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4 authors:

Mohamad Reza Baghban Golpasand
Seraj Institute of Higher Education

Ngoc Anh Do
Hanoi University of Mining and Geology

Daniel Dias
University of Grenoble

Mehdi Abbasi
Ferdowsi University Of Mashhad

TUNNELLING
SMART SOLUTIONS FUTURE GROWTH

The effect of soil type on long-term ground settlement due to tunneling

Mohammad-Reza Baghban Golpasand[1], Ngoc Anh Do[2], Daniel Dias[3] & Mehdi Abbasi[4]
1 Department of Civil Engineering, Seraj Institute of Higher Education, Tabriz, Iran
2 Hanoi University of Mining and Geology, Faculty of Civil Engineering, Hanoi, Vietnam
3 Grenoble Alpes University, Laboratory 3SR, Grenoble, France
4 Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT
In addition to the short-term settlements of the ground surface due to shallow tunneling in soft materials, long-term settlements are also among the inevitable consequences of this type of tunneling. This phenomenon is very important especially because of its unpredictable nature regarding the amount, extension, and time of settlement occurrence. Another problem about this subject is that by comparison to the short-term settlements, the studies performed on the long-term ones are not so extensive and some of its aspects are relatively ambiguous. In this study, long-term settlements occurred due to the excavation of Tabriz Urban Railway Line 2 (TURL2) tunnel, measured at definite time ranges, are discussed and the effect of soil type, as well as its geotechnical characteristics, on the settlement, will be investigated. To analyze the data, settlements graphs should be depicted on a semi-logarithmic chart, then the parameter of the (α) which is one of the most important and necessary parameters to predict long-term settlements, can be calculated. The outcomes show that although the short-term maximum settlements (S_{max}) occurred in clayey soils are lower than the settlements occurred in sandy soils, their long-term settlements are higher than in sandy soils.

1 INTRODUCTION

Urban development and the growth of population have brought about a considerable increase in urban areas tunneling projects for different purposes such as urban highways, subways and railway underpasses. Excavation of tunnels and other underground spaces disturbs the initial stress state of the soil mass which causes displacements of the soil surrounding the tunnel. Depending on the depth of the tunnel and the soil characteristics, the tunnel boundary convergence can propagate towards the surface and causes ground settlements. This problem was studied by different authors. Most of the studies are based on the work of Peck (1969) who analyzed a number of case studies and indicated that the transverse profile of surface settlements can be described by an inversed normal distribution (Gaussian) curve as shown in Figure 1.

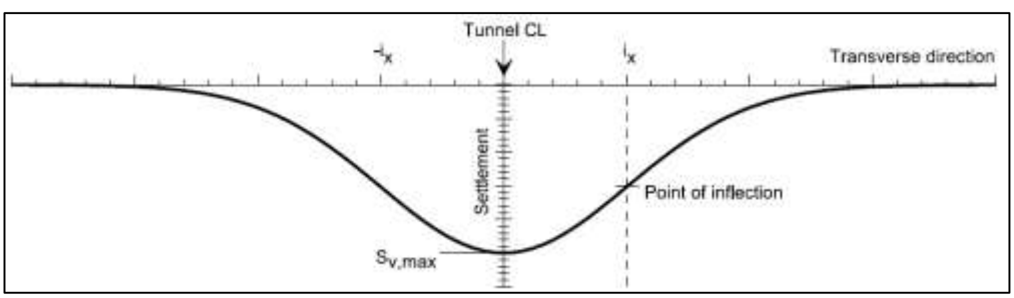

Figure 1. Transverse aspect of ground settlement due to tunneling (Baghban Golpasand et. al 2016)

The theoretical settlement (Gaussian) curve is presented by the following equation:

$$S = S_{v,max} \exp(-x^2/2i^2) \quad [1]$$

where S is the ground surface settlement at the selected point (mm); $S_{v,max}$ is the maximum ground surface settlement above the tunnel center line (Tunnel CL); x is the cross sectional distance from the selected point to the center line of the tunnel (in meters) and *i* is the transverse distance between the center line of the tunnel and the point of inflection in meters. Since that *i* has been considered through the *x* direction, it has been marked with the ix symbol in Figure 1. This topic is generally included of high importance and has been studied by several researchers during the last 50 years. Based on the main subject of this study as well as to avoid unnecessary complexity, the major emphasize of this study will be on long-term settlements instead of the regular (short-term) settlement of ground surface occurred owing to tunneling.

1.1 Long-term settlements

In addition to the short-term settlements of the ground surface due to shallow tunneling in soft materials, long-term settlements are also among the inevitable consequences of this type of tunneling. In other words, tunnels may experience settlement during construction and continue settling in the long term. According to Jallow et al. (2019), a comprehensive study done on the Shanghai Metro, the long-term settlement can be induced by the equilibration of the stresses and dissipation of excess pore pressures in the clayey layer around the tunnel, which is associated with a new drainage condition imposed by the tunnel. It may also be caused by the creep behavior of the soft soil around the tunnel or in the soil layers. For long-term settlement, most of the existing studies interpreted them in terms of consolidation theory, in which the soil layers are considered as an elastoplastic material (Shin et al., 2002; Shin and Potts, 2003). Based on this study, four possible factors influencing long-term settlement of ground surface, can be categorized as shown in Figure 2.

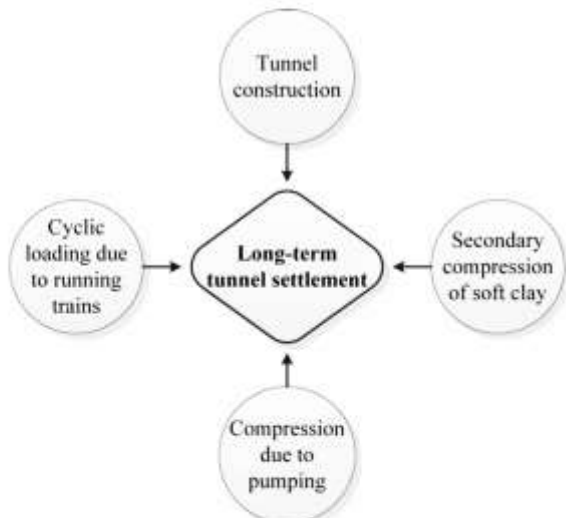

Figure 2. Possible causes of long-term tunnel settlement in Shanghai (Ng et al. 2013)

This phenomenon is very important especially because of its unknown nature regarding the amount, extension, and time of settlement occurrence. Another fact about this subject is that by comparison to the short-term settlements, the studies performed on the long-term ones are not so extensive and some of its aspects are relatively ambiguous. However, some of the studies on long-term tunnel settlement are Wu et al. (2011), Wang et al. (2012), Ng et al. (2013), Shen and Xu (2011), Cattoni et al. (2016), Soga et al. (2017), Jallow et al. (2019), Zhu and Li (2017).

2 TABRIZ URBAN RAILWAY LINE 2 (TURL2)

Tabriz is one of megacities in Iran. It is located in the northeast region of the country. Tabriz Urban Railway Line 2 (TURL2) tunnel with an approximate total length of 22 km and 20 stations runs from the west region to the east part of the city (Baghban Golpasand et. al 2022). The layout of TURL2 tunnel in the Tabriz metropolitan is shown in Figure 3. This study is focused on the western part of the tunnel between the west S01 station and S02 station (chainage from 3200 to 3800). In this part, the main geological unit is Quaternary alluvium. The layers are characterized by a broad range of soil ranging from well-graded gravel to some fine-grained soils such as silts and clay terms. One of the main parameters for soil classification is the percentage of fines (passed form No.200 sieve). Considering this parameter and other factors such as mechanical properties, cohesive (for fine-grained soils), and permeability (for coarse-grained soils) the tunnel's surrounding soil strata could be classified into 4 geological units named TG1-TG4 (Table 1). The geological cross section along the tunnel route and tunnel alignment is presented in Figure 4. The depth of the phreatic level varies between 13m to 16 m, from the ground surface, along the studied area. As seen in Figure 4, the tunnel passes mainly through TG-4 and TG-3 types and overburden layers contain TG-2, TG-3 and filling material.

Figure 3. The route of TURL2 tunnel and the under-study region

Table1 Engineering geological characteristics of geological units (soil types)

Engineering geological types	TG1	TG2	TG3	TG4
Soil description	Silty clay or clayey silt with a little sand	Clayey silt or silty clay with sand and gravel	Very silty clayey sand with gravel	Sandy gravel or gravely sand with silt or clay
Passing from N.200 sieve (%)	>75	50-75	25-50	<25
USCS	CL, ML, CL-ML, rarely CH	CL, ML, CL-ML	SM, SC, SC-SM, rarely GM	SM, SP, GP, SW, GW , GM

The TURL2 tunnel has been excavated using EPB-TBM with a cutting-wheel diameter of 9.49 m. The TBM shield length and thickness are 9 m and 50 mm, respectively. The shield has an external diameter of 9.46 m at the face and 9.44 m at the tail. The cutter head of TBM is shown in Figure 5, at the time of entering to one of the stations.

Figure 5. The cutter-head of TBM (TURL2 Project)

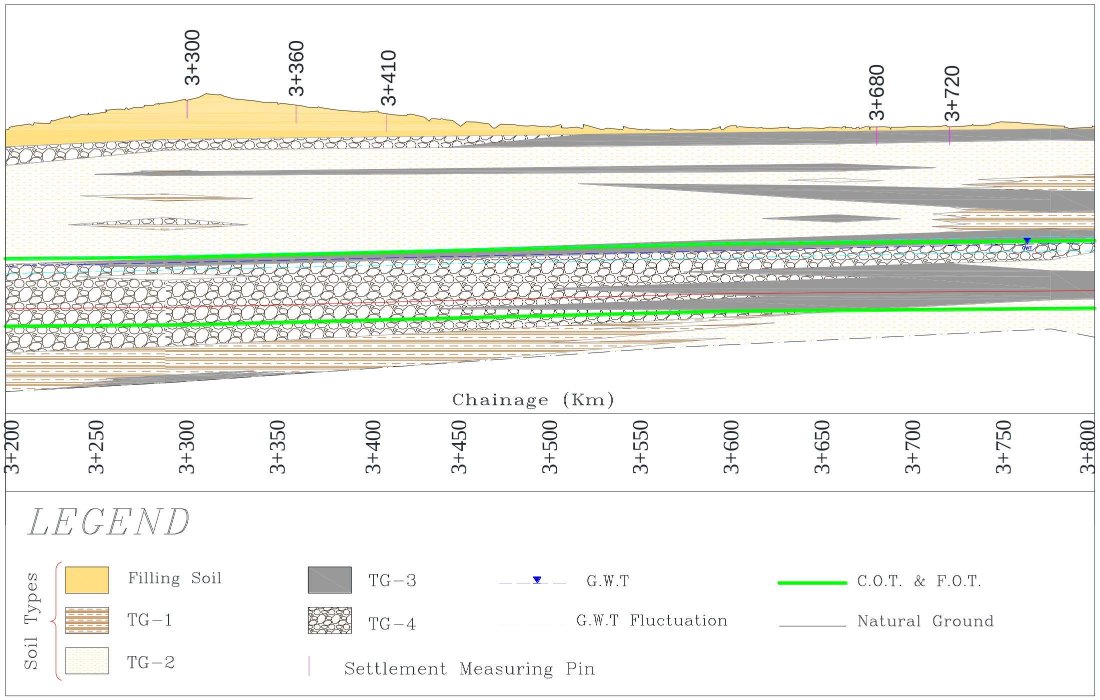

Figure 4 Geological cross section of TURL2 tunnel and the categorized units

3 MEASURING THE REAL (IN-SITU) SETTLEMENTS AT TUNNEL SITES

Leveling and surveying methods were carried out in order to measure the surface settlements induced by the excavation of TURL2 tunnel. Some control points were selected on the ground surface above the tunnel center line (C.L.) and measuring equipment (pins) were installed at these points. Parts of the locations of the pins installed through the studied part of the tunnel center line, between S01 and S20 stations, are indicated in Figure 6. The ground surface is often covered by asphalt or pavement in urban areas. Therefore, the measuring equipment must be bolted in depths lower than the level of the asphalt or pavement and the upper part of the equipment's rod (approximately 20 cm) must be free from the ground (Figure 7). Regarding the main purpose of this study and the limitations in urban areas, only the S_{max} (maximum ground settlement which occurred above the C.L. of the tunnels) was measured and subjected to more discussion. The monitoring of the displacements was started before the passing of the shield machine and continued until reaching a constant value corresponding to the maximum settlement (S_{max}). The process of the settlement recording continued nearly around 15 to 30 days after the crossing of the shield machine. Figure 8 shows the short-term settlements in bar chart features that have been measured regularly before, during and after TBM passage and stopped when the settlements reaching to a constant value. According to this figure, the amounts of settlements from 7mm to 34mm are measured daily through the tunnel excavation. To study in detail, the behavior of the pins during tunnel excavation, it is necessary to design the graphs longitudinally (Baghban Golpasand et. al 2018). Figure 9 shows the longitudinal graphs of S_{max} for the pins between 3+700 to 3+800 (for example), during the tunnel excavation in the time range of 20 days. Figure 10 shows several parts of a displacement graph in a selected pin that has been installed on the point of 3+410 (again for example). As shown in this figure, a vertical displacement at this point reaches 16 mm after 17 days. As previously indicated, settlement measuring has been continued until the pins reached the constant level or their displacements were stopped.

3.1 Long-Term Settlement

Ground displacement due to tunneling is regularly continued even after TBM passage and segment installation owing to several reasons such as soil consolidation, fluctuation of the ground water table and other factors as shown in Figure 2. To analysis of this phenomenon, periodic settlement measuring should be done on the selected pins. Then, the settlements are compared together and their increase is a main indicator for continuing ground settlement over time.

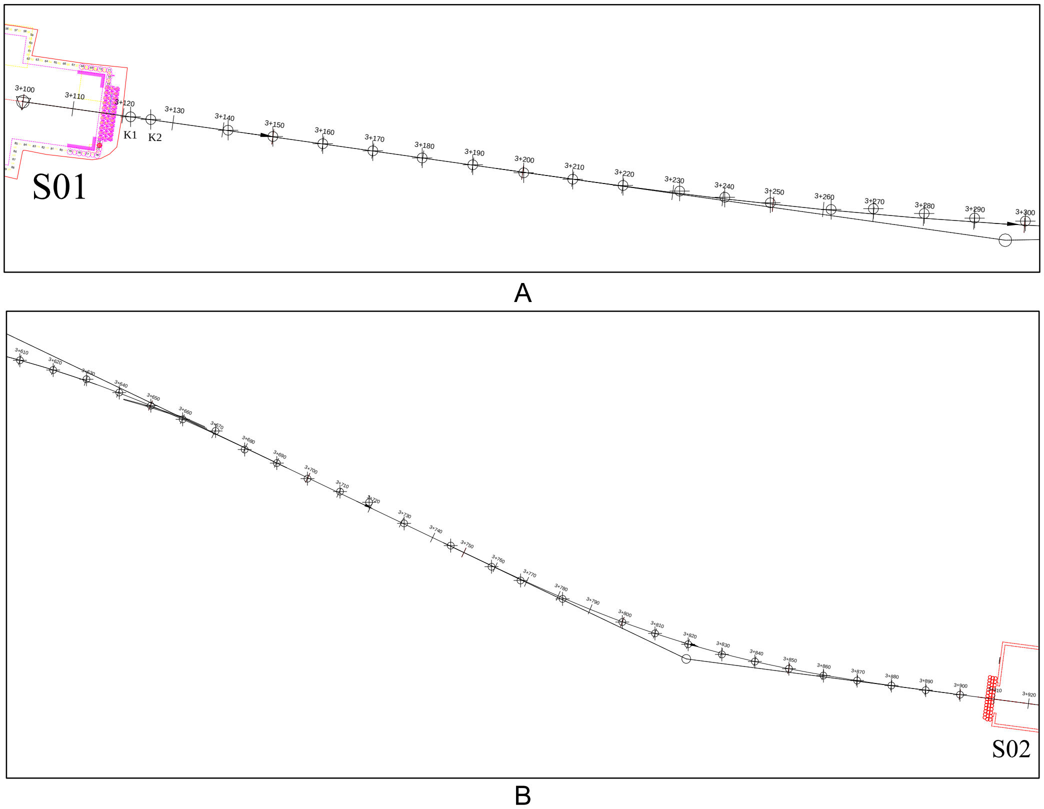

Figure 6. Plan of the settlement measuring pins

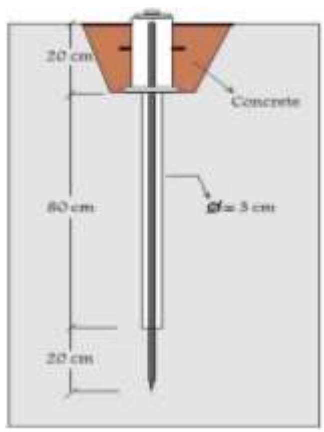

Figure 7. Schematic design of a settlement measuring pin.

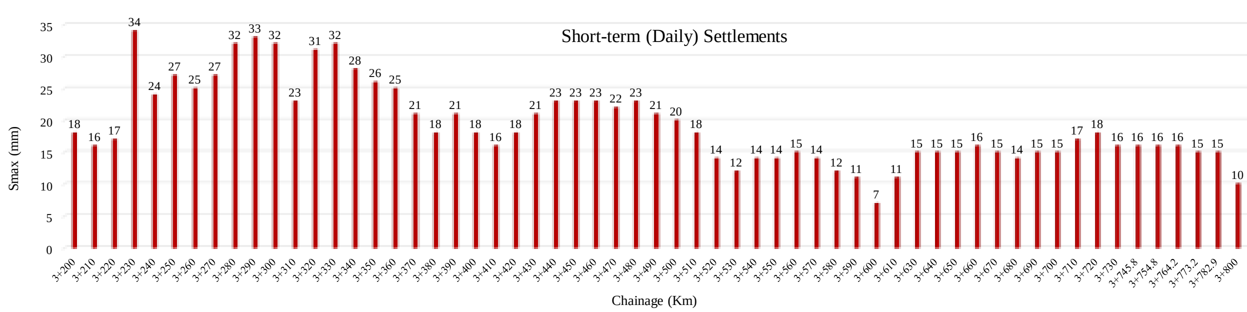

Figure 8. Bar chart of short-term settlement through the studied area

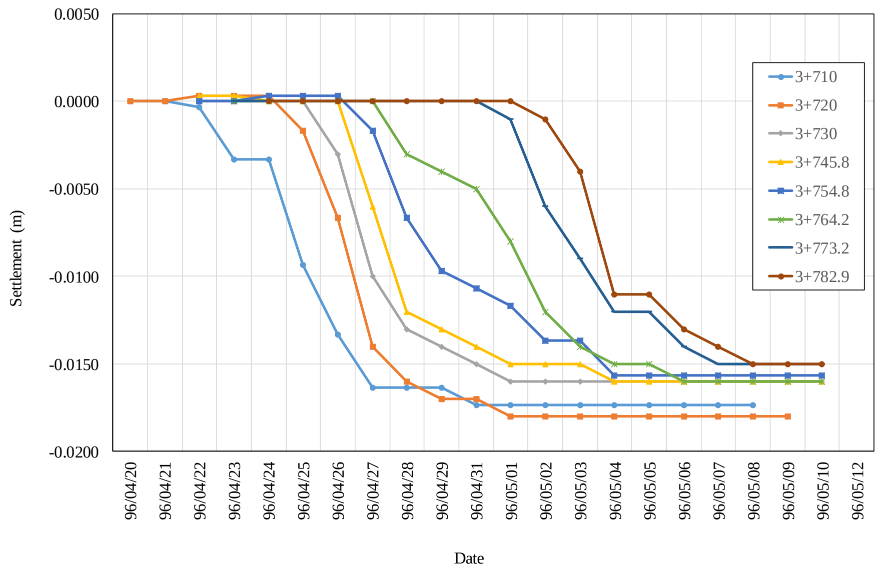

Figure 9. The samples of the values of S_{max} measured on the pins 3+700 to 3+800

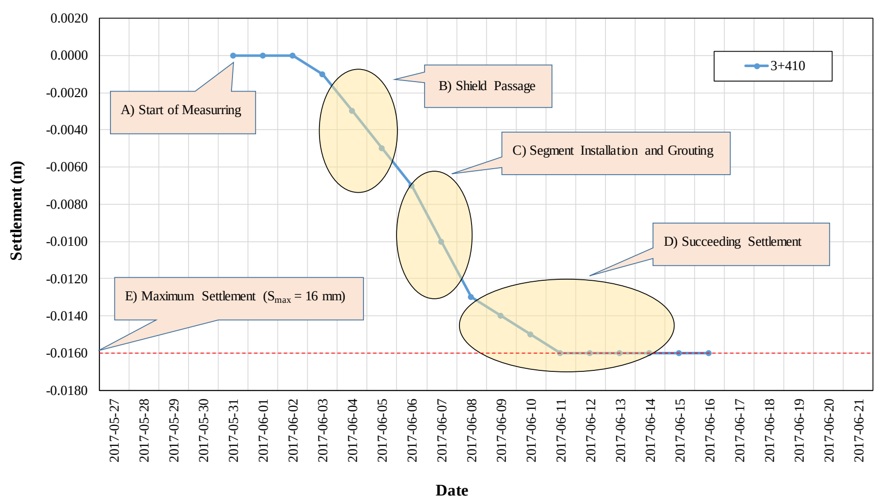

Figure 10. Several parts of a displacement graph in 3+410 pin

Furthermore, the slow and gradual effects of long-term settlements on the surface and subsurface buildings and infrastructures is an essential subject after tunnel construction. For example, the cracks created on the walls owing to tunnel excavation are mostly widened during the time and can cause damage to the buildings. In the present study, and based on the accessible facilitates of the periodic settlement measuring in a few selected pins, progressive ground settlement was measured in definite periods and the graphs were depicted as shown in Figure 11. The most important risk in this process is to pass over the settlements from allowable range and entering in unallowable ones. Given the importance of the subject, it is necessary to be explained briefly.

3.2 3.2- Allowable settlements

The range of allowable settlements is mostly specified based on several factors such as surface and subsurface condition of the ground which is subjected to tunneling, the importance of structures and infrastructures, vulnerability of buildings, etc. This means that for instance, the allowable settlements are not equal for a case of tunneling under an unused empty land and the case of tunneling under an important structure such as hospitals, schools and other sensitive buildings. Due to the continuous nature of ground displacement, it is possible that the short-term settlements, which have been measured and recorded as allowable settlements, exceed and cause the occurrence of unallowable settlements which can possibly cause damage to buildings. This process has been illustrated clearly in Figure 12. As shown in this Figure, the short-term (nearly 20 days) settlement equal to 16 mm, is recorded and considered as allowable settlement; however, the displacement of the pin has continued over the longer time (nearly 200 days) and has reached to 24 mm which is considered as unallowable settlement.

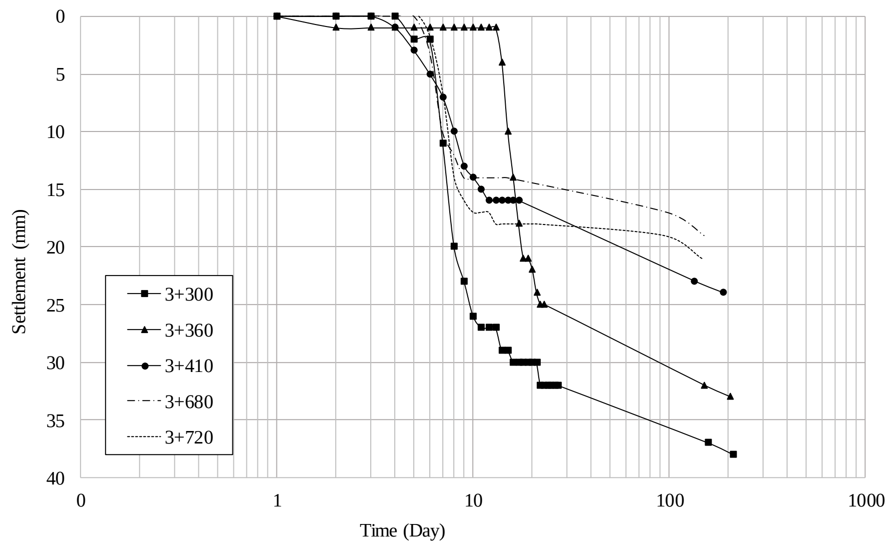

Figure 11. Long-term displacement graphs

Several criteria have been suggested for this subject to protect the buildings against damages, among them the criteria of Burland 1997, Rankin, 1988 and Chirioitti, 2003 are more citable. A study has been performed by Piciullo, et al. 2021, is one of the most comprehensive and recent studies about building damage due to excavation-induced displacements. In present study, the settlement of 20 mm has been considered as the maximum allowable settlement.

4 DISCUSSION

As argued previously, several reasons and mechanisms have been proposed for the occurrence of long-term settlement of ground surface induced by tunneling. Environmental evidences show that consolidation of fine-grained layers is one of the most important reasons relating to this phenomenon and is the main factor in geological and geotechnical term relative to the other reasons and is in direct connection with the compressibility of soil. To discuss more on this subject, the secondary consolidation coefficient of soil (α) should be considered. This parameter has been conceptually indicated in Figure 13. As seen in this figure, the parameter can be derived simply by designing the graph of settlement versus the log-time diagram and determining its slope through the linear part of the end of the graph. It is clear that the graph in Figure 13 is schematic; however, this procedure can be done in real graphs as shown in Figure 14. In this Figure, the settlement log-time graphs for a number of selected pins have been illustrated. It is clear that in all of the graphs, the end part is linear so the parameter of (α) can be determined via the equation [2]:

$$\alpha = \frac{S_2 - S_1}{Log_{(\frac{t_2}{t_1})}} \qquad [2]$$

Where *S* and *t* are settlement and time, respectively. As seen on the Figure 14, the graphs in this chart can be categorized into two groups: the graphs of the pins 3+300, 3+360 and 3+410 have an approximate α between 8 and 9 while the amount of α is derived among 2 and 3 for graphs of the pins 3+680 and 3+720. It seems that the soil type is the main factor influences on the value of this parameter. It means that based on environmental evidences and the site technical data, except of soil type, other factors such as tunnel construction, cyclic loading due to running trains and compression due to pumping (Figure 2), don’t have a considerable effect on the long-term settlement of ground surface due to excavation of TURL2 tunnel in studied section; however, the secondary compression of soft clay which is related highly on soil type, is the main effective factor on the long-term ground settlement due to excavation of the tunnel. This topic is discussed through the next section.

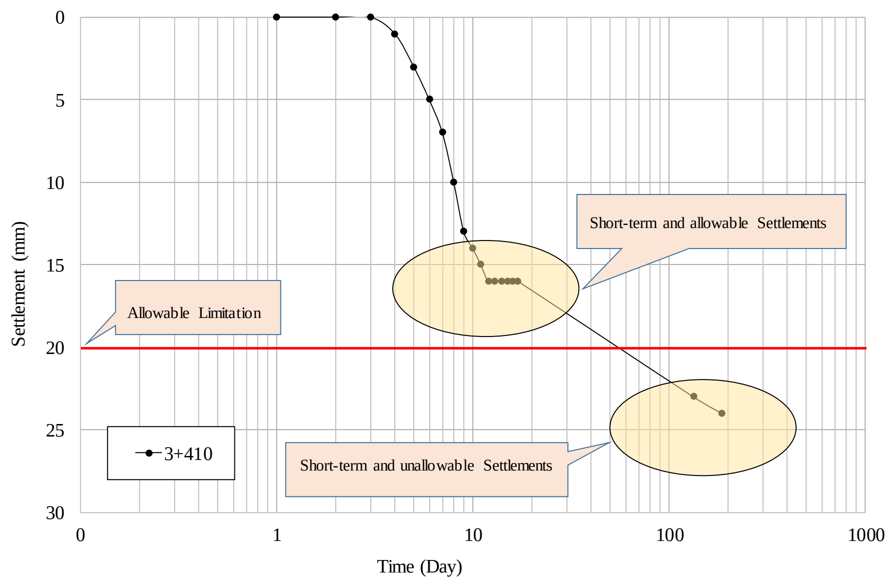

Figure 12. The graph of long-term displacement and its several parts

5 THE EFFECT OF SOIL TYPE

Basically, the type of soils existent in any region is an exact indicator of the geology of that region as well as the rocks are exposed in neighbor hills and mountains. The soil type is also, one of the most important factors influencing on ground reaction against tunneling. In other words, the behavior of fine-grained and cohesive soils due to tunneling isn't similar to the behavior of coarse-grained and non-cohesive soils. Considering the several differences between these two types of soil, the potential of compressibility is among the most of them. Fine-grained soils, clays for example, have a huge tendency to be compressed and deformed when they are subjected to a large loading or unloading action. This means that tunneling in coarse-grained soils leads mostly to immediate settlement and the long-term settlements constitutes a little portion of total settlement. In case the fine-grained soils; however, the behavior is fundamentally different and large portion of total settlement is belonging to long-term settlement while immediate settlements are generally low amounts.

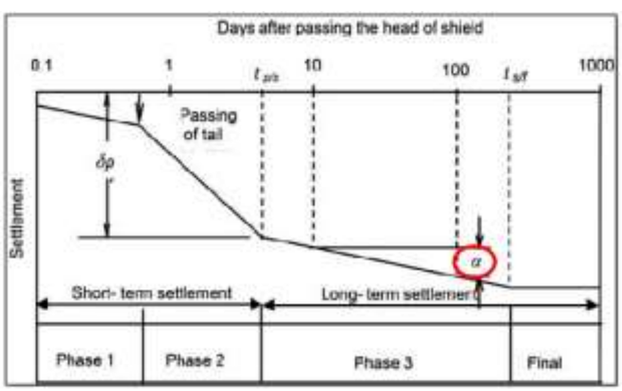

Figure 13. Concept of (α) in the diagram of settlement log-time (Hwang and Moh, 2006)

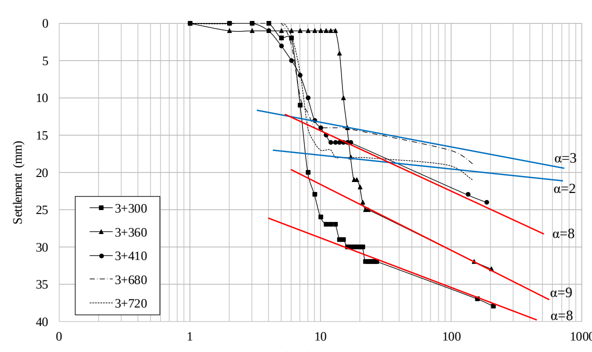

Figure 14. Determination of (α) in settlement-log time diagrams

As said previously, in the studied area some of the installed pins were selected for long-term settlement measuring and the graphs were shown in Figures 11 and 14. To investigate on the effect of geology on long-term settlement, it is necessary to be careful on the geological section of tunnel route and the pin locations and the designated graphs then an analysis of trend of graphs should be done. According to this Figure, the geology (soil type) of whole section is not uniform and location of 3+300, 3+360 and 3+410 pins are geologically different from the location of 3+680 and 3+720 pins. The first group pins are layouted mostly in fine-grained soils (TG-2 unit), whereas the second group pins are located in the materials consist of the mixture of fine-grained and coarse-grained soils (TG-2 and TG-3 unit). It can be expected that long-term settlements of the first group pins to be higher than those of the second group pins because of the high potential for compressibility of TG-2 unit. The relationship between geological characteristics of materials and the long-term settlements due to excavation of TURL2 tunnel, kilometer 3+200 to 3+800, are summarized perfectly in Table 2. The contents of this Table show that existence and abundance of fine-grained soils generally lead to higher long-term settlement, whereas lower long-term settlements are expected from the coarse-grained soils.

Table 2. Brief relationship between geology and the long-term settlements

Pin Number	Total settlement (mm)[1]	Short-term settlement (mm) / (%) [2]	Long-term settlement (mm) / (%)	α	Geological Unite (Figure 5)	Remarks
3+300	38	30 / 79	8 / 21	8	Mostly TG-2	Due to abundance of fine-grained
3+360	33	25 / 76	8 / 24	9	Mostly TG-2	soil types, high potential for
3+410	24	16 / 67	8 / 33	8	Mostly TG-2	compressibility is expected.
3+680	19	14 / 84	5 / 16	3	TG-2 and TG-3	Coarse-grained soil types cause
3+720	21	18 / 86	3 / 14	2	TG-2 and TG-3	low potential for compressibility.

[1] up to last measurement (200 days)
[2] determined based on total change in graph slope / percent of total settlement

6 CONCLUSION

In this paper, ground settlements due to the excavation of the TURL2 tunnel are evaluated and the effect of soil type (geology) on long-term settlements was investigated using real settlements measured in definite time periods. According to the geological profile of the study area, the tunnel route is situated into the soil layers composed of fine-grained and coarse-grained materials, and from an engineering geological view, the materials were categorized into four soil types which behave differently when subjected to tunneling. Based on the measurement of the settlements that occurred due to tunnel excavation in the studies area and analysis of them, the following conclusions can be drawn:

- In general, ground displacement due to tunneling is a continuous phenomenon and goes on exponentially over years after TBM passage which is called “Long-term” settlement.
- Several factors are influencing long-term settlements and the compressibility of soil is among the most geology-based factor. In this relation, the parameter of (α), has a basic role and can be derived by designing the graph of settlement versus the log-time diagram and determining its slope through the linear part at the end of the graph, which is the main index.
- Analysis of the graphs of long-term settlements and comparing the trends of the graph as well as the amount of settlements clear that the graphs of fine-grained soils have a steep slope in their linear end part. In contrast, the graphs of coarse-grained soils have obviously gentle slope at the same part. Correspondingly, the graphs of fine-grained soils have a higher amount of (α).
- Eventually, a comparison of the graphs and settlements improves that fine-grained soils have a higher tendency to long-term settlements relative to coarse-grained soils. Therefore, the necessary cautions should be considered against the probable risks and damages to buildings.

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