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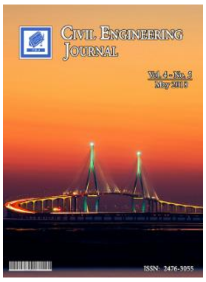

Geotechnical Challenges of Tehran Metro Line 7 (South Northern Route)

Farzad Sadjadi [a], Ahad Bagherzadeh Khalkhali [a*]

[a] *Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.*

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Abstract

Tunneling in urban areas, has raised the level of difficulty and challenge in respecting the constraints deriving from human presence and, therefore, the necessity for the study of geological and geotechnical properties and parameter, classification of the soils according to their engineering behavior, choosing the right TBM, determine groundwater level and determining possible geological hazards. In this paper some geological and geotechnical study took place along the tunnel route. This investigation is done by the result of 73 machinery borehole and 32 manual borehole that took place in the process of studying the tunnel route and continued by the result of field tests and laboratory tests and according to the result, the geological zone classified in 6 zone in tunnel route; due to the result of Cerchar abrasivity test and since Alluvial soil is the main soil in most of the tunneling route, the excavation soil classified as highly abrasive. In some part of tunnelling there is a risk of clogging due to the high amount of clay. Based on the results of Lofran tests the permeability of most of the classified soils in route of the tunnel was obtained less that 10E-7 m/s.

Keywords: Liquefaction Potential Index; Geographic Information System (GIS); Yangon City; Liquefaction Potential Map; SPT Data.

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1. Introduction

The north-south section of Tehran Metro Line 7 begins on the mountain road (West Side) near the Yadgar Imam highway in northwestern Tehran, and continues east-westward to the Cave Field. Around the northern part of the Cuyor field, it moves along the path to the highway. The tunnel route in the Hemmat highway with torsion to the east along the Chamran highway and then Navab highway to the intersection of Qazvin Street continues and connects to the eastern-western part at 7N station. This section of the tunnel route has a length of about 14 kilometers and contains 12 stations, which are shown in Figure 1 of the north-south section of the route on the satellite image. Deep sections of drilling are located in lowlands and shallow parts of the plain. The sensitivity of studies in these projects is very high due to drilling inside the city. Therefore, accurate and comprehensive identification is necessary in order to understand the geotechnical position of the road along the route and to investigate the hazards caused by the existence of some natural and artificial factors.

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* Corresponding author: a-bagherzadeh@srbiau.ac.ir

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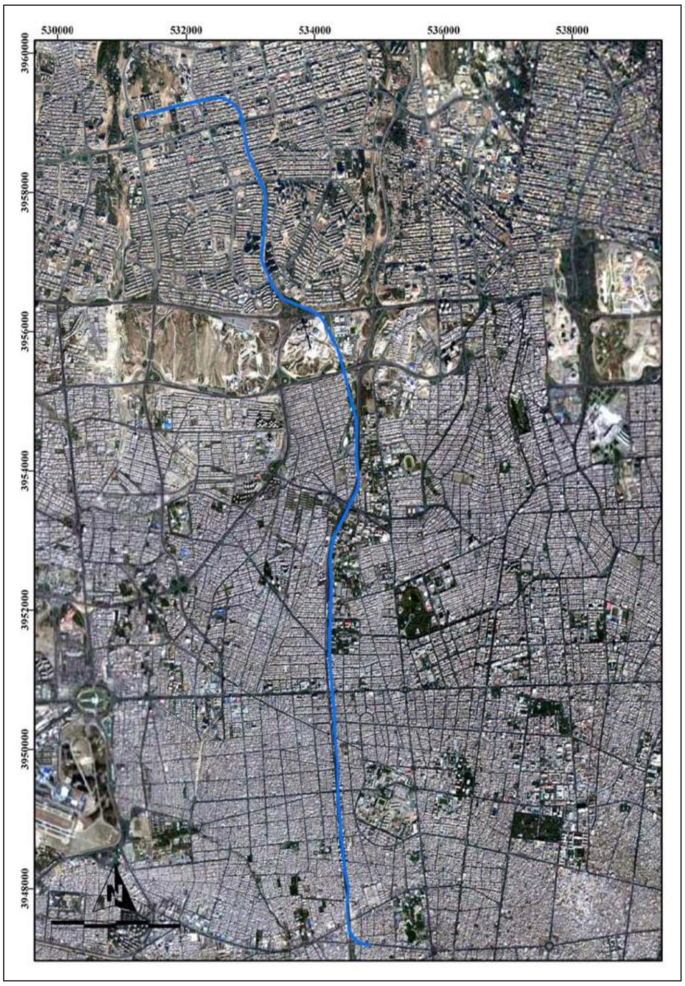


Figure 1. The location of the drilling path on the satellite image

2. Geological Studies

Geotechnical studies including boreholes and wells drilling and field and laboratory tests at various stages of the project have been carried out by various geotechnical companies. All analyzes and results presented in this report are based on the information obtained from the above studies.

2.1. Exploratory Drilling

During the preliminary studies, 22 boreholes and 8 exploration wells on the north-south section of the 7th line of the Tehran metro have been excavated by the Fanvaran Company. Then, during the complementary studies, 51 boreholes and 24 wells were drilled in a station location, a total of 32 wells with a total length of 775.5 meters and 73 boreholes with a total length of 2927.2 meters were drilled.

2.2. Field Experiments Are in Place

Field tests such as plate loading test, direct shear, pressure meter, SPT, Lofran permeability test and local density in drill holes and wells drilled, in situ, and perimeter by various geotechnical contractors, field test results has been extracted and analyzed from different geochemistry reports. The list and number of tests used in this report are presented in Table 1.

Table 1. List of field tests of the north-south section of Tehran Metro Line 7

Experiment	In-situ Direct Shear	Plate loading	Pressure meter	SPT	Lofran		Density at site
					constant	Falling	
Number	70	95	48	914	121	121	88

2.3. Laboratory Tests

Laboratory tests such as direct shear, three-axis, Soil gradation and Atterberg limits, consolidation, permeability and preparation of XRF sections, single-axis, soil and water chemistry, Cerchar test, Los Angeles test, thin-film thickness on samples taken from wells and speculations have been carried out in different stages. The number and type of tests performed in Table 2 are presented.

Table 2. Laboratory Examples of Northern-Southern Section of Tehran Metro Line7

The experiment	Direct shear	Three axis	Consolidation	phase relations and physical characteristics	Cerchar test	Los Angeles test	The hardness of the mouse	XRF	Thin section	Water chemistry	Soil chemistry	Single axial	Buckling	gradation	Permeability	
		CU													fall down	constant
Number	184	54	39	298	10	10	11	11	11	34	100	36	16	795	60	60

3. Geology of the Tunnel Route

The north-south section of Tehran Metro Line 7 is located in Quaternary alluvial plain of Tehran plain. The drilling path also passes through the Ayoubi fault zone and Tarsht fault. In this study, the criteria for Thewes (2007) criteria were used to select an interval for fine-grained particles. According to the results of field and laboratory studies, the soil layers comprising the tunnel route are divided into six units (types) of engineering geology (Table 3).

Table 3. Specifications of Engineering Geology Units in the tunnel route

Engineering Geology Unit	ET-1	ET-2	ET-3	ET-4	ET-5
Soil description	Sandy GRAVEL & gravely SAND	Very gravely SAND with silt & clay	Very silty clayey SAND with gravel, very sandy CLAY (or SILT) with gravel	Clayey silty SAND with gravel	Clayey SILT & silty CLAY with sand, very sandy CLAY (or SILT)
Passing percent from sieve No.200	3-12%	12-30%	30-60%	22-34%	>60%
Soil Type (USCS)	GW, GW-GM, GP-GC, SW & SP	SC, SC-SM & GC	SC, SM & CL	SC, SM	CL, ML & CL-ML (rarely CH)

By studying the soil units, the ET-1 line was not suitable for drilling with the Earth Pressure Balance (EPB) machine, and it is necessary to improve the parameters of the soil by using arrangements such as adding foam, polymer and fine mineral materials especially in presence of high pressure water. Fortunately, this unit is not widely expanded and is lensed in the tunnel pathway. The ET-2 line also has a greater capacity to operate in the area where the water pressure is greater than 2 bar due to the coarse aggregates and should use special polymers to improve soil parameters.

Geological studies based on the geological categorization of allied units of Tehran indicate that parts of the unit ET-3 that are located in unit A of the Tehran subway are cemented and relatively hard. Of course, the study of drilled wells in this section of the ET-3 unit indicates a lack of information in this area. However, because of the increased resistance of the soil and the cementation phenomenon of the ET-3 unit in the end sections of the path, this part of the ET-3 unit is subdivided into a subunit named ET-3 * subunit. The engineering features of this sub-site were determined based on the results of existing laboratory tests and engineering judgment due to the lack of appropriate test data on it.

The tunnel route is zoned based on classification of the soil and condition of the soil. Accordingly, in total, the tunnel route is divided into 29 geological and geotechnical zones. The starting and ending of each area along with its constituent units is presented in Table 4. According to the geological engineering section of the tunnel engineering as well as Table 4, units ET-2, ET-3 and ET-5 are respectively the most widely spread in the tunnel path, and ET-1, ET-4 mostly developed as lenses of sand and gravel lenses.

Table 4. Area of the drilling path based on the expansion of the soil units in the chest

Geological Geotechnical Zoning	Zone Position (From Km to Km)	Length (m)	Engineering Geological Type					Water table presence
			ET-1	ET-2	ET-3 ET-3*	ET-4	ET-5	
1	12.140-12.530	390	L				▨	🟦
2	12.530-13.268	738		▨	M			🟦
3	13.268-13.870	598		▨				
4	13.870-13960	90	L	▨				
5	13960-14.370	410		▨				
6	14.370-14.705	335		▨		L		
7	14.705-15.215	520		▨				
8	15.215-15.475	260		▨		L		
9	15.475-16.865	1190		▨				
10	16.865-17.120	255		▨	M			
11	17.120-17.790	670		▨				
12	17.790-18.020	230		▨		L		
13	18.020-18.340	320	L	▨		L		
14	18.340-18.595	255		▨		L		
15	18.595-19.180	585		▨				🟦
16	19.180-19.278	98		▨	M			🟦
17	19.278-19.900	622			▨			🟦
18	19.900-20.312	412		▨	M			🟦
19	20.312-20.436	124			▨		▨	🟦
20	20.436-20.750	314					▨	🟦
21	20.750-21.095	345				L	▨	🟦
22	21.095-22.200	1105					▨	🟦
23	22.200-22.580	380				L	▨	🟦
24	22.580-23.060	480					▨	🟦
25	23.060-23.325	265		▨	M		▨	🟦
26	23.325-23.775	450			▨			🟦
27	23.775-24.060	285		L	▨			🟦
28	24.060-25.300	640			▨			🟦
29	25.300-26.296	996		▨	M		L	

L: Lense

M: Mixed face

4. Determination of Geotechnical Parameters of Soil Units

In order to statistically analyze the parameters obtained from field and laboratory tests, calculations have been made to estimate the value of each parameter and also a confidence interval for the value of each parameter. To estimate the value of the parameter, firstly, distant or remote data was identified for each experiment. In this regard, box diagrams have been used to identify pertinent data. After abandoning outbound or outdated data, the average of the remaining data is calculated, and thus the value of each parameter (for each experiment separately) is estimated. After having determined an approximate value for each of the relevant parameters, called "Estimates", a confidence interval is also determined for each of them. In order to estimate the confidence intervals for the dual impedance solution in brackets, the confidence intervals for each of the parameters obtained from the experiments are determined.

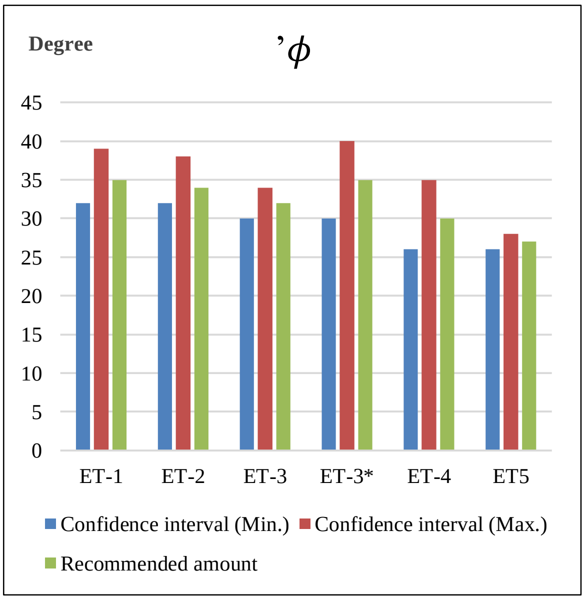
$$(\bar{X} - t_{1-\frac{\alpha}{2}}(n-1)\frac{s}{\sqrt{n}}, \bar{X} + t_{1-\frac{\alpha}{2}}(n-1)\frac{s}{\sqrt{n}} \quad (1)$$

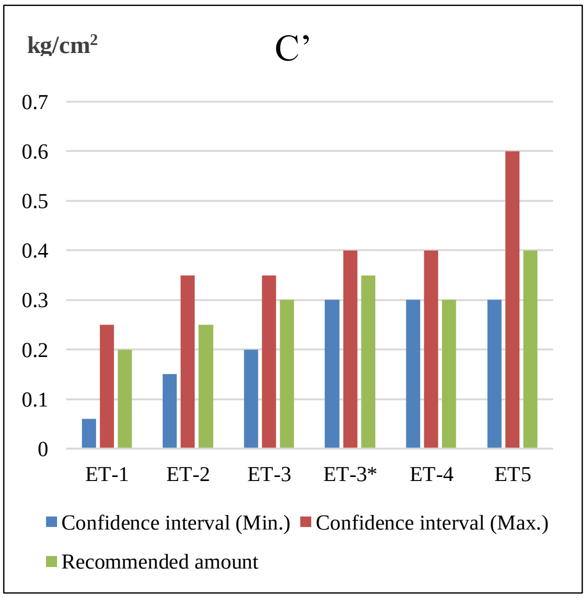
In the above equation, the average estimated parameter is the number of tests, the sign of the data variance, the confidence level sign, and the amount determined by the quantity being known and distributed. In these analyzes, the value is considered to be 95% -90. Since several laboratory and laboratory tests have been performed to determine a specific parameter, in order to determine the proposed value for each parameter, the logic tree method was used. The statistical parameters of the test results are presented in Table 5 In this regard, various methods or experiments are weighted based on the benefits of each of them. In these studies, the parameter C (soil adhesion) has been estimated based on three different experiments, such as in-situ cutting, tri-axial, and direct-shear testing. In order to determine the proposed amount, considering the advantages of in situ cutting such as lack of soil irregularity and preservation of tissue and its natural cement and the conditions of each of the units, the highest weight was allocated to the field cutting test (40 to 50%) and to each One of two other tests (ie triangular tests and direct lab tests) was assigned a weight of about 20 to 35 percent. Finally, according to the above-mentioned explanations, the proposed values for effective shear strength, modulus, density, and ... parameters are determined using the above-mentioned method. Due to the lack of field tests in the ET-3 * sub-unit and the unreliability of laboratory test data and sample failure, the parameters of this sub-unit were more based on engineering judgment. Another point to be noted in these analyzes is the difference in the results of in situ and in vitro experiments. Generally, the amount of soil adhesion obtained from the intersection test is greater than the results of laboratory tests (such as three axes and direct cutting). The reason for this is the preservation of cement, texture and age (aging) in field tests. The effect of these factors due to soil dispersal in the laboratory is very weak in laboratory tests. In this regard, only experimental tests have been carried out to estimate the values of unstressed shear strength (CU) parameters, but in order to estimate the shear strength parameters, in addition to laboratory tests, an in situ test has been performed, so with Baccalaureate applied values were determined for the reinforced-unplanned shear strength parameters.

Table 5. Statistical parameters of the field and laboratory tests (per each unit of engineering geology)

Plate loading	**Direct shear test Slow**		**Direct shear test Slow**		**Three-axis CU test**		**In-situ Direct Shear Test**		**Statistical Parameters**	**Engineering Geology Unit**
E (kg/cm^2)	**ϕ**	**C (kg/cm^2)**	**ϕ**	**C (kg/cm^2)**	**ϕ CU**	**C (kg/cm^2)**	**ϕ**	**C (kg/cm^2)**		
1436.4444			39.2125	0.065			32	0.2625	Mean	ET-1
721			38.5	0.005			29	0.25	Median	
2490197.778			21.276	0.011			11.19524	0.012	Variance	
1578.03605			4.61254	0.10337			125.333	0.11087	Std. deviation	
486			33	0			22	0.15	Minimum	
5200			46.7	0.24			48	0.4	Maximum	
4714			13.7	0.24			26	0.25	Range	
2.145			0.387	1.348			1.437	0.482	Skewness	
4.351			-0.71	-0.109			2.586	-1.7	Kurtosis	
1095.3636	38.0333	0.0522	35.9	0.2106	39.4667	0.165	32.4	0.4011	Mean	ET-2
838	38	0.03	35	0.105	39.5	0.145	35	0.4	Median	
692540.814	0.02	0.002	17.561	0.044	11.067	0.009	7.14899	0.054	Variance	
832.19037	0.14142	0.04494	4.19061	0.20934	3.32666	0.09731	51.108	0.23177	Std. deviation	
390	37.9	0.03	25	0	34.8	0.05	14	0	Minimum	
3958	38.4	0.16	46	0.85	44	0.34	41	0.86	Maximum	
3568	0.5	0.13	21	0.85	9.2	0.29	27	0.86	Range	
2.284	2.652	2.193	0.215	1.463	-0.058	1.219	-1.581	0.445	Skewness	
5.998	7.75	4.522	0.619	1.675	-0.678	2.474	2.259	-0.054	Kurtosis	
642.5	34.2	0.115	32.95	0.1465	32.55	0.21	34.5	0.33	Mean	ET-3
640	34.2	0.115	34	0.08	32.55	0.21	35	0.3	Median	
58728.091	6.48	0.001	23.587	0.033	0.405	0.029	7.03065	0.01	Variance	
242.33879	2.54558	0.03536	4.85666	0.18268	0.6364	0.16971	49.43	0.10012	Std. deviation	
320	32.4	0.09	16	0	32.1	0.09	33	0.21	Minimum	
1113	36	0.14	42	0.85	33	0.33	37.5	0.5	Maximum	
793	3.6	0.05	26	0.85	0.9	0.24	4.5	0.29	Range	
0.487			-1.448	2.886			0.845	0.902	Skewness	
-0.547			3.14	8.573			0.954	-0.24	Kurtosis	

	26.2917	0.3417			16.925	0.425			Mean	ET-3*
	27.75	0.28			16.8	0.47			Median	
	43.259	0.076			9.329	0.016			Variance	
	6.57716	0.27643			3.05437	0.12662			Std. deviation	
	-0.276	0.767			0.223	-1.702			Minimum	
	-0.496	-0.466			0.227	2.981			Maximum	
	15.4	0			13.4	0.24			Range	
	36	0.85			20.7	0.52			Skewness	
	20.6	0.85			7.3	0.28			Kurtosis	
872.7692	35.6	0.355	32	0.2414	26.52	0.272	40.9	0.346	Mean	ET-4
891	35.6	0.355	38	0.2	23	0.26	39	0.33	Median	
159260.026	18	0.068	101.333	0.03	69.012	0.018	1.43391	0.011	Variance	
399.07396	4.24264	0.26163	10.06645	0.17209	8.30735	0.1348	2.056	0.10359	Std. deviation	
320	32.6	0.17	15	0	16.4	0.1	34.1	0.22	Minimum	
1663	38.6	0.54	41	0.54	36	0.45	50	0.49	Maximum	
1343	6	0.37	26	0.54	19.6	0.35	15.9	0.27	Range	
0.525			-0.981	0.665	0.132	0.111	0.472	0.361	Skewness	
-0.35			-0.574	0.856	-2.134	-0.643	-2.303	-0.395	Kurtosis	
378	27.3375	0.645	16.3333	0.9767	28.375	0.435	32.6	0.64	Mean	ET-5
378	26	0.505	16	1	28	0.395	34	0.2	Median	
450	72.454	0.195	12.333	0.005	31.125	0.064	7.0946	0.581	Variance	
21.2132	8.512	0.44211	3.51188	0.06807	5.57898	0.25225	50.333	0.7621	Std. deviation	
363	16.5	0.13	13	0.9	21	0.12	25	0.2	Minimum	
393	43	1.5	20	1.03	37	0.97	39	1.52	Maximum	
30	26.5	1.37	7	0.13	16	0.85	14	1.32	Range	
	0.752	1.017	0.423	-1.361	0.372	1.366	-0.816	1.732	Skewness	
	0.453	0.78			-0.868	2.988			Kurtosis	





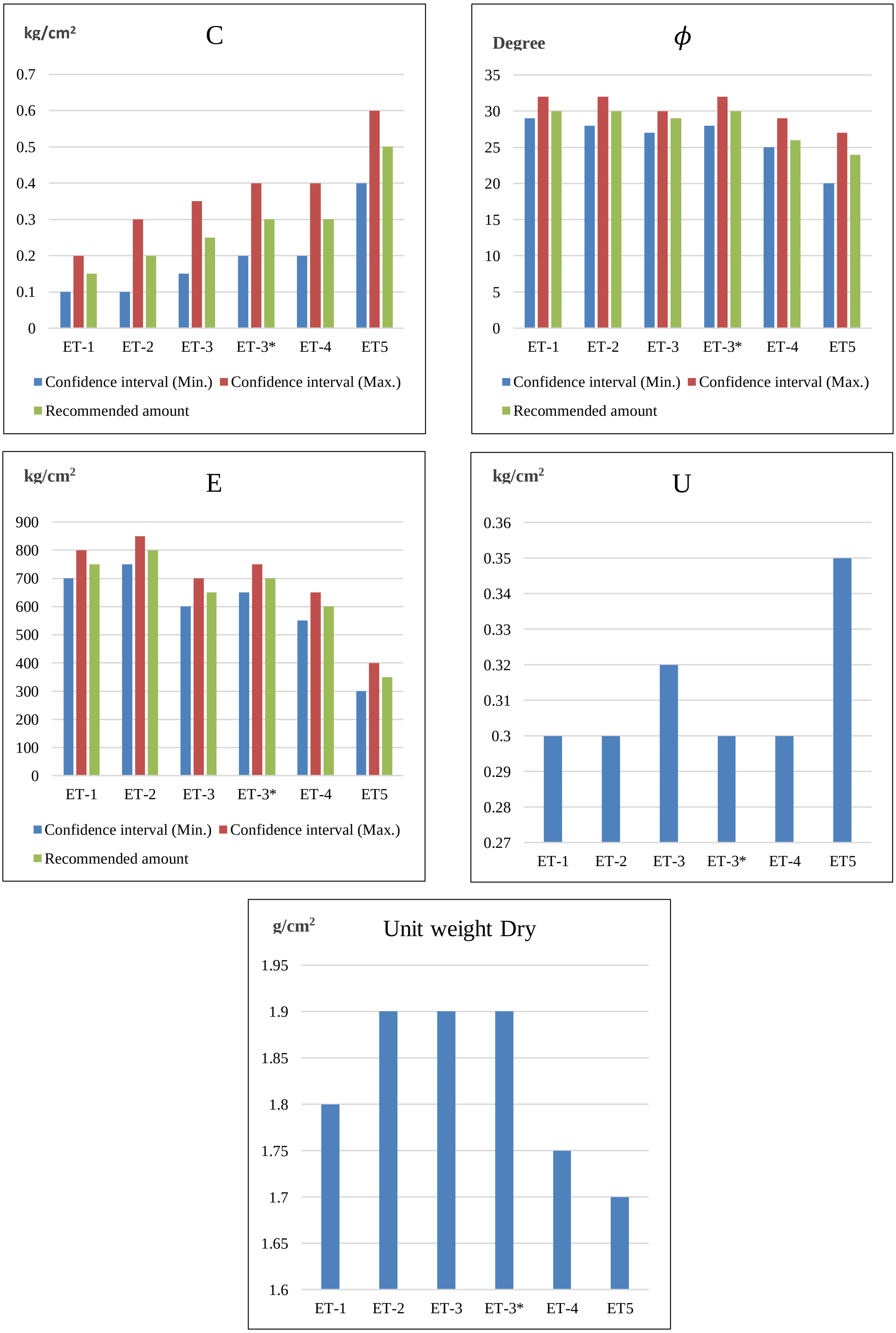


Figure 2. Proposed Geotechnical Parameters Values for Tunnel Route Geology Engineering Units

5. Possible Geotechnical Hazards in the Drilling Path

Considering that one of the main goals of these studies is to provide information that could predict the specific geological conditions that could be encountered during tunneling. According to a study by the National Tunnel Technology Commission on more than 100 tunnels, it has been shown that the main problem with 12% of the tunnels was rock boulders. Generally, in mechanized tunnels that are drilled through a full-blown machine, when faced with boulders, the machine faces a very difficult material, which is very difficult to crush at many times. The machine used in this project has the ability to pass stone pieces with dimensions of about 35 cm. considering that in the study stage, in the wells of the end of the route, the parts larger than 35 cm were observed, it is likely that the machine face stone pieces larger than 35 cm during the tunnel excavation. In any case, it is likely to be pulled out of its place along the path of the boulders and is shifted by the rotary force of the cutter head out of the tunnel range, or shredded by the shearing tool, or may remain in the chest area and rotate with the cutter head. In such cases, the machine's torque will rise abnormally, and eventually the machine's progress will be stopped and the jacking system will be blocked until the boulders are manually crushed and removed from the machine path.

The passing percentage of soils from sieve No. 200 in tunnel area is less than 12% in the distance of 12140 to 12500 and 18000 to 18500. In addition there is also the same condition in other parts of the tunnel which require special measures such as soil conditioning.

The strength index has been calculated for the soil layers in tunnel area with the following Equation $Ic = \frac{LL-w}{LL-PL} = \frac{LL-w}{PI}$. According to the results, the highest frequency is related to soils without plasticity behavior and then to very hard to hard soils. Generally, in the tunnel pathway, the frequency of very soft layers is very small (about 1 percent), and the greatest concentration of unplasticized soils is in the tunnel's primary portions, where the front should be maintain still and the shield works closed.

Table 6. Soil classification based on strength index

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

Generally, soil particle adhesion to the shear tool, disc cutter, cutter head, pressure chamber and even a spiral strip can cause a blockage or collage phenomenon in the machine, in which case the machine should be completely stopped and the chassis and pressure chamber are completely cleaned. In this report, Thewes and Burger 2004 has been used to investigate the risk of obstruction. In this method, based on the strength index and the dough index, the potential for occlusion phenomenon is categorized into three low, moderate, and high risk groups. Based on this criterion, most of the tunnel paths are within the low and medium risk range.

The permeability coefficient, along with groundwater pressure, is one of the factors controlling the yield of the machine pellet so that the machine's performance at a water pressure of a maximum of 2 bar is limited to an infiltration coefficient of 510 m/s. Based on the results obtained from 242 Lofran test experiments on tunnels, most of the tunnel paths soils permeability is less than 10E-7 m/s. The only small sections of the tunnel pathway, which are mostly lenses of the ET-1 unit, have permeability of 10E-4 to 10E-5 meters per second.

In order to estimate the overall risk of roughness of the coarse-grained track, a number of Cerchar tests have been performed on samples taken from boreholes and wells and classified as a highly abrasive category. The results of these experiments, as shown in Table 7, show that the samples are generally in the north-south section of Tehran Metro Line 7 due to the fact that in most of the path, the soil that forms the chest is composed of coarse-grained alluvium, The risk of abrasion of the soil is one of the most important drilling hazards, but due to the angularity of the materials, the particle size and the percentage of passing sieve No.200, it seems that in some tunnel areas, the risk of abrasion is more than other parts. The sections with a potential abrasion for them are about 9.5 kilometres from the tunnel route.

Table 7. The results of Cerchar tests on soils in the north-south section of the subway line 7

No	Sampling location		Pin-1			Pin-2			Pin-3			Pin-4			Pin-5			Ave.	Cerchar Abrasion Index (CAI)	Rock Abrasion Class
	Test Pit No.	Depth (m)	Shape	Diameter		Shape	Diameter		Shape	Diameter		Shape	Diameter		Shape	Diameter				
				1	2		1	2		1	2		1	2		1	2			
1	TP-E4R7	30.0	Irregular Circle	85	95	Irregular Circle	100	110	Ellipsoid	105	85	Ellipsoid	110	100	Circle	95	100	95.50	5.81	Very Abrasive
2	TP-E4R7	32.0	Circle	103	95	Irregular Circle	100	90	Circle	110	100	Circle	90	85	Circle	95	93	97.10	5.73	Very Abrasive
3	TP-S7	30.0	Circle	95	98	Irregular	105	100	Circle	85	80	Circle	100	95	Circle	95	95	93.50	5.52	Very Abrasive
4	TP-S7	33.0	Circle	90	95	Irregular Circle	90	80	Irregular	100	97	Irregular	110	110	Circle	110	110	99.20	5.85	Very Abrasive
5	TP-T7	36.0	Circle	85	80	Irregular Circle	85	95	Irregular Circle	80	80	Irregular Circle	100	95	Circle	90	88	87.80	5.18	Very Abrasive
6	TP-T7	38.0	Circle	80	85	Circle	85	80	Circle	85	90	Circle	80	82	Circle	81	70	81.80	4.83	Very Abrasive
7	TP-T7	40.0	Irregular Circle	100	110	Ellipsoid	100	110	Ellipsoid	100	100	Ellipsoid	105	85	Circle	80	95	98.50	5.81	Very Abrasive
8	TP-T7	42.0	Circle	95	95	Circle	100	95	Circle	93	85	Circle	100	90	Circle	100	90	94.30	5.56	Very Abrasive
9	TP-T7U7	36.0	Irregular Circle	100	95	Circle	85	85	Irregular	100	90	Irregular	110	105	Ellipsoid	110	95	97.50	5.75	Very Abrasive
10	TP-T7U7	39.0	Circle	80	75	Ellipsoid	75	70	Irregular Circle	70	65	Irregular Circle	68	68	Ellipsoid	68	62	70.10	4.14	Very Abrasive

6. Conclusion

In the course of studies, a total of 32 wells with a total length of 775.5 meters and 73 boreholes with a total length of 2927.2 meters were drilled. According to the results of field and laboratory studies, the soil layers include the tunnel route classified to six units of engineering geology called ET-1, ET-2, ET-3, ET-3 *, ET-4 , ET-5 which the particle size reduce respectively, in the ET-1 region there is sand with gravel and boulder, and in the ET-5 there is clay and silt-sanded. The ET-1 and ET-2 lines are not suitable for drilling with the EPB machine, and it is necessary to improve the parameters of the soil using measures such as adding foam, polymer, and fine ground materials; otherwise, increasing machine torque, decreasing penetration rate and risk of falling is possible.

Depending on the design of the cutter head and its opening, boulder larger than 35 cm cause problems such as blocking the mocking system and increasing the torque of the machine and stopping the machine until breaking and removing the boulders. By examining the clogging or clogging phenomenon, ET-5, ET-3 and ET-4 due to their clay content have the most risk of clogging respectively, which should reduce and remove the risk by using special polymers and foams. A number of Cerchar tests have been carried out in order to estimate the total amount of abrasion on samples taken from boreholes and wells, which shows that the north-south section of Tehran Metro Line 7 is due to the fact that in most of the path, the soil in drilling path is mostly coarse-grained alluvium and classified as highly abrasive, which in some parts of tunnels has a higher risk of abrasion than other parts, and this abrasion potential is about 9.5 kilometers from the tunnel pathway.

7. References

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