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ORIGINAL PAPER

Determining the best depth of subway tunnel excavation considering ground type, support system characteristics, and tunneling cost: case study of Tabriz subway, Line 2

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Abstract

The cost of subway construction is especially dependent on stations' construction cost. In order to minimize these costs, an optimum depth for subway tunnels should be adopted. This study intends to investigate the best depth of tunnel construction for Tabriz subway, Line 2. The study is carried out in two categories of technical and financial studies. In technical studies, surface settlement is the ruling criteria, which its allowed limit is 25 mm. Results showed that depths less than 1.5 times the tunnel diameter bear settlement above the limit; therefore, tunneling in such depths is not recommended. Financial studies consist of a cost analysis of tunneling and subway station construction. To do so, the depth of station construction and their distance from each other have been analyzed. Results indicated that the construction costs are highly dependent on the stations' depth and their distances. To put it more clearly, the least subway costs are achieved when the overburden is at minimum and station distance is at maximum. To be more specific, along the 17 km of the route, when the station depth is greater than twice the tunnel diameter, and their distance is 750 m, the unit cost of construction reaches 29 M$, while it is at its minimum (7 M$) when the stations' depth is less than tunnel diameter, and their distances are 3000 m. Eventually, the optimum depth for Line 2 of the Tabriz subway is 1.5 to 2 times the tunnel diameter, while obviously, more distanced stations cost less.

Keywords Tunnel · Station · Optimum depth · Tabriz subway · Surface settlement · FLAC3D

Introduction

One of the most important issues in development of underground spaces in urban areas is determining the optimum depth for construction. The depth of construction of underground spaces, such as subway tunnels and stations, affects the technical aspects of the project on the one hand, and can alter the construction costs on the other hand. Ground surface settlement is accounted as of the most important technical aspects affected by the depth of underground spaces. Prior to tunnel excavation, the host ground experiences natural stresses, which any change can disrupt stress states and cause great damage. Surface settlement is an important adverse effect of tunneling and underground space excavation, especially in urban areas. Therefore, it is necessary to predict and control surface settlements to prevent tunneling-induced damage to surface structures (Khademian et al. 2017).

Moreover, cost estimation is an essential factor in the success of any tunneling project. Accurate cost estimation of tunneling and construction of stations is more important in the preliminary stages of the project design, where the variety of geotechnical conditions can change early estimates significantly.

The aim of this study is to determine the optimum depth of subway construction in Line 2 of Tabriz subway. There are multiple previous studies focused on determining the

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optimum depth of tunneling, which a brief review of them can bring a general understanding of the subject of this research. This review can be divided in two sections; at first, the impact of construction depth on critical issue of surface settlement is discussed, and in the next part, studies conducted on the influence of construction depth on tunneling cost are reviewed.

Lack of sufficient knowledge about tunneling-induced ground movement can certainly bring many risks, especially in urban areas. Settlement causes damage to buildings and structures on the surface and also bring some destruction to subsurface facilities like sewerage system and gas and electricity lines. Taking countermeasures against settlement requires a perfect understanding of the mechanisms of ground movements (Sharifzadeh et al. 2015).

Terzaghi first noticed soil type's influence on the surface settlement during a series of experiments. Accordingly, due to the dilation effect, ground movement in granular soil gradually decreases as it approaches the surface. However, this volume change is too low in clay strata due to cohesion; therefore, less settlement is witnessed (Koyama 2003).

Gathering data from more than twenty case studies, Peck (1969) presented a report in which he modeled surface settlement trough using a Gaussian curve, using normal distribution to predict surface settlement trough. O'Reilly and New (1982) proposed Eq. 1, based on normal distribution. Mair et al. (1993) confirmed O'Reilly's new equation through field measurements and centrifuge experiments.

$$S = S_{\max}.\exp\left(-\frac{x^2}{2i^2}\right) \tag{1}$$

where $S_{\max}$ is maximum surface settlement above the tunnel axis, S is the surface settlement of a point at a horizontal distance of x from the tunnel axis in transverse direction, and i is the distance of trough inflection point to tunnel axis, i.e., surface settlement trough width parameter.

The real value of volume loss due to the tunneling of Abuzar tunnel in Tehran was investigated and its influence on ground settlement was evaluated by Golpasand et al. (2016). For this purpose, the volume loss was investigated using semi-empirical and numerical methods. Their results were compared to the calculated volume loss obtained using back-analysis methods performed on the monitoring settlements. Analysis of findings showed a high correlation between numerical modeling and monitoring results for settlement.

Moreover, based on instrumentation data and shield operation in three separate EPB tunneling projects in Singapore, Goh et al. (2018) established relationships between the maximum surface settlement and some major influencing factors, including the operational parameters, overburden depth, and ground conditions. Also, Hajjar et al. (2015) proposed a Gaussian equation to describe the influence of tunneling depth on longitudinal distribution of the ground surface settlements. In this study, Plaxis 3D was used to investigate influential parameters on the longitudinal settlement profile. Their study showed that the settlement width trough depends only on the overburden depth and not on the strength parameters of the ground. In another study, using a physical modeling setup, Moussaei et al. (2022) evaluated the influence of tunneling depth on the extent of ground settlement. For this purpose, they simulated the excavation procedure of a full-face circular tunnel by using silica sand with four different densities and three different cover-to-tunnel diameter ratios. The results showed that there is a direct relationship between the height of the loosened zone and the depth of the tunnel.

When using empirical methods, it should be noted that these methods cannot give an accurate answer due to simplifications and the discrete nature of relationships. This is while numerical methods can apply many detailed conditions and features of the real project into the numerical model. Since the numerical method can consider various aspects of a tunneling project and multiple influencing factors, it is accounted as more comprehensive than empirical and analytical methods. So, numerical methods are used as the main tool to model the project and simulate ground-tunnel interactions and behaviors. In numerical modeling, the accuracy of results depends on the level of awareness of in situ conditions and the condition of the enclosed environment (Akbarzadeh et al. 2022).

As mentioned earlier, along with technical aspects of tunneling, its financial aspects, i.e., construction costs, are of great importance, and therefore, it has attracted the attention of many researchers. Moavenzadeh and Markow (1976) used the tunneling cost model to improve the uncertainty in estimating tunneling costs. This model was derived from tunneling on hard ground, and its results reflect tunneling costs' uncertainties. Their results showed that construction of 3657-m tunnels in shale and limestone costs as much as 7.5 to 10.5 M$, in a timeframe of 210 to 305 days. These time and cost spans indicate the low certainty in estimating tunneling time and cost.

Based on a series of data collected in nine subway tunneling projects in Greece, Paraskevopoulou and Benardos (2013) had some studies regarding tunneling cost analysis. They estimated tunneling costs for five classes of rock masses based on 2011 prices. Results showed a particular relationship between geotechnical conditions of the field and tunneling costs. GSI index was used as the indicator of geotechnical conditions in this study.

Rostami et al. (2013) proposed a model to estimate construction costs of tunnels in various conditions in the early stages of projects. This study was based on nearly 270 projects and an analysis of tunnel construction costs with various sizes, ground conditions, and tunnel applications. Several cost estimation models were introduced for different applications like water transfer and subway in soft grounds and rock formations. Rostami et al. (2013) showed that tunneling costs increase as the tunnel diameter increases on both soft and hard ground.

In another study, the influence of tunneling depth on tunneling costs has been noticed by Sayadi et al. (2015). They presented a cost estimation model for tunneling projects using univariate and multi-variate regression techniques. This study was based on 12 tunneling projects in the North West of Iran and different parameters including RMR, tunnel depth, and the type of tunnel support were included in the cost analysis. The presented model provides the possibility of estimation of the tunneling costs at the prefeasibility stage of projects.

Mahmoodzadeh and Zare (2016) found that tunneling cost and time and predicting ground conditions are effective in planning and designing a tunneling project. Accordingly, they proposed a heuristic approach for estimating construction cost and time and ground condition of the Hamro road tunnel, which was originally a combination of a ground condition prediction approach based on the Markov process and variance analysis of time and cost based on Monte Carlo simulation. Results showed that, at a 50 percent confidence level, the Hamro project could be completed with 25.4 M$ of cost in 6 months. It is notable that these figures are for the case when the tunnel is driven from one end, and if the tunnel is to be driven from both sides, construction time will reduce by half.

Using an artificial neural network, Liu et al. (2021) presented a model to calculate subway construction costs based on rock and excavation machine properties. Ahmed (2021) evaluated road and railroad tunnels' costs by multiple regression analysis based on 25 constructed cases in west Europe. Developed models not only considered tunnels' length and diameter but also take excavation method (mechanized or conventional) into account, which is itself influenced by geological conditions. Results showed a high correlation coefficient of 0.978 and 0.79 for mechanized and conventional tunneling, respectively.

Benardos et al. (2021) used cost-benefit analysis to examine the costs and profit of the construction of the Egaleo–Aghia Marina subway project. The analysis was conducted both before and after the project construction, and then they compared figures derived from two analyses. Results showed that cost-benefit values indexed by net present value are twice greater than the estimated ones before project construction.

Based on the Markov chain algorithm, Mahmoodzadeh et al. (2021) investigated the influence of geological and geotechnical uncertainties on estimating the construction costs and time of the Ghalaje road tunnel. They acquired the required data by using the opinions of some tunneling experts through questionnaires, and then by comparison of predicted and actual results, they reduced the uncertainty of estimations.

Considering the above reviewed researches, it can be concluded that there are various successful approaches and methods for predicting tunneling-induced settlement in urban areas. Moreover, a wide variety of studies focused on the tunneling costs and used multiple models to consider multiple parameters such as uncertainty in prices and time, rock or soil type, and the type of boring machine. However, the tunneling depth, as an influential parameter, has been neglected in most of these studies.

The depth of tunneling directly affects the costs of tunneling and station construction in subway development. Minimizing these costs is a general goal for all tunneling project managers. This study aims to investigate the effect of tunneling depth in Line 2 of the Tabriz subway from both technical and financial viewpoints and determine the optimum tunneling depth in the project. For this purpose, a methodology in the form of a two-phase series process is implemented. As the first phase, different depths are evaluated from technical point of view, and then, as the second phase, the approved depths by the first phase are examined from financial aspects to determine the optimum depth eventually.

In technical studies, the surface settlement will be the governing criteria so that when it exceeds the limit of 25 mm, tunnel overburden should be increased until settlement reaches below the limit. The limit of 25 mm is determined based on instructions provided by Iran's Plan and Budget Organization.

In financial studies, the optimum depth of tunneling is determined by analysis of tunneling and station construction costs. To do so, different scenarios of tunneling depth and distances between stations are investigated, and their costs are compared.

Increasing the construction depth causes a significant increase in the cost of stations construction and as a result increases the subway construction costs. Therefore, it is of great importance to determine a depth that is not so low to cause surface settlement in urban areas, and not so high as to impose unbearable costs on the project.

It should be noted that although previous studies used technical or financial viewpoints for determining the optimum depth of subway tunneling, none of them used both of them together. So, the novelty of the adopted mythology in this research lies in the combined use of these two perspectives to determine the optimal depth. However, the results obtained for Line 2 of Tabriz subway may not be generalized to other projects, but the presented methodology can be adopted for other subway construction projects in urban areas.

Features of Line 2 of Tabriz subway

Line 2 of Tabriz subway, with 22.4 km of length, is the longest subway line in Tabriz in North West of Iran (Fig. 1a). There are 20 stations along the line 2 which starts in Gharamalek district in northwest of Tabriz and ends in Basij Square in southeast. The route of Line 2 of Tabriz subway is shown in Fig. 1b. The tunnel of Line 2 is planned to be excavated with EPB TBM, while its outer and inner diameters are 9.49 and 8.48 m, respectively, and trapezoid segments (universal) are used as the support system of the tunnel (Imensazan 2015).

The entire route of Line 2 can be classified in two modes based on two criteria of ground type and overburden height of the tunnel. In the first mode, considering the geotechnical properties of different layers, the route is classified into four groups of the ground type. The classification is based on different geotechnical properties of the ground derived from exploratory boreholes. Considering the fact that the purpose of the modelling is to estimate the surface settlement, the classification has been done in such a way that the characteristics related to the movement of soil particles, including particle size, young modulus, and NSPT, have a greater effect.

These four groups of ground types are illustrated along the route of Line 2 in Fig. 2a, considering the overburden of the tunnel. Most of the first group consists of silty sand, the second group consists of low plasticity silts and clays, and the third group consists of silty sands and some clays and silts, while the fourth group is the hard marl and sandstone. These four groups will be abbreviated as ground A (Si-s), ground B (Si-c), ground C (C-S), and ground D (S-M) in the following.

The route of Line 2 consists of 7000 m of ground A, 2425 m of ground B, 6325 m of ground C, and 6350 m of ground D. This means that silty sand is the dominant ground type of the route, while the silt-clay group covers the least part.

In the second mode, the route of Line 2 is classified into four classes based on the height of the overburden, from tunnel crown to ground surface, as shown in Fig. 2b. This classification is described in Table 1 too, based on the H/D ratio. Notably, just 17 km of the route can be classified in this relationship because the rest of the route will be constructed by open cut method.

Statistical studies indicate that the overburden of the tunnel is always between the tunnel diameter and about three times it, except one percent from the beginning of the route. Class 3 is the dominant class in this regard and covers about half of the subway route. For clarification, Fig. 3 illustrates shares of each of the four classes from the Line 2 route.

Analysis of surface settlement

As the first phase of the study, the tunneling-induced surface settlement in Line 2 of the Tabriz subway will be investigated in this part. For this purpose, at first, tunneling process is modeled with numerical modeling software; then, the model is validated based on a real settlement acquired by monitoring installed instrumentations. In the following, the obtained settlement values are analyzed and discussed to determine the best depth of tunneling from the technical point of view.

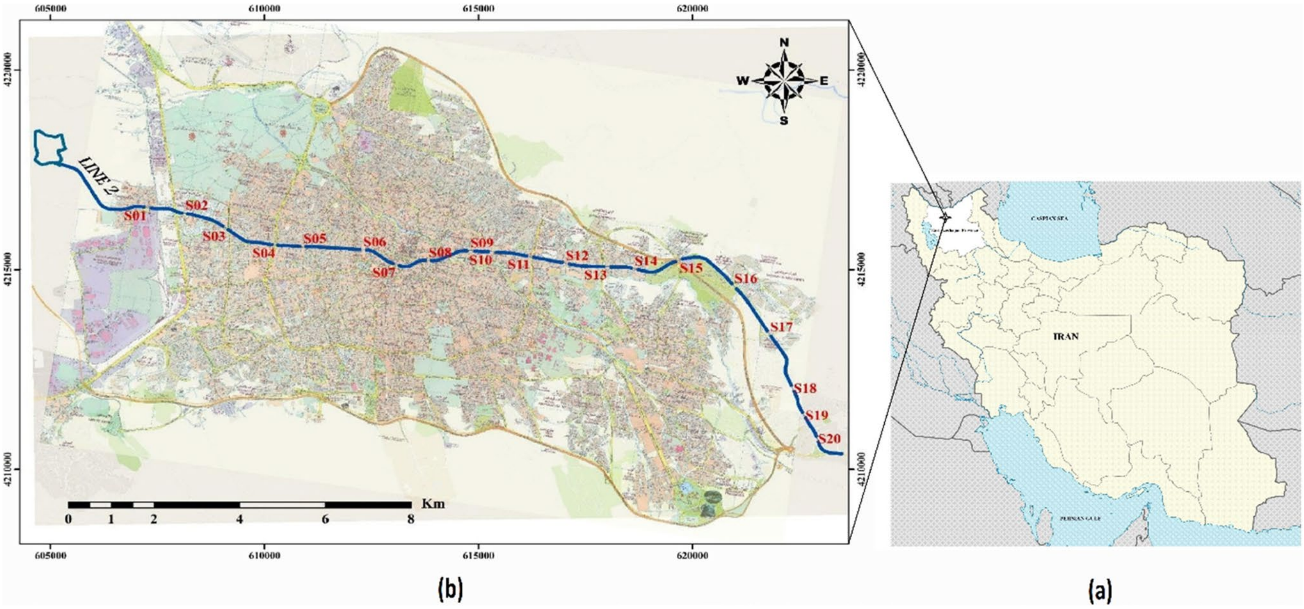


Fig. 1 **a** Location of Tabriz in Iran, **b** route of subway Line 2 in Tabriz

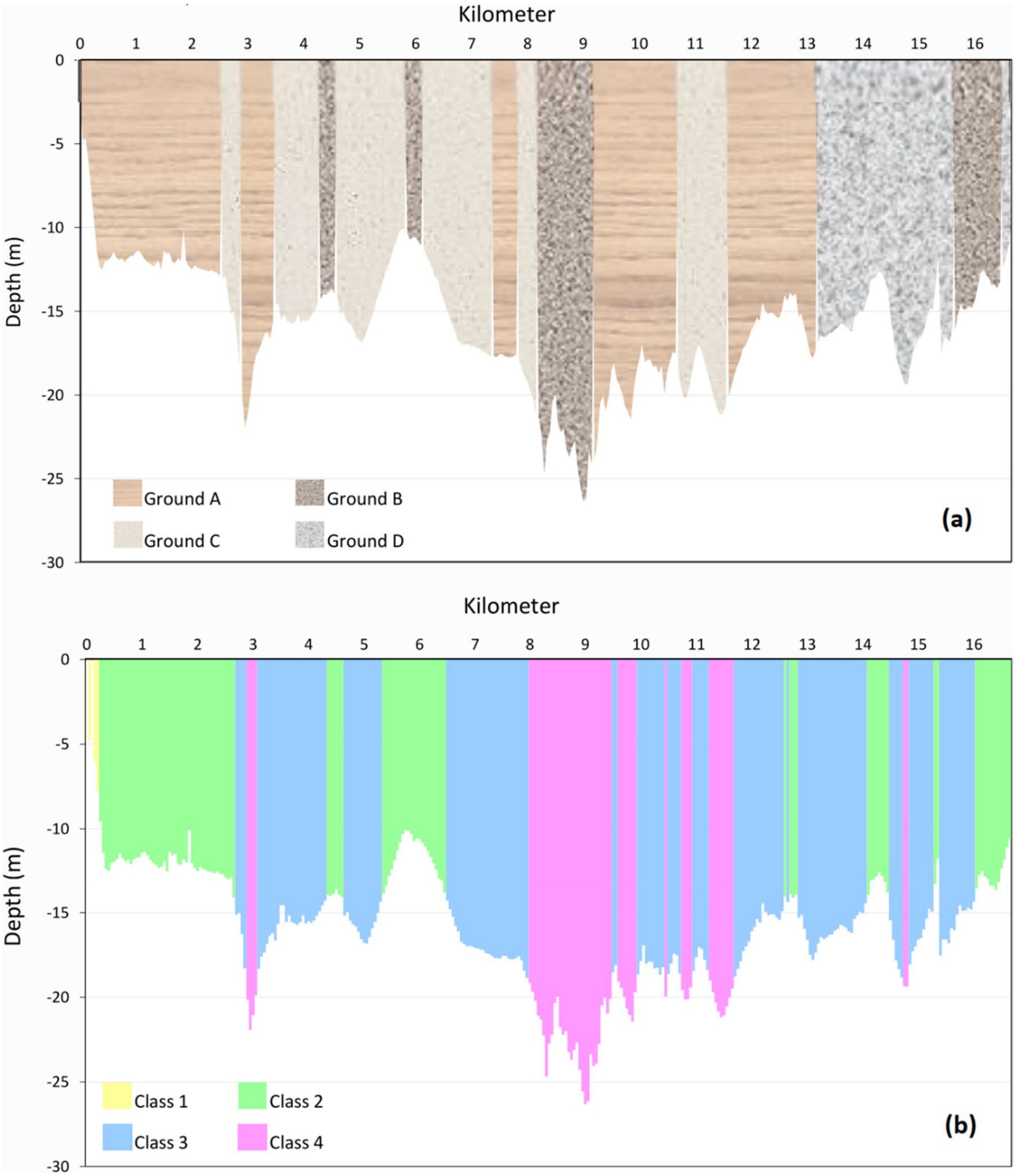


Fig. 2 Classification of line 2 route based on: **a** the ground type and **b** overburden amount

Table 1 Classification based on overburden

Class	Overburden
Class 1	0.5 < H/D < 1
Class 2	1 < H/D < 1.5
Class 3	1.5 < H/D < 2
Class 4	2 < H/D < 2.77

Model development

This study uses numerical modeling software of FLAC3D as a tool to predict tunneling-induced surface settlement and to investigate its change due to change in overburden amount. The modeling steps using FLAC3D software include the following steps: model geometry

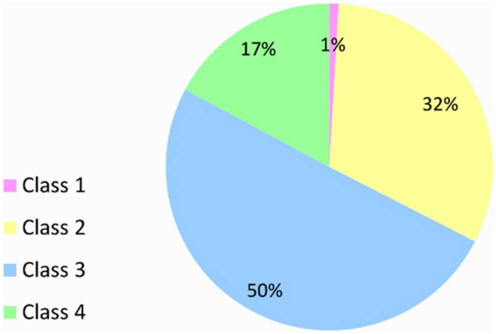


Fig. 3 Share of different classes from the route

creation, assigning a constitutive model, applying boundary conditions, applying initial conditions, primary solving, alteration of the model as required by the problem, final solving of the model, and examination of model response.

The tunneling-induced surface settlement has been investigated in different conditions by constructing sixteen different models. The description of these models has been summarized in Table 2. In the table, in the model column, the letter indicates the ground type while the numbers show the class of overburden amount. Four categories of geotechnical parameters are introduced in Table 2, which are associated with previously mentioned four classes of ground type. Similarly, the chosen overburden for modeling is one of the four overburden classes mentioned earlier.

The support face pressure (total active earth pressure) is calculated by the Dutch Center Underground Bowen (COB) relation proposed by Guglielmetti et al. (2008) as Eq. 2.

$$Sa = Ka\,\sigma_v{}' + u + 20KPa \tag{2}$$

where Ka denotes the active earth pressure coefficient and is calculated as $\mathrm{Ka} = \tan^2\left(45 - \frac{\varnothing}{2}\right)$, $\sigma_v{}' = \gamma h$, and u is water pore pressure.

The selection of model dimensions has been carried out so that semi-infinite geometry simulation would be possible and boundary conditions would not affect the model responses (Nematollahi and Dias 2019). Therefore, the model's geometry dimensions have been selected according to equations 3-5, and the resulting geometry is shown in Fig. 4.

$$\mathrm{Model\ Height} = \mathrm{H} + 4\mathrm{D} \tag{3}$$

$$\mathrm{Model\ Length} = \mathrm{H} + 3\mathrm{D} \tag{4}$$

$$\mathrm{Model\ Width} = 3\mathrm{H}\ (\mathrm{for\ semi-infinite\ model}) \tag{5}$$

Also, boundary conditions have been applied so that all boundaries are constrained in terms of displacement, except the upper surface representing the ground surface. In this way, roller boundaries are created on all sides of the model, and a pinned boundary guarantees zero displacements at the bottom of the model while the surface is free for displacement.

Table 2 Parameters used in different models constructed by FLAC3D

No.	Model	Overburden (m)	Young modulus (MPa)	Poisson's ratio	Internal friction angle (°)	Density (kg/m^3)	Cohesion (KPa)	Work pressure (KPa)	Grout injection pressure (KPa)
1	A-1	6.04	44	0.34	28	1920	15	60	110
2	A-2	12.31	44	0.34	28	1920	15	123	173
3	A-3	16.45	44	0.34	28	1920	15	164	214
4	A-4	21.31	44	0.34	28	1920	15	213	263
5	B-1	6.04	33	0.38	19	1700	44	67	117
6	B-2	12.31	33	0.38	19	1700	44	138	188
7	B-3	16.45	33	0.38	19	1700	44	184	234
8	B-4	21.31	33	0.38	19	1700	44	238	288
9	C-1	6.04	37	0.38	21	1700	29	64	114
10	C-2	12.31	37	0.38	21	1700	29	131	181
11	C-3	16.45	37	0.38	21	1700	29	176	226
12	C-4	21.31	37	0.38	21	1700	29	227	277
13	D-1	6.04	47	0.37	21	1750	54	66	116
14	D-2	12.31	47	0.37	21	1750	54	135	185
15	D-3	16.45	47	0.37	21	1750	54	181	231
16	D-4	21.31	47	0.37	21	1750	54	234	284

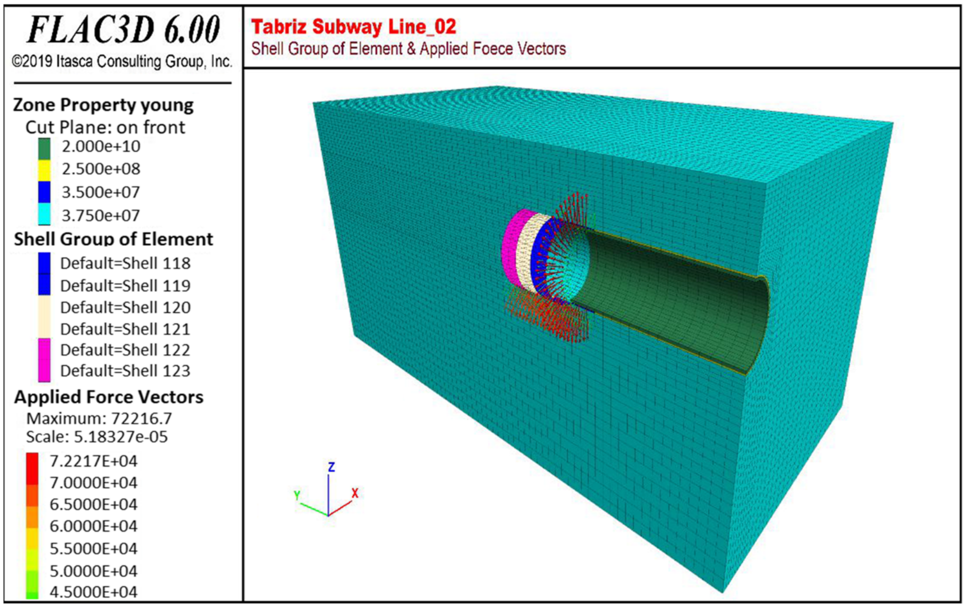


Fig. 4 Modelling of tunnel in FLAC3D

The ground was assumed to be homogeneous and without stratification in all models to facilitate the modeling. Also, medium mesh sizes are adopted in the model, except in the vicinity of the tunnel, where fine mesh sizes are chosen.

During the modeling process, shell structural elements were used to simulate the conical shape of the TBM shield. Specifically, TBM shields were modeled in three parts of front shield, middle shield, and rear shield, each of which had a different Young's modulus. The elastic modulus of the front section was determined as 100 GPa, while for the other two sections, the elastic modulus was determined based on sensitivity analysis. This type of elastic modulus assignment caused its linear decrease along shield sections from the front to the ending section, so that it was determined as 10 GPa and 1 GPa for the middle and the rear sections, respectively.

Mohr-Coulomb model was chosen as the constitutive model in the modeling process. The equilibrium limit is set as 10e-7 for all models, and after setting the sufficient steps for solving the model, alterations of the model (materials' excavation, support installation, etc.) are made.

Validation of modeling results

In order to investigate the accuracy of the modelling process and validate its results, the maximum surface settlement values produced by the model in four different sections along the route are compared with real values acquired by instrumentation and settlement values estimated by Peck's empirical relation. It should be noted that for modeling of chosen sections, a reference point 60 m behind the face is selected to monitor the settlement in various sections. Also, modelling parameters used in this section are shown in Table 2. Peck's relation used to estimate the maximum surface settlement is shown in Eq. 6.

$$S(\mathrm{Max}) = 0.313\left(\frac{V_{\mathrm{L}}D^2}{i}\right) \tag{6}$$

where V_{L} is the ground loss, and i is an empirical dimensionless parameter which is defined by geological and geotechnical characteristics of the soil. Considering TBM shield type, tunnel route, and experience of the operator, ground loss parameter was adopted as 1.5 percent in peck's relation.

Table 3 Settlement results derived from modeling, instrumentation, and empirical relation

No.	Maximum ground settlement values (mm)	Different overburden amounts			
		Class 1	Class 2	Class 3	Class 4
1	Average modeled settlement (mm)	39.0	29.0	19.0	13.0
2	Real settlement values (mm)	38.5	29.2	16.0	12.0
3	Experimental settlement values (mm)	41.3	26.1	21.0	17.1

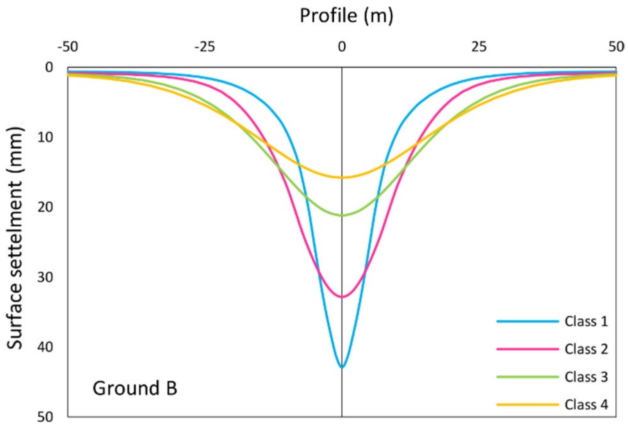


Fig. 5 Settlement profiles for different depths in Ground B

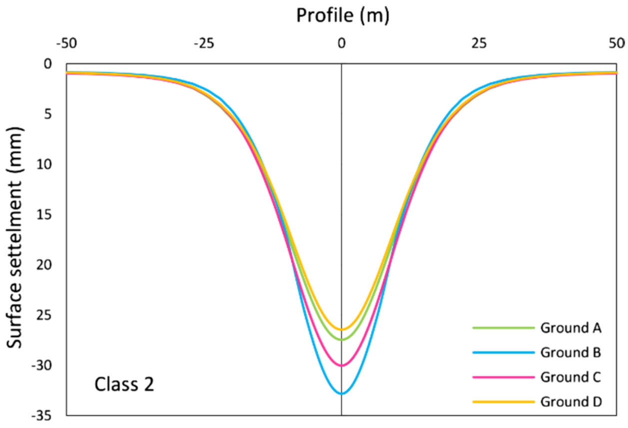


Fig. 6 Settlement profiles for 12.31 m of overburden in different ground types

The average surface settlement values derived by numerical modelling as well as real values and empirical values are reported in Table 3. These results indicate that the average settlement values obtained from the modeling are very close to the real and empirical values. As it can be seen, the least difference is for class 2, and the biggest difference is for class 3. Therefore, it can be concluded that numerical modelling process used in this study is valid and reliable.

Ground settlement estimation in various depth

After validation of the modeling process, it is possible to investigate the influence of different depths of mechanized tunneling of Line 2 on surface settlement and to determine the optimum depth. If the settlement amount is higher than 25 mm, the overburden of the tunnel should be increased until the settlement reaches under the limit.

This way, by running 16 different models, maximum surface settlement in ground types of ground A, ground B, ground C, and ground D has been calculated for different depths. Four overburden depths of 6.04, 12.31, 16.45, and 21.31 m were examined for each ground type, named class 1, class 2, class 3, and class 4 and illustrated in blue, pink, green, and orange colors, respectively, in related figures. The influence of depth and ground type on maximum surface settlement values is examined in all ground types and for all classes of overburden depths. Figures 5 and 6, as examples, illustrate the influence of various tunneling depths and various types of ground on surface settlement, respectively.

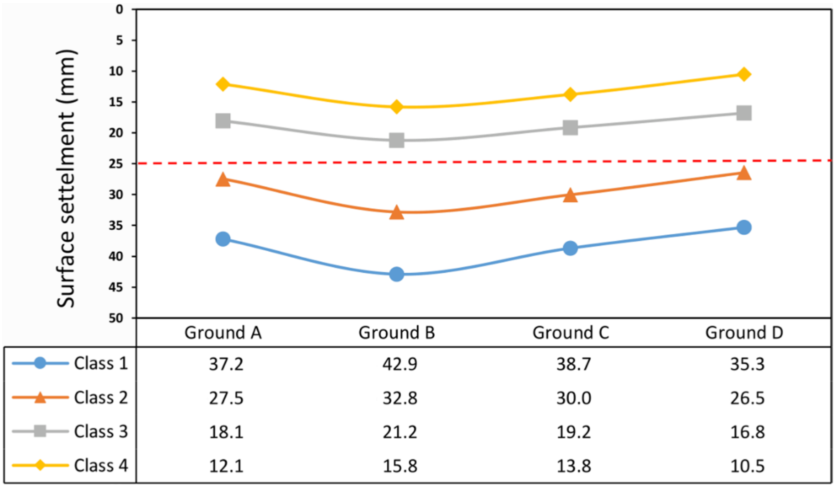
As seen in Fig. 5, maximum surface settlement in ground B for overburden depths of class 1, class 2, class 3, and class 4 equals 42.9, 32.8, 21.2, and 15.8 mm, respectively. The difference between the highest and lowest value in ground B is about 27 mm, indicating depth's significant effect on reducing surface settlement.

The overburden depth of about 30 percent of the line 2 route is between 1 and 1.5 times of tunnel diameter. As Fig. 6 shows, the maximum settlement of ground A, ground B, ground C, and ground D in the constant depth of class 2 equals 27.5, 32.8, 30.0, and 26.5 mm, respectively. The difference between the highest and lowest values of settlement in constant overburden of class 2 is 6 mm, indicating that tunnel depth's influence on the ground settlement is much greater than ground type. The results of class 2 show that the maximum settlement of all models of this class is beyond the permissible limit, meaning tunneling with overburdens less than 1.5D is hazardous and not recommended. Maximum settlement values for different ground types and different overburdens are reported and illustrated in Fig. 7.

The permissible limit of settlement, which is 25 mm, is shown with a red dashed line in Fig. 7. The blue and brown lines demonstrate settlements more than the limit. Therefore, tunneling with overburdens less than 1.5D is not allowed. A further survey of obtained results shows that the average maximum surface settlement due to tunneling in depths of class 1, class 2, class 3, and class 4 equals 38.5, 29.2, 18.8, and 13.1 mm, respectively. In other words, the average surface settlement for class 1 depth is about three times greater than class 4 depth. As expected, the maximum amount of surface settlement is related to the tunnel with the least overburden (class 1), while the minimum surface settlement is for the tunnel with the highest overburden (class 4).

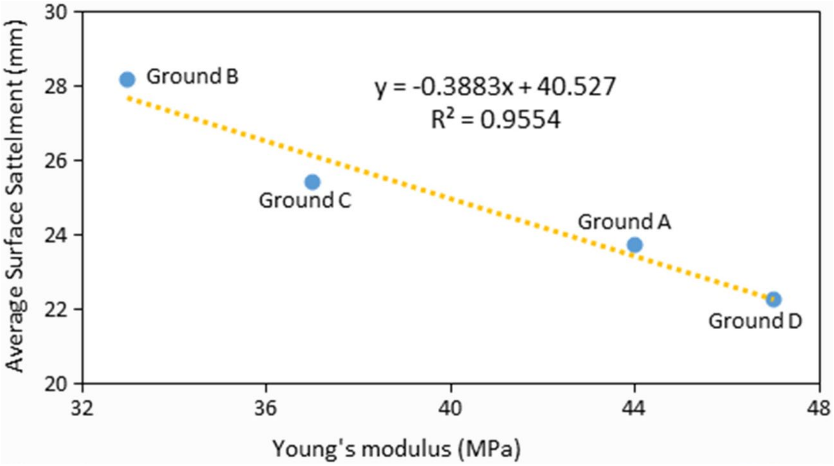
Another finding from Fig. 7 is that the average maximum surface settlement for different depths in ground types of ground A, ground B, ground C, and ground D equals 23.7, 28.2, 25.4, and 22.3 mm, respectively. These figures show that maximum surface settlement descends in the order of ground B, ground C, ground A, and ground D. Further investigating ground geotechnical parameters of the route and comparing them with settlements value conclude that

Fig. 7 Maximum surface settlement values for all studied modes



	Ground A	Ground B	Ground C	Ground D
Class 1	37.2	42.9	38.7	35.3
Class 2	27.5	32.8	30.0	26.5
Class 3	18.1	21.2	19.2	16.8
Class 4	12.1	15.8	13.8	10.5

Fig. 8 Correlation of Young's modulus and maximum surface settlement



maximum surface settlement is highly dependent on Young's modulus of that soil, so that Young's modulus of ground B, ground C, ground A, and ground D is 33, 37, 44, and 47 KPa, respectively. Figure 8 shows the correlation of Young's modulus and maximum surface settlement in different depths.

According to all discussions mentioned before, it can be concluded that, from the technical point of view, tunneling in depths less than 1.5D generates impermissible settlement amounts, and tunnel construction is not recommended.

Table 4 Rebar consumption in each ring of the tunnel

No.	Overburden to diameter ratio	Rebar consumption in each ring (kg)	
		Rebar Diameter <10mm	10 mm <Rebar diameter < 18 mm
1	0.5–1	1123	1253
2	1–1.5	958	1069
3	1.5–2	826	921
4	2–2.7	991	1106

Financial assessment of subway construction

As the second phase of the study, the influence of construction depth of Line 2 of Tabriz subway on construction costs should be evaluated too. Although technical studies indicated that tunneling in depths less than 1.5D is not permissible in the project, in order to provide a more comprehensive assessment, the construction costs for all four classes of overburden will be evaluated. To do so, tunneling costs are evaluated first, and then station construction costs in different depths are discussed. Moreover, the unit cost of tunnel and station construction for various distances of stations are investigated in different scenarios.

Table 5 Tunneling costs in different depths

No.	Overburden to diameter ratio	tunnel construction Cost (M$/km)
1	0.5–1	4.80
2	1–1.5	4.64
3	1.5–2	4.51
4	2–2.7	4.67

Financial estimations of tunneling

In order to estimate tunneling costs for Line 2, prices of consumable items and contractors' salaries are extracted from the price list announced by the country's Plan and Budget Organization for road, railways, and airport runways, in the year 2021. It should be noted that the amount of consumed rebar has been inquired from the project officials, and its costs are calculated accordingly. Detailed figures of consumed rebar in each ring of the tunnel based on its overburden are listed in Table 4.

In order to evaluate the costs of construction for each meter of the tunnel, construction costs for constant depth are extracted from the mentioned price list. The tunneling cost for different overburdens has been calculated.

Tunneling costs for all four modes of overburden depths are calculated (Table 5), and detailed calculation of costs for the case of overburden between 1D and 1.5D is summarized in Table 6, as an example.

By dividing the total cost of tunneling by tunnel length, the construction cost of each meter of the tunnel is obtained. This value should then be multiplied by correction factors of the site mobilization factor and overhead cost factor, which have been adopted as 1.04 and 1.30, respectively, in this study. Tunneling costs for all four modes of overburden are calculated and are summarized in Table 5.

Table 5 shows that increasing the tunnel overburden to 2D decreases the tunneling costs while increasing the overburden to more than 2D increases the costs to 4.67M$.

Financial assessment of stations construction

The most important costs of station construction are the building, acquisition and equipment, access galleries, escalator, elevator, ventilation, facilities, and spaces required for personals and facilities. Station construction costs can be classified into five main categories: main structure, trench support, electrical facilities, mechanical facilities, and interior finishing works. The share of each category from the total cost is shown in Fig. 9.

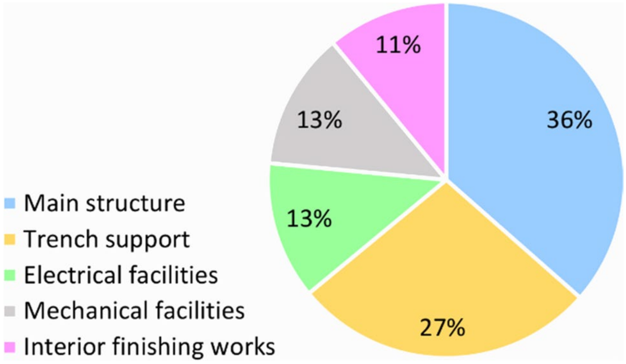


Fig. 9 Classification of stations construction costs

Average station construction costs for Line 2 of the Tabriz subway have been inquired from the project's officials, which are reported in Table 7.

As Table 7 shows, naturally, the number of floors increases with the depth of the tunnel, and this causes an increase in the number of stairs, elevators, access galleries, ventilation, and spaces for facilities too. This means more costs of station construction with more depth of tunneling.

Summation of tunnel and stations construction costs

In order to make a more comprehensive evaluation of tunnel and station construction costs, the distance between the stations should also be considered. The typical distance between subway stations in urban areas is around 800 to 1200 m. This issue is more noticeable when the distance between the stations increases due to reasons such as residential settlements on the outskirts of cities.

In this study, seven different scenarios for comparison of tunnel and station construction costs have been considered. In the 17 km of the studied route, which a TBM machine will excavate, distances between stations are considered in seven modes 750, 1000, 1250, 1500, 1750, 2000, and 3000 m. In these conditions, the total costs of subway construction for different distances of stations and different depths of overburden along the total 17 km of the route are estimated, and then the unit cost of subway construction for 1 km of the route is calculated by simple averaging and the results are summarized in Fig. 10 for different scenarios.

In Fig. 10, it is clear that decreasing the distance between stations and increasing the overburden depth increases the unit costs of subway construction. To determine the optimum tunneling depth from a financial point of view, further analysis in Fig. 10 concludes that different

Table 6 Costs of full-faced mechanized tunneling for depths between D and 1.5D based on announced price list

No	Description	Unit	Amount	Unit price (US $)	Total price (US $)
1	Construction of tunnel with cross sections of 40 m^2, in non-rocky ground, by using any type of TBM machine	m^3	1,583,617	143.43	46,719,022
2	Price fraction per square meter more than 40 square meters and less than 140 (per m^2)	Percentage	−0.45	−14,341,422	−6,453,640
3	Extra pay to full face tunneling with TBM row in depths more than 250 m, for second 250 m one time and for the third 250 m two times, and so on for greater depths	Percentage	1	5,240,247	5,240,247
4	Performing all required operation for installing three-point convergence instrumentation in tunnel during excavation	Seri (3 times)	23	7.96	183
5	Performing all required operation for reading convergence instrumentation in tunnel during excavation for each point	Reading	230	2.73	628
6	Extra price for installing each convergence point in addition to the first three points	Number	20	5.33	107
7	Performing all required operation for installing and reading of any divergence instrumentation in tunneling, for length less than 5 m	Meter of length	115	28.16	3238
8	Extra price for additional length of instrumentation more than 5 m	Meter of length	460	6.27	2883
9	Providing, installing and reading of instrumentation	-	1	342,801	342,801
10	Providing, cutting, bending and installing ribbed bar type AIII with diameter up to 10 mm for reinforced concrete with winding	kg	14,306,444	0.58	8,347,060
11	Providing, cutting, bending and installing ribbed bar type AIII with diameter 12 to 18 mm for reinforced concrete with winding	kg	15,959,892	0.47	7,571,961
12	Providing and installation of precast concrete elements for installation in tunnels excavated with TBM machine	m^3	217,280	61.44	13,348,994
13	Transportation of materials in asphalt roads, for more than 1 and less than 10 km	m^3–km	137,760	0.026	3542
14	Providing equipment and implementing ventilation system for tunnels for construction lifetime	m^3	1,270,444	0.463	587,938
15	Providing and installation of lighting equipment for tunnel for construction lifetime	Meter of length	22,400	12.73	285,189
16	Extra price for ventilation and lighting for additional distance more than 250 m, one time for the second 250m and two times for the third 250 m, and so on for greater lengths	Percentage	7	97,934.42	685,541
17	Providing and performing dewatering operation in tunnels	m^3	2,240,000	0.025	55,901
18	Providing and installation of pipes for transferring of pumped water to outside of tunnel	Meter of length	22,400	1.344	30,101
19	Transporting ironware and packaged cements additional to 30 km and less than 75 km	Tone–kilometer	4,186,582	0.022	89,841
20	**Total cost of tunnel construction**	**United States Dollar**		**76,861,537 (US$)**	
21	**Cost of each meter of tunneling**	**United States Dollar**		**3431 (US$)**	
22	**Cost of each meter of tunneling including site mobilization and overhead costs:**	**United States Dollar**		**4639 (US$)**	

distances between stations bring different subway costs. As expected, increasing distances between stations reduce the costs. In other words, the greater the depth of the tunnel and the shorter the distance between the stations, the higher the construction cost of the subway; also, the lower the depth of the tunnel and the greater the distance between the stations, the lower the construction cost of the subway. More specifically, the unit cost of subway construction along the route reaches 29 M$ per kilometer when the overburden is greater than 2D and the station distance is 750 m. In comparison, it decreases to its minimum amount of 7 M$ per kilometer when tunnel overburden is

Table 7 Station construction costs in various depths

No.	Number of floors	Overburden to diameter ratio	Station construction costs (M$)
1	One	0.5–1	6.50
2	Two	1–1.5	8.57
3	Three	1.5–2	11.67
4	Four	2–2.7	17.13

less than tunnel diameter (1D), and the station's distance is 3000 m.

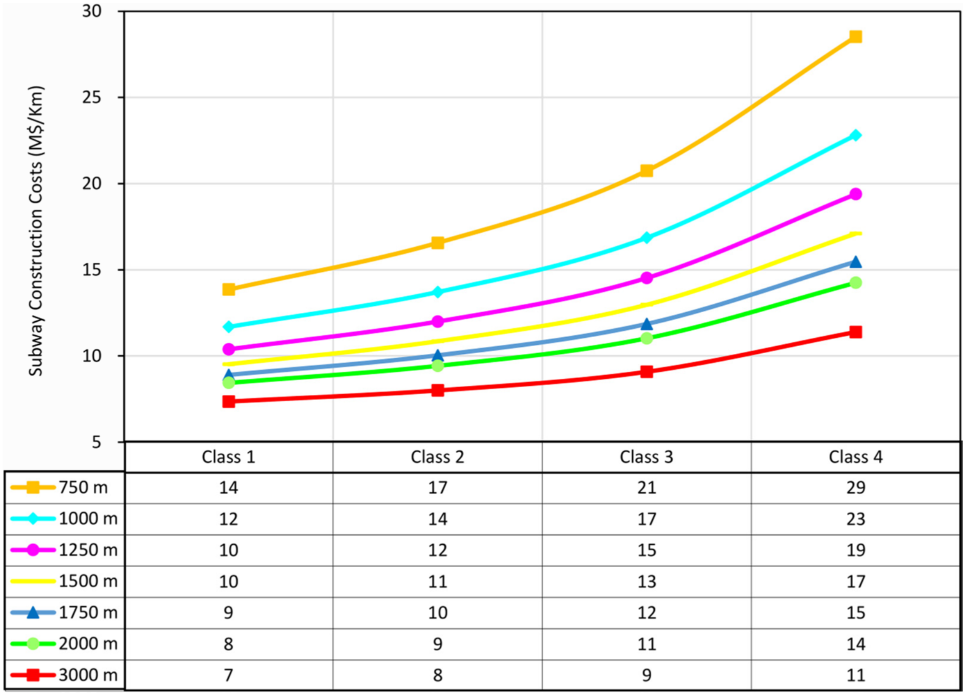
Normal distances between stations in urban areas differ from interurban areas of residential settlements on the outskirts of cities. Considering this issue, it is possible to determine the optimum tunneling depth from a financial point of view, using the results obtained from this study. It should be noted that in all scenarios, the lowest depth of tunnel brings the least costs for constructing tunnels and subway stations.

Since the technical studies showed that depths more than 1.5 times the tunnel diameter (class 3 and class 4) are recommended for subway construction in the project, and financial studies indicated that the least depth bring the least costs, it can be concluded that considering both technical and financial points of view, the most optimum depth for constructing Line 2 of the Tabriz subway is when the tunnel overburden is 1.5 to 2 times the tunnel diameter.

Conclusions

In this study, the influence of different depths of tunneling in Line 2 of the Tabriz subway has been evaluated from both financial and technical points of view, and the optimum depth of tunneling has been determined. In technical studies, the surface settlement was chosen as the main criteria so that if it reaches 25 mm, the overburden should be increased until the value of ground settlement reaches less than 25 mm. Evaluation of costs of construction of tunnel and station forms the financial viewpoint of this study, which means an optimal depth is considered to have the lowest cost of subway construction along the tunnel route. The most important result of this study are as follows:

- Results of tunnel construction modeling in different depths showed that even though ground type affects surface settlement, overburden depth is a more effective parameter. Modeling results indicated that overburden depths less than 1.5D bring impermissible surface settlement, and tunneling in such conditions is not recommended.
- With the increase in depth, the costs of tunnel construction first decrease, and then when the tunnel overburden is more than twice the tunnel's diameter, they start increasing again. Costs of tunnel construction in different depths vary between 4.5 and 4.8 M$ for Line 2. This indicates that overburden depth does not have a significant influence on tunneling costs.
- As the station depth is less than the tunnel diameter, the construction costs of each station are equal to 6.5 M$, and they increase gradually with increasing the depth so



	Class 1	Class 2	Class 3	Class 4
750 m	14	17	21	29
1000 m	12	14	17	23
1250 m	10	12	15	19
1500 m	10	11	13	17
1750 m	9	10	12	15
2000 m	8	9	11	14
3000 m	7	8	9	11

Fig. 10 Subway construction costs in different depths and scenarios

that when the construction depth is greater than 2D, it reaches 17.1 M$, which is about 2.5 times greater than the previous case. This indicates that the construction depth of subway stations in urban areas has a significant influence on the cost of construction.

- Subway construction costs depend highly on the depth of construction and the distance of stations from each other. To put it more clearly, the lowest subway construction costs are in the case where the subway has the least overburden and the longest distance between train stations, and vice versa. To be more specific, in Line 2 of the Tabriz subway, the unit cost of subway construction for every kilometer of the route is 7 M$ when the depth is less than the tunnel diameter and the station distance is 3000m, while the unit cost increases to 29 M$ when the depth is greater than 2D and station distance is 750 m.
- Considering both technical and financial points of view, the most optimum depth for constructing Line 2 of the Tabriz subway is when the tunnel overburden is 1.5 to 2 times the tunnel diameter.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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