of soil types, geological–geotechnical risks (oversize grains, clogging, soil abrasiveness, fine grain content, permeability and groundwater fluctuation) and the engineering geological subsurface model. The encountered soil materials have been divided into four categories according to physical characteristics and engineering properties. In this study, the characteristics of the ground and the hydrogeological regime indicate that an EPB-TBM is rather a slurry-TBM. Although the engineering geological conditions of the ground along the tunnel are favorable for EPB-TBM, stickiness of fine-grained soils, abrasiveness of soils, existence of coarse-grained soils with low fine content and groundwater fluctuations are the most important risks for applying mechanized tunneling method in this specific project.

1. Introduction

The East–West lot of Tehran Metro line 7 (EWL7TM) is planned to be 12 km long, and composed of a 9.16 m diameter tunnel and 12 underground stations. The proposed tunnel route will be constructed at a depth of 15 to 25 m beneath an urban area. The tunnel will be excavated by a fully-mechanized method.

Characterizing the ground along the tunnel and predicting the geological, hydrogeological and geotechnical conditions with respect to mechanized tunneling are essential tasks to perform before the design and construction of a tunnel. Any unforeseen adverse geological and hydrogeological condition, especially in mechanized tunneling projects, can increase construction time and cost and cause more risks for the workers, additional environmental damages and more ground settlement problems (Rienzo et al., 2008). If ground conditions, geotechnical hazards and difficult soils are not known or expected, the ensuing outcome will often be costly, delayed and disputed during tunnel construction. Good geological predictions and identification of geotechnical risks are required for TBM design and use (Parker, 2005; Price, 2009). To correctly identify the risks involved, a thorough assessment of ground condition would be necessary, which in addition to the general subsoil data must also include all the information regarding the sporadically occurring risks such as obstacles or difficult local subsoil conditions (Thewes, 2007). The anticipated geotechnical conditions and geological hazards along the alignment are critical to the selection of the machine. Some research works have recently been presented on the assessment of difficult soils and the prediction of geological–geotechnical risks for EPB tunneling, including the stickiness and clogging risks (Thewes and Burger, 2004; Martinotto and Langmaack, 2007; Marinos et al., 2008, 2009; Sass and Burbaum, 2008; Ball et al., 2009) and abrasiveness of soil (Nilsen et al., 2006a, 2007; Plinninger and Restner, 2008; Thompson et al., 2008; Thuro and Käsling, 2009; Tarigh Azali and Moammeri, 2012). In the present study, based on the geological predictions and normal distributions of soil properties, the types of hazards have been predicted and their intensities were estimated over the entire length of the considered tunnel. The study starts with a literature review regarding the geology and geotechnical characteristics of the project area. A preliminary site reconnaissance has been undertaken to assess the existing trenches and excavations and to decide on possible borehole and test pit locations (Figure 1). The detailed investigation of the tunnel site has been carried out by drilling boreholes and test pits, performing in-situ tests, selecting soil core samples for laboratory testing, core logging, and by performing laboratory tests.

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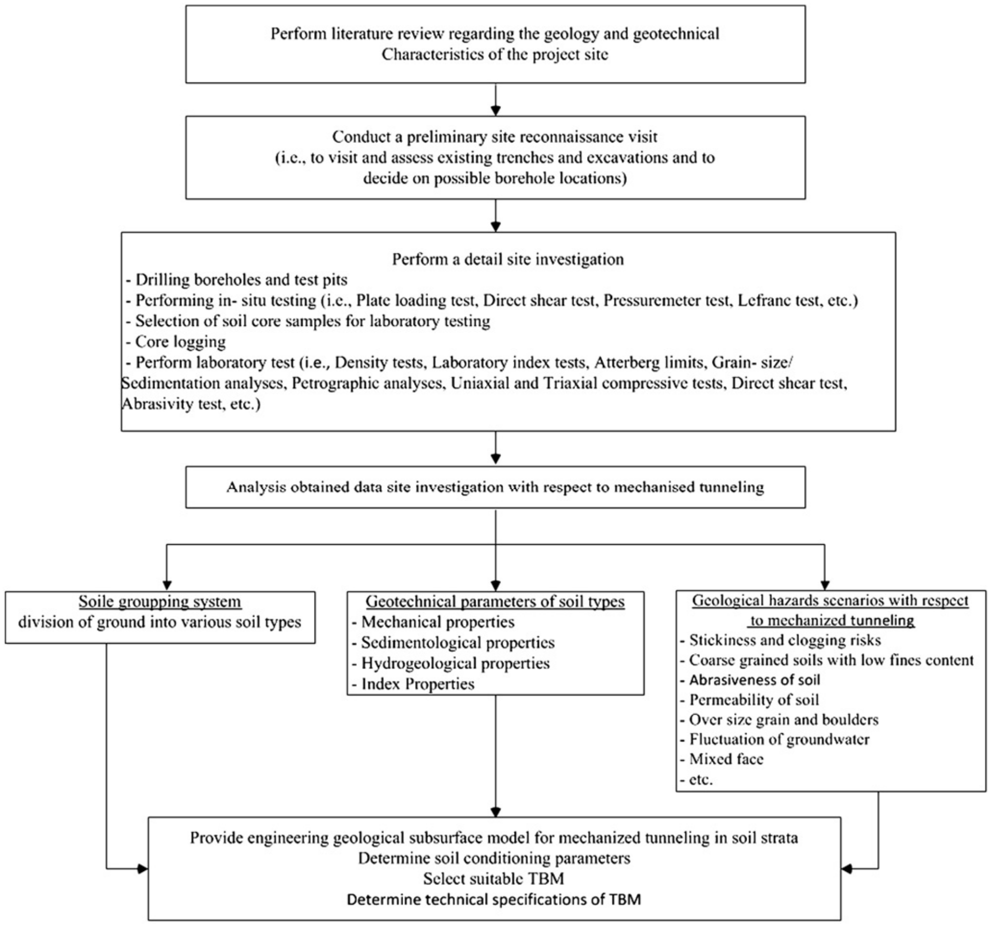


Fig. 1. Flow chart of engineering geological investigation for mechanized tunneling in soft ground.

2. Geological setting

Tehran is situated in front of the Alborz Mountain ranges, a tectonically active region between the Caspian Sea and Iran plateau. The Tehran region is confined to the north by the Alborz Mountains, to the south by mount Bibi Shahrbanoo, and to the east by mount Sepahieh. Tehran is divided into three structural and stratigraphic zones including the northern mountains, eastern and southern mountains, and the Tehran plain. The Tehran plain mainly consists of quaternary formations, which are often the result of erosion and re-deposition of former sediments. The plain extends to the south as a young fan, and generally consists of unsorted fluvial and river deposits. The effects of climatic processes as well as recent tectonic activities have caused an alluvium of various types, thicknesses and grain sizes to be formed (Shafiee and Azadi, 2007). Rieben (1955, 1966) and Pedrami (1981) classified the Tehran plain into four formations identified as A, B (Bn and Bs), C and D (from oldest to youngest), as shown in Fig. 2. The A formation is mainly composed of cemented, hard and homogenous conglomerate, with a maximum thickness of 1200 m. The A formation is overlain by the B formation which consists of heterogeneous conglomerate with a maximum thickness of 60 m. The B category has variable cementation, but it is usually weakly cemented. Pedrami (1981) has divided the B category into two units of Bn in the north and Bs in the south. The C category is composed of variable grain sizes from clay to cobble, and has a thickness of less than 60 m. The cementation of the C formation is less than that of the A formation. The youngest formation in the Tehran alluvium is the D formation, which consists of non-cemented soil with variable grain sizes (from clay to boulder) (Fakher et al., 2007). The proposed tunnel route will pass through the D formation (at shallow levels) and the C formation (at deeper levels).

3. Site investigation

In this study, subsurface stratification, groundwater conditions and geotechnical characteristics of the ground have been investigated by performing a detailed geological/geotechnical investigation in the project area. Geotechnical investigations have mainly included some field explorations and surveying, in-situ testing, laboratory tests, desk studies and data processing and analyzing.

3.1. Drilling

Borings were made at the project site to verify subsurface conditions and to obtain soil samples for laboratory testing. A total of 78 boreholes and 20 test pits were drilled along the proposed tunnel alignment. In most cases, boreholes and test pits were extended more than 5 m below the invert level, and had minimum and maximum depths of 20 and 60 m, respectively. Deeper boreholes were drilled to reach the water table and obtain the hydrogeological data and groundwater fluctuation regime. To obtain the required geotechnical parameters and evaluate the ground conditions along the tunnel route, in addition to field tests and observations, a plan was arranged for systematic sampling and laboratory testing during the site investigation program. Thus, the required disturbed and undisturbed samples were obtained from the test pits and boreholes. Most of the boreholes were equipped with piezometers to collect hydrogeological data during the construction.

3.2. Evaluation of ground conditions

In this study, the required geotechnical data (such as permeability) have been obtained from borehole logs and in-situ tests, and other

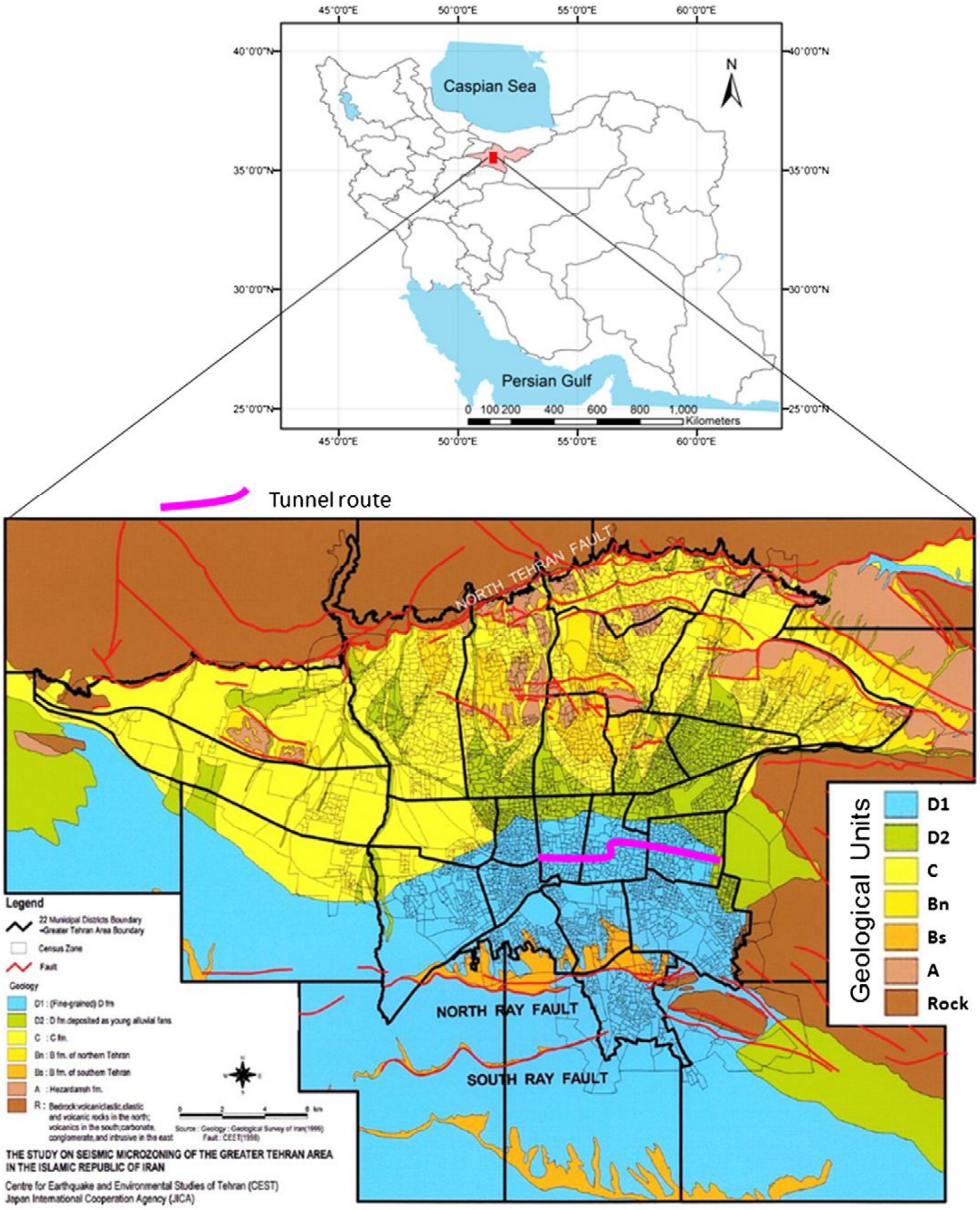


Fig. 2. Geological map of Tehran plain and distribution of different members of Tehran Alluvia (JICA, 2000).

geotechnical data (such as particle size distribution and Atterberg limits) have been acquired from various laboratory tests. The raw collected data have been analyzed using the ordinary statistical methods, and the results have been presented in the form of graphs and cross sections for tunnel alignment. These results have been briefly discussed in the following sections.

3.2.1. Grain size distribution

The soil's grain size distribution has been studied through particle size analysis of some selected soil samples in the laboratory, using the combined method of sieving and sedimentation. The sieve analyses were conducted according to the American Unified Soils Classification System (AUSCS). The soil samples collected for that purpose were numerous and as representative as possible of the actual conditions along the tunnel alignment area. Fig. 3 shows the spatial distribution of soil classification (according to the AUSCS) along the tunnel alignment. It is clear from Fig. 3 that the coarse-grained soils (sand, gravel) are predominant along the eastern parts, yet there are restricted areas where deposits with fine particle size (silt and clay) might be encountered. As mentioned before, the grain size of the soil layers in the project area lies in a wide range, from cobble to colloidal clay.

3.2.2. Consistency limits

The plasticity characteristics of the fine fractions of the soil layers have been studied by performing the consistency limit (Atterberg limits) test on selected soil samples in the laboratory, in order to determine the plastic limit (PL), liquid limit (LL) and plasticity index (PI) of the fine-grained portions of the soil strata.

In terms of the liquid limit (LL), the soils were divided into four categories (Bell, 2000): 1) lean/silty (LL < 35); 2) intermediate (35 < LL < 50); 3) fat—very fat (50 < LL < 90); and 4) extra fat (LL > 90). The liquid limit values of soil samples have been presented graphically on the pie chart of Fig. 4a. This chart displays the

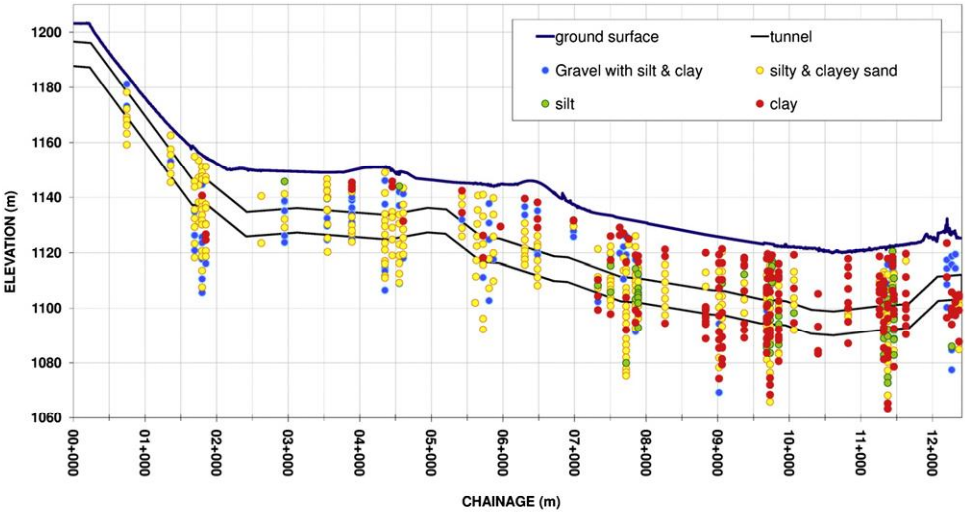


Fig. 3. Distribution of soil type classified according to the USCS along the tunnel alignment.

contribution of each value to the total. As shown in Fig. 4a, most of the samples can be classified as lean/silty soils (LL < 35%).

The test results for plasticity index (PI) classify the soil types into four categories (after Anonymous, 1979): non-plastic to slightly plastic (PI < 7), moderately plastic (7 < PI < 17), highly plastic (17 < PI < 35), and extremely plastic (PI < 35). The plasticity index values of the soil have been presented graphically on the pie chart of Fig. 4b. As shown in Fig. 4b, most of the samples are in the moderately plastic category (PI = 7–17%).

'Consistency index' or 'Relative consistency' (CI or Ic) is defined as the ratio of the difference between liquid limit and natural water content to the plasticity index of a soil (Venkatramaiah, 2006):

$$CI = (LL-w)/PI.$$

In the above relation, w = natural water content of the soil (water content of undisturbed soil in the ground).

According to Bell (2000), six categories are considered with regard to the consistency index of cohesive soils (Table 1). If the natural water content (w) is greater than the liquid limit (LL), Ic < 0, the soil behaves like a liquid. In addition, if Ic > 1, the soil is in a semi-solid state and is classified as very stiff to hard.

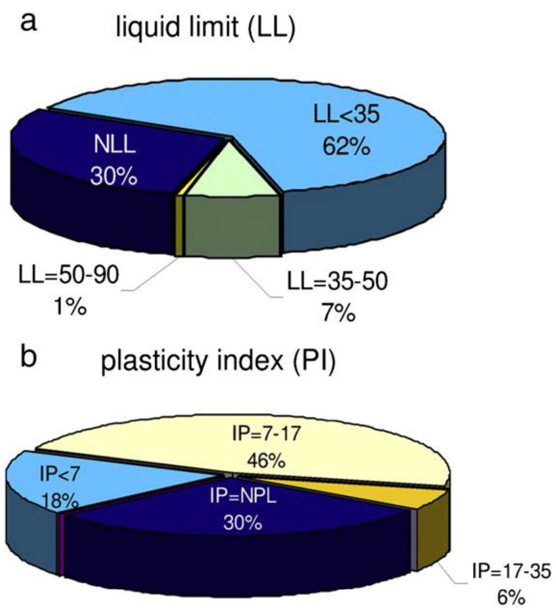


Fig. 4. Distribution of liquid limit (a) and plasticity index (b).

Fig. 5 shows the spatial distribution of consistency index (Ic) values along the tunnel alignment. As shown in Fig. 5, "no plasticity" and "very stiff" to "hard" conditions are predominant in the overburden and at tunnel depth. However, in the area between chainage 9 + 600 and 9 + 700, samples of lower consistency were identified.

3.2.3. Soil classification

In selecting and specifying a TBM, parameters such as the excavation requirements (e.g., ground conditioning), soil behavior in response to mechanized tunneling, and the content of fine and coarse particles of soils are very important and must be investigated carefully (Heuer and Virgens, 1987; DAUB, 1997, 2010; Erickson et al., 2008).

It is important to categorize the soils with respect to their behavior in tunneling operations. In this research, the encountered soil materials have been divided into four groups according to grain size distributions (content of fine and coarse particles) and engineering properties (Table 2). According to Table 2, these soil groups include:

- Group 1 (ET-1): well graded and poorly graded sandy GRAVEL & gravely SAND (GW, GW-GM, GP-GC, SW, SP), less than 12% passing No. 200 sieve (Figure 6a).
- Group 2 (ET-2): gravely SAND with silt/clay (SC, SC-SM, GC), 12 to 30% passing No. 200 sieve (Figure 6b).
- Group 3 (ET-3): very silty/clayey SAND with gravel, very sandy CLAY/SILT with gravel (SC, SM, CL), 30 to 60% passing No. 200 sieve (Figure 6c).
- Group 4 (ET-4): clayey SILT with sand, silty CLAY with sand, very sandy CLAY/SILT (CL, ML, CL-ML, rarely CH), more than 12% passing No. 200 sieve (Figure 6d).

3.2.4. Physical/mechanical parameters

In-situ and laboratory tests were carried out to determine the physical and mechanical properties of soil types. In-situ tests included the

Table 1
Consistency classification of cohesive soils (Bell, 2000).

Consistency index (Ic)	Consistency
>1	Very stiff to hard
0.75–1	Stiff
0.5–0.75	Firm
0.25–0.5	Soft
0–0.25	Very soft
<1	Liquid

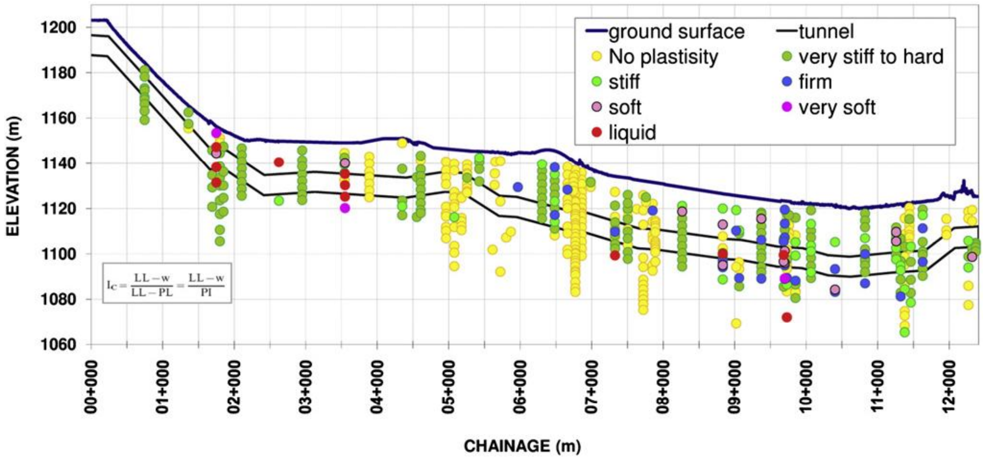


Fig. 5. Consistency index (Ic) distribution graph along the area of the alignment.

Lefranc permeability test, and the in-situ direct shear and plate load tests. The laboratory tests performed on core samples, based on the geotechnical standards, included the determination of bulk unit weight and moisture content, deformability tests, unconsolidated undrained triaxial (UU) test, consolidated undrained triaxial (CU) test, and the fast and slow shear box tests.

In this study, in order to determine the physical and mechanical properties of soil types, a descriptive statistical analysis was performed on the results of the in-situ and laboratory tests. Fig. 7 shows the boxplots of the in-situ and laboratory test results of different soil types. As shown in Fig. 7, the ET-3 and ET-4 soil types have more variations than the others. Based on the in-situ and laboratory test results and engineering judgment, the proper physical and mechanical properties of soil types have been determined and presented in Table 3.

3.3. Hydrogeological conditions

According to hydrogeological studies in the project area, the direction of groundwater flow is from N-NE to S-SW. Investigations show that in the eastern parts of the project, the water table level is lower than the tunnel invert level, while in the central and western sites, it lies above the tunnel level, and the tunnel will pass through saturated zones of soil profile. Based on the relative position of water table and tunnel, the tunnel route can be divided into five different hydrogeological zones as follows:

- Zone 1 (from 00 + 000 to 04 + 300, L = 4300 m): no water head.
- Zone 2 (from 04 + 300 to 05 + 100, L = 800 m): water head is 0–2 m.
- Zone 3 (from 05 + 100 to 05 + 600, L = 500 m): water head is 2–10 m.
- Zone 4 (from 05 + 600 to 11 + 500, L = 5900 m): water head is 10–15 m.
- Zone 5 (from 11 + 500 to 12 + 200, L = 700 m): water head is 5–10 m.

As can be seen in the above table, zone 4, which is the longest zone, is the most critical zone from hydrogeological point of view. In addition, it is observed that almost 35% of tunnel route at eastern parts lies above the water table. In this area, water and wastewater in the unsaturated zone can infiltrate the tunnel. In other parts, the tunnel is submerged, and in about 50% of the tunnel, water head stands at more than 10 m from the tunnel invert.

4. Geological–geotechnical hazards with respect to mechanized tunneling

From the assessment of geological, geotechnical and hydrological parameters, different hazard scenarios with respect to mechanized tunneling and their probability of occurrence were determined along the tunnel alignment. For this Metro line, six different hazard scenarios were established consisting of stickiness and clogging, coarse grained soils with low fine content, abrasiveness of soil, permeability of soil, oversize grain and fluctuation of groundwater.

4.1. Stickiness and clogging of soils

Some types of cohesive soils, especially those consisting of highly plastic clays, have the tendency to develop sticky behaviors (adhesion of clay particles to metal surfaces and/or cohesion of clay particles and their sticking to one another), which may lead to clogging in the cutterhead, working chamber, and screw conveyor of an EPB machine and induce "balling" problems in the pipes and at the separation plant of a slurry TBM or obstruct the shield advance due to friction (Marinos et al., 2008).

Table 2
Soil grouping system description.

Group symbol	Description	Criteria	USCS symbol
ET-1	Generally consists of sandy GRAVEL or gravely SAND. Cobbles and potentially boulders may also be present. These soils are non-plastic, have a high wear potential, and are considered non-sticky.	Less than 12% passing No. 200 sieve.	GW, GW-GM, GP-GC, SW, SP
ET-2	Generally consists of gravely SAND with clay/silt and sandy GRAVEL with clay. These soils have moderate wear potential with low stickiness potential.	12 to 30% passing No. 200 sieve. Mainly the percent sand is more than the percent gravel.	SC, SC-SM, GC
ET-3	Generally consists of very silty/clayey SAND with gravel and very sandy CLAY/SILT with gravel mixtures. These soils have low to moderate wear potential with low to moderate stickiness potential.	30 to 60% passing No. 200 sieve.	SC, SM, CL
ET-4	Generally consists of clay, silt and silt/clay mixtures of low to moderate plasticity that may contain minor amounts of fine sand. These soils have a low to moderate stickiness potential and rarely high stickiness potential. These soils are considered to be low to non-abrasive.	More than 12% passing No. 200 sieve.	CL, ML, CL-ML (rarely CH)

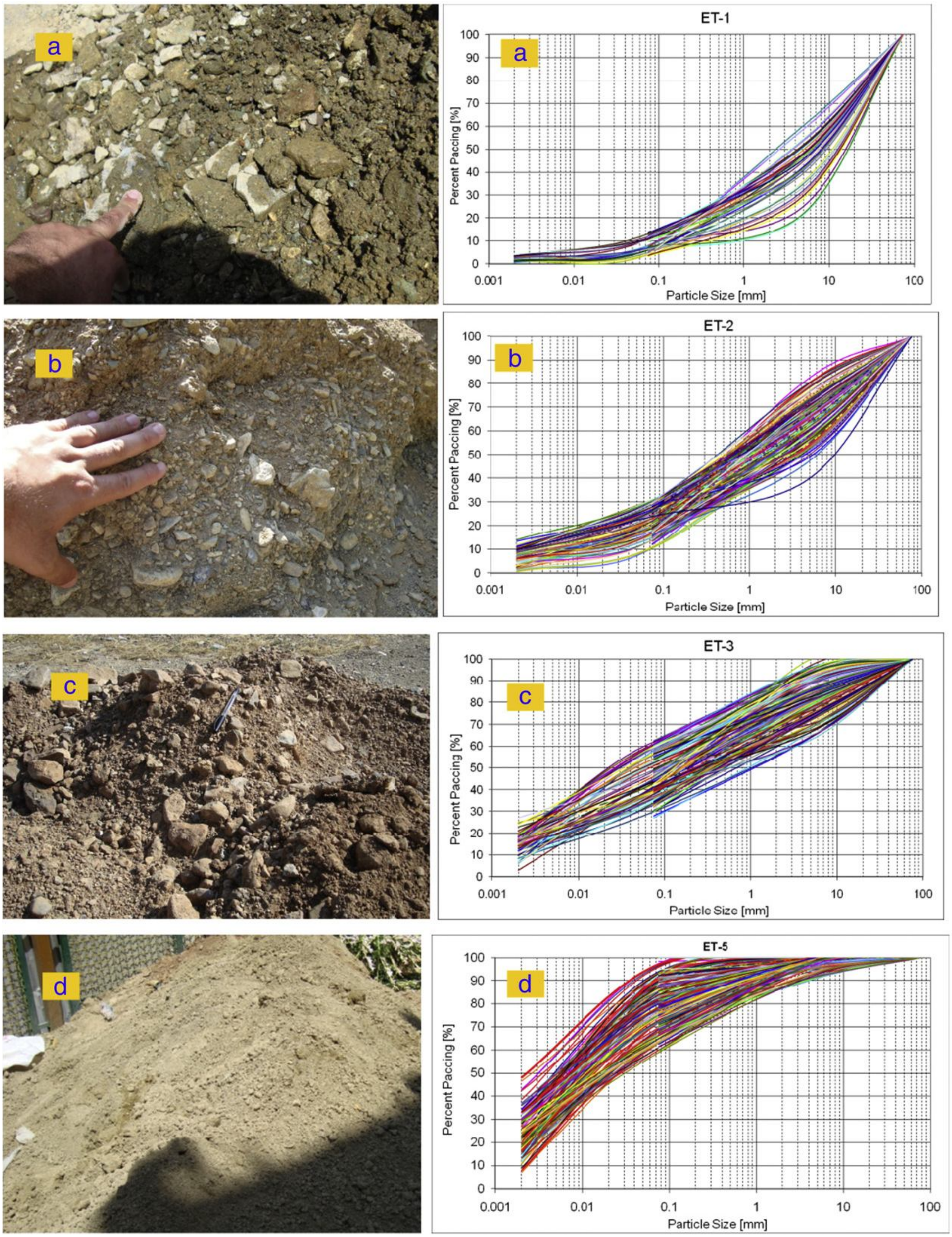


Fig. 6. Grain size distribution curves and view of different soil types: (a) ET-1 soil type, (b) ET-2 soil type, (c) ET-3 soil type and (d) ET-4 soil type.

Recently, this problem occurred in some mechanized tunneling projects driven by EPB-TBMs (Thewes and Burger, 2004; Langmaack and Feng, 2005; Rieker, 2005; Martinotto and Langmaack, 2007). When such clogging occurs, the tunnel driving process has to be stopped to allow for the cleaning of the cutting wheel and/or extraction chamber, with consequential delays and impact on the budget. It is therefore important that the adhesive properties of soils are investigated in geotechnical and geological studies in order to gain qualitative as well as quantitative information.

In this study, the potential for the occurrence of clogging during construction is discussed with regard to the approach introduced by Thewes and Burger (2004). These researchers use empirical data from

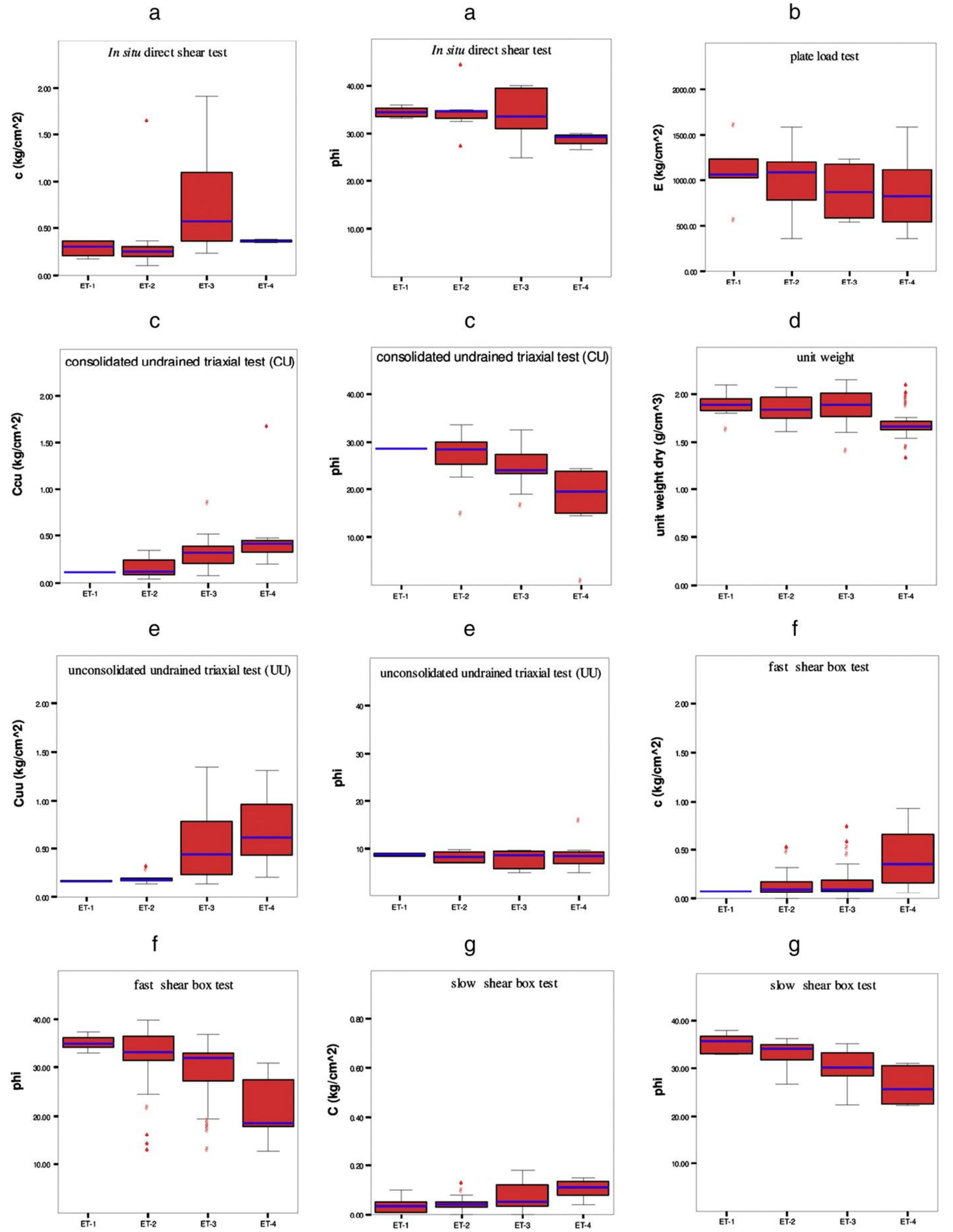


Fig. 7. Boxplots of the test results for all soil types: (a) in situ direct shear test, (b) plate load test, (c) consolidated undrained triaxial test (CU), (d) unit weight, (e) unconsolidated undrained triaxial test (UU), (f) fast shear box test and (g) slow shear box test.

Table 3
Physical and mechanical properties of the soil types.

Soil types	C′ (kg/cm^2)			Φ′ (degree)			Ccu (kg/cm^2)			Φcu (degree)			E (kg/cm^2)			Poisson ratio υ	Unit weight dry (g/cm^3)
	Range		Av.	Range		Av.	Range		Av.	Range		Av.	Range		Av.		
ET-1	0.09	0.20	0.14	33	35	34	0.11	0.24	0.16	29	30	29	700	850	800	0.3	1.86
ET-2	0.11	0.19	0.15	32	34	33	0.13	0.22	0.18	28	30	29	700	850	750	0.3	1.84
ET-3	0.24	0.36	0.30	28	38	33	0.32	0.48	0.40	22	27	23	450	550	500	0.32	1.90
ET-4	0.27	0.34	0.31	26	31	28	0.38	0.48	0.43	17	20	19	300	400	350	0.35	1.70

mechanized tunnel projects to highlight three categories of clay clogging potential based on the consistency (Ic) and plasticity (IP) indices, and show where each category occurs on the soil consistency versus plasticity curve illustrated in Fig. 8. This approach has recently been used for the assessment of fine-grained soils in some research (Martinotto and Langmaack, 2007; Marinos et al., 2008, 2009; Ball et al., 2009).

The categories of clogging potential proposed by Thewes and Burger (2004) and the recommended changes in the procedures of EPBM tunneling are as follows:

- Soils with high clogging potential cause substantial excavation problems and require daily cleaning operations. Machine modification only leads to the reduction, not the eradication of the problem.
- Soils with medium clogging potential can be handled following a number of mechanical modifications in the shield machine and soil transport system, along with changes in the operation of the machine.
- Soils with low clogging potential require a reduction in the advance rate, but making major alterations to the EPB is unnecessary.

The results of Atterberg limits and water content tests were used for determining the consistency (Ic) and plasticity (IP) indices, and then these indices were plotted in Fig. 8 to find the corresponding clogging potential category. As shown in Fig. 8, most of the samples were categorized as medium to low clogging risks, while samples with high clogging risks are seldom distributed and can be ignored.

Fig. 9 presents a distribution graph along the tunnel alignment for the likelihood of clogging risk at tunnel depths. Samples with high to medium clogging risks are likely to be encountered in the area from chainage 12 + 000 to 12 + 250.

4.2. Soils with low fine content

The slurry shield method is applicable to a wide variety of soils, from clay to sand and gravel (EFNARC, 2005), while the use of EPB machines is limited to relatively soft and fine-grained soils (particles smaller than 75 μm or particles able to pass through a No. 200 sieve). Therefore, another difficult soil for EPB tunneling is coarse-grained soil with insufficient fines combined with free water. In order for an EPB to properly

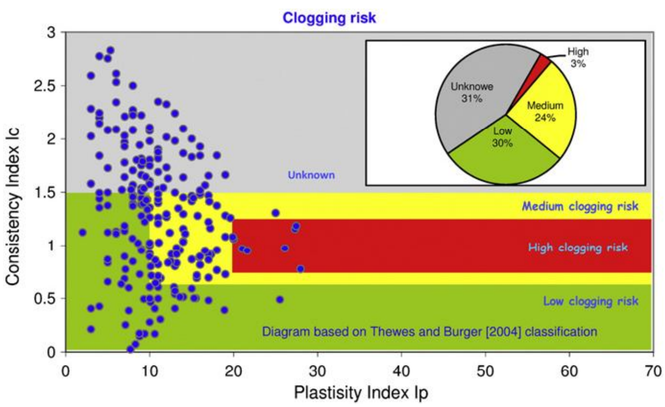


Fig. 8. Clogging risk of cohesive soils of line 7 of Tehran metro area (based on Thewes and Burger (2004) classification).

control face pressure while excavating, it must dissipate the face pressure along the length of the screw conveyor. “Toothpaste” is a term often used to describe the ideal consistency of conditioned soil mixture for an EPB-TBM. The material in the screw must be a stiff viscous fluid like toothpaste in order to properly dissipate the face pressure. Some coarse-grained soils have insufficient fines to achieve the consistency of toothpaste. Instead, they tend to drain free water and segregate it, providing undesirable spoil characteristics for the EPB-TBM spoil (Ball et al., 2009). Coarse-grained soils that segregate and drain free water do not behave like a viscous fluid, and could not be expected to dissipate pressure along a screw conveyor. If fine particles are absent in the grain size distribution, they must be added artificially (bentonite, polymers, foam) (Wassmer et al., 2001). How much fines are needed is a point of discussion. In the British Tunneling Society (BTS) guideline for closed face tunneling, a minimum value of 10% is recommended (BTS, 2005); but this would rely on the addition of polymer. Without the addition of polymer, 20% fines is the considered minimum.

Fig. 10 presents a distribution graph along the tunnel alignment showing the percentage of particles smaller than 75 μm. Samples with less than 10% grains passing the No. 200 sieve are likely to be encountered in the area from chainage 03 + 648 to 04 + 333. In addition, samples with more than 10% and less than 20% grains passing the No. 200 sieve are likely to be encountered in the areas from chainage 00 + 848 to 01 + 117, chainage 03 + 479 to 03 + 648 and also chainage 07 + 991 to 08 + 888.

4.3. Abrasiveness of soil

The term “abrasiveness” describes the potential of a rock or soil to cause wear on a tool (Plinninger and Restner, 2008). In abrasive grounds, wear can occur on several parts of the TBM, including wear on the excavation tools as well as on front, rear and periphery of the cutterhead structure, bulkhead and plunging wall structures, and on outlet devices such as screw conveyors on EPB-TBMs (Nilsen et al., 2006a, 2007). Downtimes for the changing of tools and worn parts, for example the jammed disc cutter of a TBM, are then unavoidable. Thus, it is clear that abrasiveness of rock not only determines the tool wear but also represents a considerable time factor (Thuro and Käsling, 2009).

Growing economic pressures on tunneling and mining operations has made the investigation methods for the assessment of rock and soil abrasiveness very important. Such investigations can be based on a wide variety of testing procedures and standards, and can cover a wide range of scales, from real-scale tests on the site to model tests with simplified tools, along with microscopic and chemical analyses of rocks and minerals (Plinninger and Restner, 2008). Several well-acknowledged tests and prediction methods already exist for rocks; however, there is very limited knowledge available on soil abrasiveness and its impact on soft-ground TBM operations. Three model tests are usually employed for determining the abrasiveness of rock materials, including the Cerchar test (Cerchar, 1986; West, 1989; Plinninger and Restner, 2008), LCPC test (Thuro et al., 2007; Plinninger and Restner, 2008; Thuro and Käsling, 2009) and NTNU test (Bruland, 1998; Plinninger and Restner, 2008). In contrast to model tests, geotechnical indices use a different approach for abrasiveness assessment. Some of the most often applied geotechnical wear indices include the Schimazek

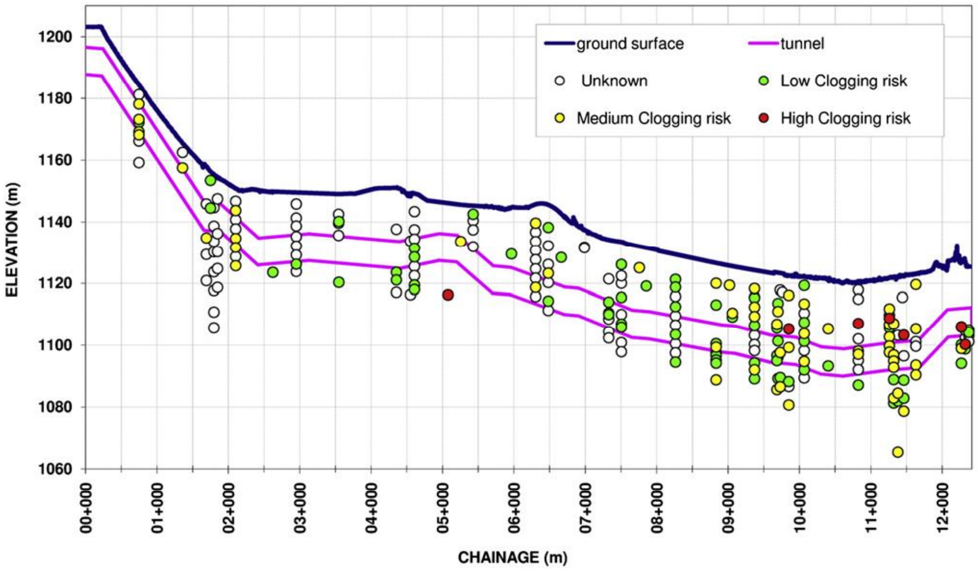


Fig. 9. Distribution graph of clogging risk of soils along the tunnel alignment.

Index, Vickers Hardness Number of the Rock (VHNR), Equivalent Quartz Content (EQC), and the Rock Abrasiveness Index (RAI) (Plinninger and Restner, 2008).

Although there is an extensive volume of literature on the abrasiveness and wear prediction of rocks, there is, in contrast, very little material on this subject for soils. The Cerchar abrasivity test is only practical for single pieces of large components of coarse gravels, cobbles and stone and block layers. Currently, Trondheim is developing his own method (Nilsen et al., 2006b) based on the classic NTNU testing suite (Bruland, 1998). Up to now, in the NTNU testing method, only the soil fractions of less than 4 mm can be tested, which reduces its application to sand. The LCPC method tests only the 4 to 6.3 mm fractions (coarse-grained material). Fine grains (<4 mm) and very coarse-grained material (>6.3 mm) are not included in the original LCPC test. Therefore, these tests are much more limited for soils than for rocks. For overcoming these limitations, in this study, the abrasiveness and wear potentials of soils along the tunnel alignment are discussed with regard to the approach introduced by Thuro and Käsling (2009). In this approach, the effective soil properties, which are quite significant in practice (i.e., mineral content, grading distribution and the roundness of grains), are reproduced by the LCPC test in the laboratory and are then entered in a diagram, in which the average grain size of a 50% mass fraction is plotted against the LCPC abrasivity coefficient LAC (Figure 12). The absolute grain size is therefore reflected in the grain size mixture prepared for the LCPC test. This leads to a classification diagram (Figure 11), in which there are fields for various soils (Thuro et al., 2007; Thuro and Käsling, 2009).

To use this classification diagram, first, the mineral contents were determined by micro-petrographic examination of some soil particles. According to the micro-petrographic examination results of the selected samples, given in Table 4 with proper photos taken in ordinary and polarized lights, these particles are mostly made of rocks with genetic groups of acid volcanic, intermediate intrusive and pyroclastic materials. The mineral composition, texture, and rock name of the examined particles are also listed in Table 4. Therefore, based on the micro-petrographic examination results, the proper field in the diagram for this soil (Figure 11) is "*coarse-grained soil with high content of crystalline components*". Next, the test results of particle size analysis were used to obtain the average grain size of a 50% mass fraction, and then these indices were plotted in the chart presented in Fig. 11 (in the field of "*coarse grained soil with high content of crystalline components*") to find the corresponding classification of abrasiveness and wear potential of

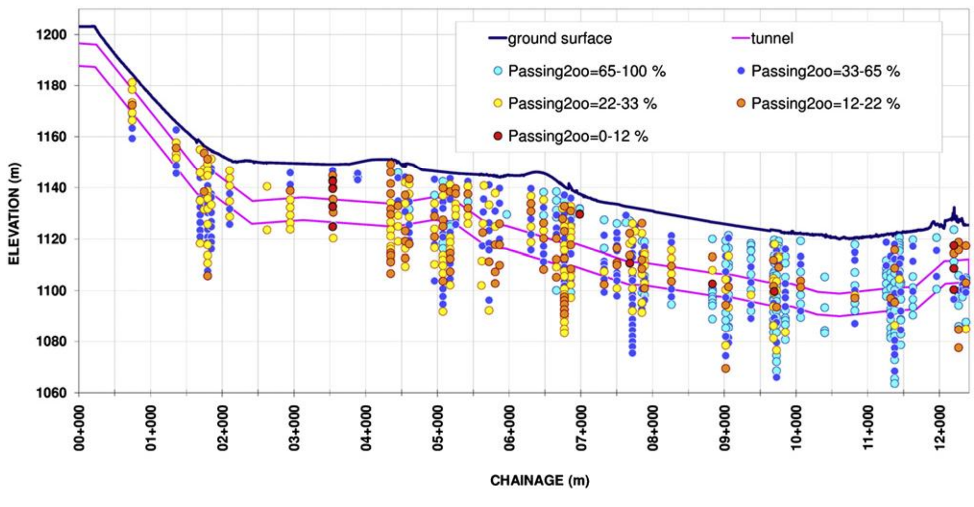


Fig. 10. Distribution graph of percentage of particles smaller than 75 μm or particles able to pass through a No. 200 sieve along the tunnel alignment.

soils. As shown in Fig. 11, most of the samples can be classified as soils with high to very high wear potential.

Fig. 12 presents a distribution graph along the tunnel alignment showing the classification of soil abrasiveness. Samples with high wear potential are likely to be encountered in the area from chainage 01 + 000 to 10 + 250.

4.4. Permeability of soil

Regarding permeability, the British Tunneling Society (BTS) and the Institution of Civil Engineers (ICE) (BTS, 2005) indicate a ground permeability of 10E−5 m/s as "the point of selection" between EPBMs and slurry TBMs (Marinos et al., 2008). Typically, the use of EPB-TBM is optimal in grounds with permeability less than 10E−5 m/s. If the permeability is higher and the tunnel alignment is under a water table, pressurized water could flow into the tunnel through the screw. Therefore, the type and quantity of conditioning agent to be added to the plenum and the screw conveyor become relevant (Guglielmetti et al., 2007). For higher permeability values (>10E−5 m/s), the use of a slurry-TBM is more suitable than an EPB-TBM. Nevertheless, a slurry-TBM applies the face-support pressure through the formation of a "cake" between the slurry and the soil. The higher the soil permeability is, the more difficult the cake formation will be.

In order to determine the coefficient of soil permeability in the project area, a number of field permeability tests (Lefranc tests) have been performed in isolated sections of the exploratory boreholes (AFNOR P94-132, 1992; CAN/BNQ 2501-135-M88, 1998). The performed in-situ permeability test results are presented graphically in Fig. 13. The results of these tests have been divided into four classes. As can be seen in Fig. 13, the majority of measurements along the tunnel route fall below 10E−5 m/s. Values higher than 10E−5 m/s were recorded in the areas between chainage 02 + 393 and 04 + 477, chainage 04 + 821 and 05 + 446, as well as in the area between chainage 07 + 991 and 08 + 888.

4.5. Oversize grains (cobbles and boulders)

Oversize grains (cobbles and boulders), frequently found in tunnels excavated through soils, can pose major problems for full-face TBMs in terms of advance rate reduction, cutter damage, and abrasive wear (Dowden and Robinson, 2001; Goss, 2002; Babendererde, 2003; Frank and Chapman, 2005; DiPonio et al., 2007; Kieffer et al., 2008; Hunt and Del Nero, 2010). Cobbles and boulders are commonly found in glacial, alluvial and residual soils (Hunt and Del Nero, 2010). When a full-face machine encounters a boulder, there are a number of possibilities. If the boulder is not too large, it can be ingested by a properly designed TBM mucking system. If the boulder is too large to be ingested, and the ground is firm, it may be broken up by a suitably equipped machine cutterhead (tunnel boring machines equipped with disc cutters). If the soil matrix is weak, the boulder may be dislodged, and it may either be pushed radially outward by the rotary action of the cutterhead, and beyond the tunnel periphery, or it may stay in the face area and eventually block further progress of the machine until it is manually removed. Depending on the prevailing face condition and cutterhead chamber configuration and accessibility, manual breakup and removal can be relatively easy or very time consuming (Dowden and Robinson, 2001; Goss, 2002).

In this study, subsurface investigations and geological surveys of other as-built projects in the study area were used for the identification and characterization of cobble and boulder fractions. During the drilling of boreholes and excavation of test pits, the maximum observed dimension of large boulders was typically 30 to 35 cm, with 10 to 20 cm being the most common. Furthermore, geological surveys of other projects previously constructed in the study area approve this finding. These cobbles and boulders are likely to be concentrated in the eastern area of tunnel alignment, from chainage 00 + 000 to 02 + 500. In addition, most of these oversize grains are spherical and semispherical in shape. The lithological composition of boulders is often rhyolitic tuff, and rarely limestone. In this study, in order to estimate boulder volumes encountered during the tunneling, the average boulder volume ratio (BVR) was also determined. BVR is boulder volume as a percentage of excavation volume. Boulder volume ratio methods involve the semi-empirical correlation of geologic and investigation data with the previous results of tunnel and excavation experience in the same geologic units (Boone et al., 1998; Hunt, 2002; Hunt and Del Nero, 2010). Test pit log and previous excavation experience in the study area indicated that only trace amounts of boulders (BVR < 1%) will be encountered through most of the tunnel route.

To cope with boulders and protect the machine during the excavation, the cutterhead should be equipped with disc cutters. Due to the rolling movement of the disc cutters, single pieces – so-called chips – are broken out of the boulder. Otherwise, it may be necessary to manually split or remove the boulders in the tunnel face.

4.6. Groundwater fluctuation

Calculating the appropriate earth pressure in advance of TBM tunneling to avoid potential instability is of primary importance (O'Carroll,

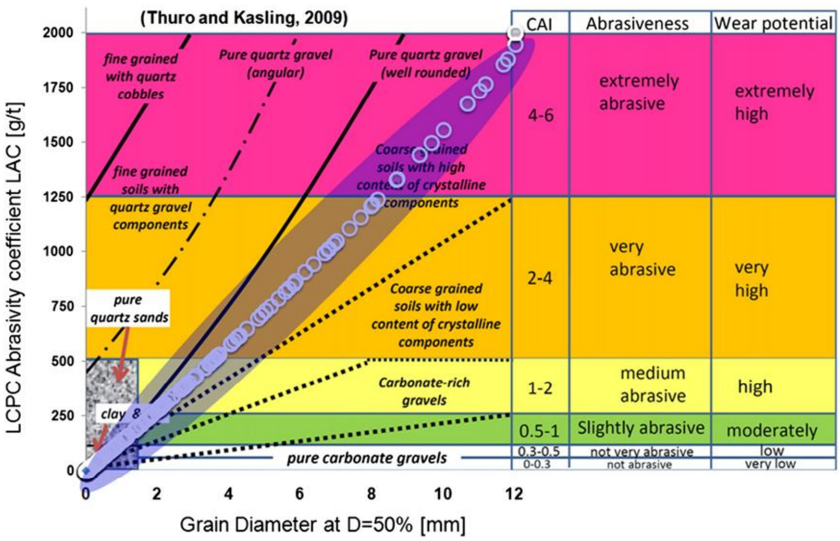
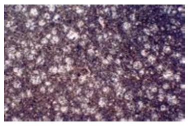
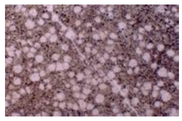
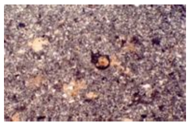
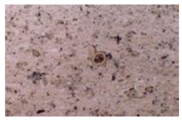


Fig. 11. Classification scheme for the abrasiveness coefficient with allocation for different soil types (after Thuro and Käsling, 2009).

Table 4
Micro-petrographic examination results of the particles of soil.

Mineral composition	Texture	Rock name	Photo	
In all probability, feldspars with free silica, opacite minerals, as iron oxides.	Cryptocrystalline/amygdaloidal	Rhyolitic tuff		
Mostly feldspars with less free silica, as quartz, alteration products, as calcite and chlorite, opacite minerals.	Aphanitic (tuffaceous)	Rhyolitic tuff		

2005). The earth pressure is directly related to groundwater head. In this study, in order to determine and monitor the groundwater head, groundwater levels in the drilled boreholes have been periodically measured. The results of groundwater monitoring indicated water head fluctuations at different levels in some areas. This phenomenon was generally caused by seasonal rains and the presence of pumpage wells. In the study area, many pumpage wells were installed to draw down the regional groundwater level. These wells withdraw the groundwater and create a depression cone. When the wells do not pump, the groundwater level increases; and in fact, the depression cone in the study area creates an artificial groundwater level (dynamic condition) even though the sewage system recharges the groundwater. It is estimated that the fluctuations of groundwater level in the central and western parts of the tunnel are about 7 and 14 m, respectively.

5. Engineering geological subsurface model

After the geotechnical investigations, a geological engineering cross section with respect to EPB-TBM tunneling was generated showing the interpreted stratigraphy of soil types along the proposed alignment (Figure 14).

6. Selection of TBM type

Due to settlement concerns in most of tunnel length, selected machine must have a pressurized face and be able to maintain positive ground control. The question is that which one of two commonly used types of pressurized face machines is more appropriate for this particular project, Earth Pressure Balance (EPB) or slurry machines. The subject of TBM selection according to the geological conditions has attracted much attention of many researchers recently (Marinos et al., 2008, 2009; Hassanpour et al., 2013). In these researches, the characteristics of the ground and the hydrogeological regime indicated that an EPB-TBM is rather a slurry TBM.

The type and configuration of TBM are decided depending on the size of the tunnel and the geological conditions of the ground. The main geological factors affecting the TBM selection are: grain size distribution, fine grain fraction, permeability, consistency index (Ic) and abrasiveness (LCPC abrasivity coefficient LAC) (BTS, 2005; DAUB, 2010).

Grain size distribution of soil layers is the most important criterion for selecting suitable machine. Figs. 15 and 16 show the grain size distribution range of four identified soil groups superimposed on Langmaack (2002) and Thewes (2007) charts, respectively. As shown in Fig. 15, the majority of the envelopes suggest that the soils to be encountered during tunneling are made up of a high percentage of fines. So, it can be concluded that an EPB machine should be able to effortlessly handle most of the soil groups identified along the project line. It seems that only gravelly soils of ET-1 group are out of the EPB application range, but since, in most cases, have enough fines, an adequate earth paste in the working chamber can be formed and it is not expected that they create severe problems to the boring procedure.

As shown in Fig. 16 conditioning agents like foams, polymers and fines must be used in granular soils of ET-1 and ET-2 groups in order to increase the plasticity and reduce the permeability of the muck as granular soils are generally highly permeable and have very poor plastic deformation behavior. Also, application of certain types of conditioning agents in ET-3 and ET-4 groups will be necessary for maintaining consistent face pressure and reducing the clogging effect.

The vast majority of the envelopes suggest that the soils to be encountered during tunneling are made up of a high percentage of fines;

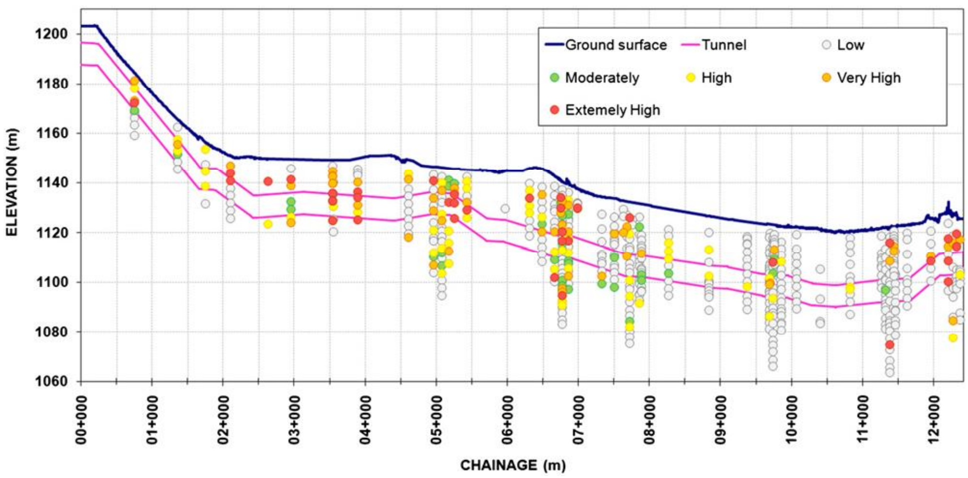


Fig. 12. Distribution graph of wear potential of soils along the tunnel alignment.

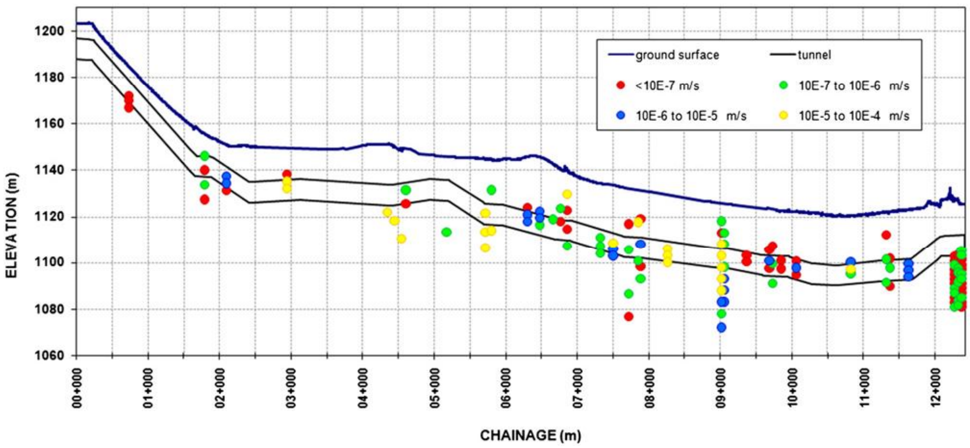


Fig. 13. Permeability (hydraulic conductivity) distribution graph along the area of the alignment.

this fact directs toward the use of an EPBM. The British Tunneling Society (BTS, 2005) suggests that a fine percentage higher than 20% renders the use of a slurry TBM questionable, whereas fines should be higher than 10% for an EPB-TBM to work properly. It is apparent from Fig. 10 that an EPB-TBM should be able to effortlessly confront the soils of the project area.

Another important selection criterion is the hydrogeological regime of the area. In terms of permeability, BTS (2005) indicates a ground permeability of 10E−5 m/s as "the point of selection" between EPB-TBMs and slurry TBMs, where the slurry TBMs are more suitable for higher values, and, accordingly, EPB-TBMs are more suitable for lower values. In Fig. 13, the in situ permeability tests were presented, and most of them indicated permeability values lower than 10E−5 m/s. Thus, an EPBM is more suitable for the largest part of the alignment, and the need for increased use of conditioning agents is reduced to just a few isolated sections of the TBM route.

In terms of consistency index (Ic), DAUB (2010) suggests that EPB-TBMs are more adequate in soils with Ic higher than 0.5. As shown in Fig. 5, soils with Ic higher than 0.5 are predominant in the overburden and at tunnel depth, thus an EPB-TBM is more suitable for the largest part of the alignment.

According to DAUB (2010), EPB-TBMs are more adequate in soils with LAC higher than 2000 g/t. In Figs. 11 and 12, the LCPC abrasivity coefficient and wear potential of soils along the tunnel alignment were presented, and approximately the vast majority of them indicated LAC lower than 2000 g/t. Thus, an EPB-TBM is more suitable for the largest part of the alignment, and the need for increased use of conditioning agents (anti-abrasion foam) is reduced to just a few isolated sections of the TBM route.

In general, an EPB-TBM appears to be the reasonable choice for the project in all aspects of tunnel safety and tunneling performance. The characteristics and parameters of the soils and the hydrogeological regime direct toward this selection, and it is expected that all the objectives, such as settlement and ground movement control, water-table level maintenance, and adequate performance, will be met by an EPB-TBM, provided it is properly operated.

7. Conclusions

This paper has explained the ground conditions, geological hazards and difficult soils encountered during the soft ground mechanized tunneling operation along the Tehran Metro line 7. In this study, six different hazard scenarios for EPB tunneling were identified consisting of stickiness and clogging, coarse-grained soils with low fine content, abrasiveness of soil, permeability of soil, oversize grains and fluctuation of groundwater.

The following conclusions can be drawn from the present study:

- In underground construction, the clogging of machinery by clayey soils and the adhesion of clays to steel surfaces of machinery may significantly reduce the machine's efficiency. This study indicated that most of the proposed tunnel route is not affected by a high clogging risk.
- EPB machines are applicable to relatively soft and fine-grained soils. The major portion of tunnel route area has soils with more than 10% grains passing the No. 200 sieve.
- The abrasiveness of soil particles along a tunnel alignment plays a dominant role in many of the major decisions that must be taken in planning, designing, manufacturing and excavation of an EPB-TBM tunneling. Soil masses around the tunnel, in some portions of the route, have a high wear potential (LAC value is more than 1500 g/t). Soil abrasiveness constitutes an important geological hazard along the tunnel route.
- Determining the frequency, size range and the shape of boulders which will be encountered in the tunnel envelope is one of the most difficult tasks in the engineering geological investigations of soft ground tunneling projects. The maximum size of large boulders encountered during the drilling of boreholes and excavation of test pits was typically 30 to 35 cm.
- Regarding permeability, the use of EPBs is optimal in grounds with a permeability of less than 10E−5 m/s. The field permeability test results indicate that most soil permeability values measured along the tunnel tube range below 10E−5 m/s.
- Based on the relative levels of water table and tunnel, almost 65% of tunnel route at western parts is below the groundwater table. The results of groundwater monitoring indicate the presence of water head fluctuation at different levels in some areas.

The results of the analyses reveal that an EPB machine is the suitable choice for the project in all aspects of tunnel safety, ground control, and tunneling performance, but four geological risks of stickiness of fine-grained soils, abrasiveness of coarse-grained soils, existence of coarse-grained soils with low fine content and groundwater fluctuations are major influencing risks for applying mechanized tunneling method.

In order to extend the application field of EPB-TBMs to various geological conditions, the soil to be excavated has to be treated with conditioning agents like foams, polymers and fines in order to modify its mechanical properties, changing it into a plastic paste and coping with geological hazards. In the case of EWL7TM tunnel, the TBM will occasionally traverse coarser-grained sandy materials which are expected to require ground treatment in some combination of foam, polymers, and fines. One sieve analysis indicates course-grained material (ET-1 and ET-2 soil groups) which could be problematic to control with

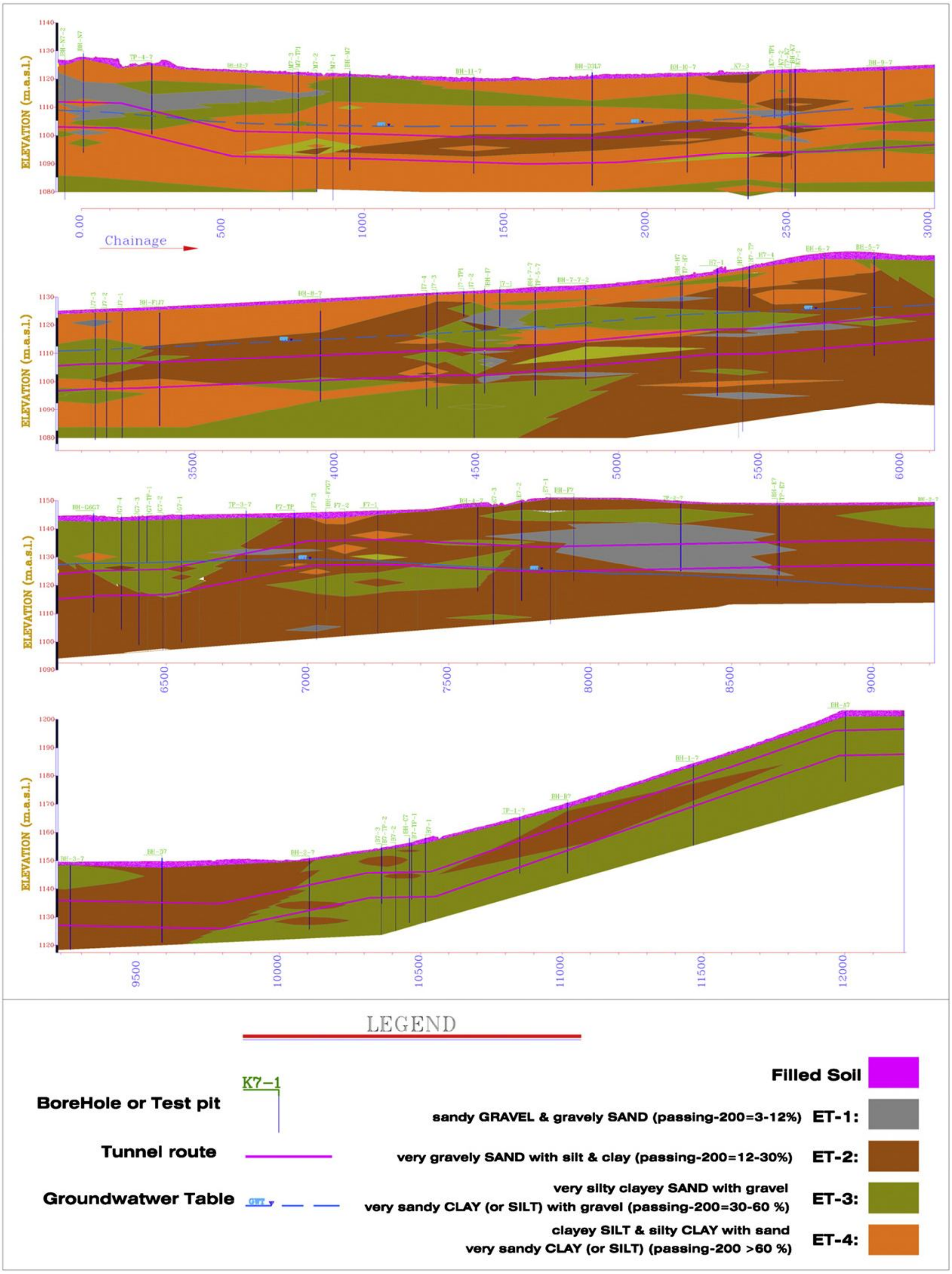


Fig. 14. Engineering geological subsurface model.

ground treatment. In addition, it can be seen that ET-3 and ET-4 soil groups fall mostly within the zone of normal Earth Pressure Balance (EPB) machine operation, but ET-4 soil group needs anti-clay foam to cope with the clogging.

There is a fundamental difference between the ways engineering geological investigations are conducted for underground construction and that of any other project. For a large-scale mechanized tunneling project, the impacts of geological hazards are increased costs and long

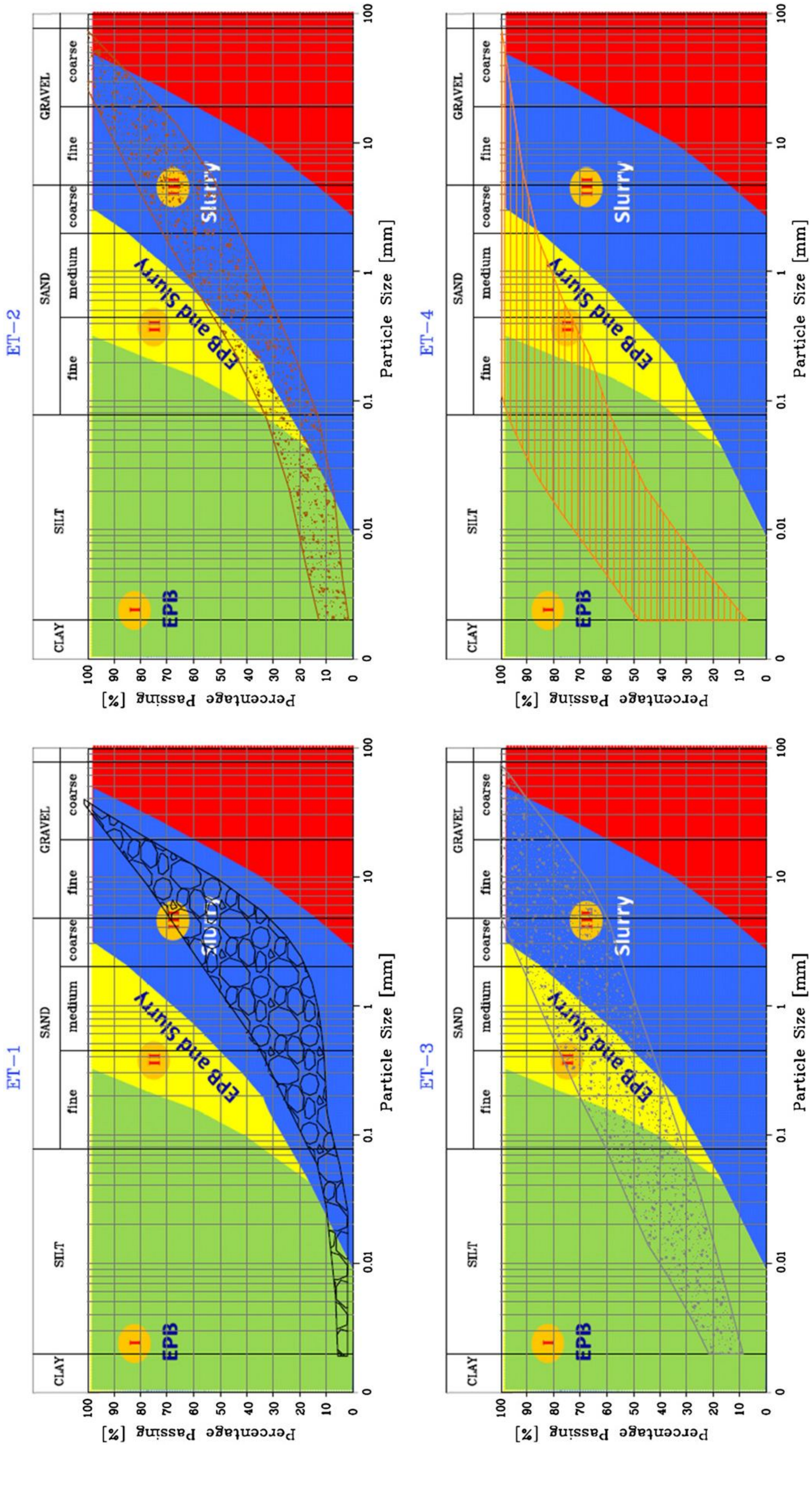


Fig. 15. Grain size distribution envelopes of four identified soil groups in Langmaack (2002) chart.

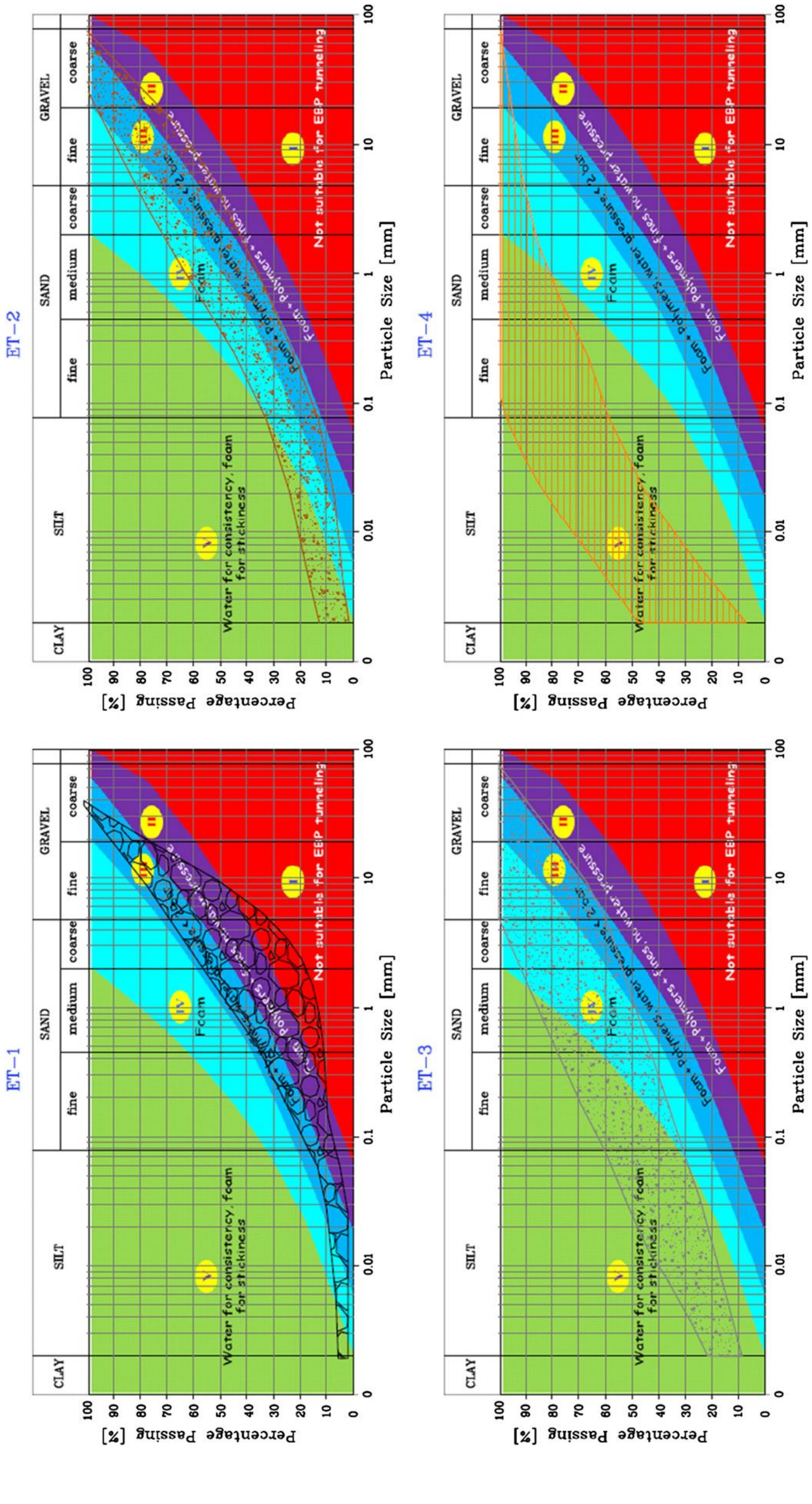


Fig. 16. Grain size distribution envelopes from sieve tests regarding the effective applicability of EPB tunneling operations (conditioning curve after Thewes, 2007).

delays. Therefore, these projects should be investigated during the design stage in order to gain a better understanding of the costs involved and a better design of the machines; otherwise, these unpredicted effects will result in various disputes and claims between the parties involved in the project.

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