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Research Paper

The investigation of Cut-and-cover, top-down construction method for a metro underground station; case study: 'Naghsh-e-Jahan Metro Station, Esfahan, Iran'

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ABSTRACT

Naghsh-e-Jahan subway station is located in Esfahan historical context with 186 meters' distance to the Sheikh Fazlolah mosque – one of the historical cosmopolitan attractions. The subway station is in a shallow depth, soft surrounding soils and with wide span and in a downtown location, have made the situation so critical that precise assessments, not only for the station support but also for compensating the ground settlement, are needed. One of the prerequisite procedures for large underground structures, the cut-and-cover approach, is constructed top-down using the Diaphragm Wall system. This method can be functional in conditions where minimum vertical displacements are essential since roof covering and improvement can be performed even when the excavation operation is not terminated. The embankment process can be done just right after the roof slab is complete and reaches reliable strength. This study uses the Finite Element method to simulate all the construction stages and analyze the ground behavior. It has been observed that the width and the length of diaphragm walls and middle barrettes on the ground settlements. Ground settlement for various stages of excavation at the cross-section and longitudinal section of the station is shown that settlements are spandrel and maximum settlements occur close to the diaphragm walls. As excavation continues, ground surface settlements become concave, and the maximum surface settlements occur at a bit of distance from the diaphragm walls for about 17mm. Furthermore, the diaphragm wall's thickness of 100 cm of diaphragm wall is recommended for optimum values.

1 Introduction

The cut-and-cover excavation can be executed in various methods. The choice of a ground support system and the method of installing it are primarily dictated by the nature of the ground and the groundwater conditions, the proximity of existing structures to the excavation, a necessity to control the ground movements, method, and sequence construction and any other

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constraints [1]. A typical list of the ground support systems used in the world over the years includes Sheet Pile walls, Soldier Pile, Secant Pile walls, Diaphragm walls, and others. When the excavations are deep enough among shoring systems, diaphragm walls can be used. It is made of reinforced concrete made primarily according to loads that need to be resisted. It can be as a part of a temporary or permanent retaining wall or both. For the deep excavation of the basement and tunnels, the diaphragm wall is the best choice. The use of slurry trench walls as structural diaphragm walls in the construction of cut-and-cover metro structures started in the late 1950s. Over the last years, the use and popularity of diaphragm walls have grown, especially where control of ground movements is critical.

Functional in stabilizing large span underground spaces in sophomoric soft soils, Cut-and-cover top-down method described and evaluated in this study utilizes the underground, reinforced concrete elements including diaphragm walls and intermediate columns respectively from Earth's surface around and inside the proposed underground space. This technique is performed before the main excavation in order to stabilize the ground during the operation. In this case, given the necessity for keeping settlement under control and expediency for reopening the ground surface, and due to the station's strategic location exposes to cosmopolitan Naghshe-Jahan square, a top-down excavation method is selected construct the desired section.

The stress redistribution caused by excavation induces movements in the earth mass and ultimately to the ground surface. The need to control surface settlement in urban areas is widely recognized. Settlement induced by underground excavation may cause severe damages to nearby structures and subsurface utilities [2, 3]. Several predicting methods for ground surface settlements are presented by [4-6]. Recent literature describes and studies various ground treatment techniques that improve underground excavation stability and reduce ground settlement. KrishanKaul (2010) described different cut-and-cover methods for metro station construction. The bottom-up (B.U.) method is the most conventional approach, with many examples in the literature. Among them, Finno et al. (1989), Finno and Nerby (1989), and Finno and Roboski (2007) reported field data for B.U. excavations in Chicago soft soil [7-9]; O'Rourke and McGinn (2006) and Hashash et al. (2008) described the performance of deep excavations carried out in Boston Blue clay (U.S.), focusing on the effect of deep mixing soil stabilization [10, 11], while Blackburn and Finno (2007) discussed the three-dimensional (3D) response of a braced excavation in the medium-stiff soil of Evanston, Illinois (U.S.) [12]. Case histories of B.U. excavations in Shanghai soft soil were reported by Wang et al. (2005)and Tan and Wei (2012) [13, 14].

On the other hand, in the top-down (T.D.) excavation method, permanent concrete floor slabs are used to prop the diaphragm walls, with a long time between two subsequent excavation stages to construct the propping level. However, the higher stiffness of the floor slabs than that of the steel struts sensibly reduces ground movements induced by the excavation. In this context, Ng (1998, 1999) illustrated the stress paths observed in the proximity of the T.D. excavation of a multistory car park in Cambridge stiff clay (U.K.) [15, 16]; and Ou et al. (1998, 2000), presented the observed performance of a deep excavation in Taipei soft clay, focusing on the effects on the nearby buildings, where they discussed the changes in pore water pressure induced by the excavation [17, 18]. Liu et al. (2005), Tan and Li (2011), Liu et al. (2011), and Ng et al. (2012) described the performance of T.D. deep excavations in Shanghai soft clay, providing field observations of wall deflections and ground surface settlements concerning changes in pore water pressure [19-21]. More recently, advances in technology and scientific knowledge promoted the adoption of hybrid excavation techniques. For example, Tan et al. (2017)introduced the definition of the semi-top-down method for excavations propped by both temporary steel struts and permanent concrete slabs [22], while Tan et al. (2018) described the performance of a deep open excavation in Suzhou as stiff clay (China) supported by composite Earth retaining system [23]. Masini et al. (2021)showed that a stiff retaining system and strict control of the construction sequence were the keys to minimize the effects of a deep excavation with a diaphragm wall in the Historical Center of Rome [24].

Many pieces of research assessing the maximum ground settlement and their shape due to a deep excavation have been done over the past decades [25-28]. In the case of Ou et al. (2006), it was anticipated that the surface settlement caused by adjacent excavation would fall into two types: Concave and Spandrel type, which are due to the value and shape of the retaining wall displacements (Figure 1) [29]. In the excavation step, the maximum movements are attributed to the retaining wall; spandrel type of settlement occurs at the early stages of excavation, and when the excavation proceeds, settlement turns to concave and occurs with a distance to the retaining wall.

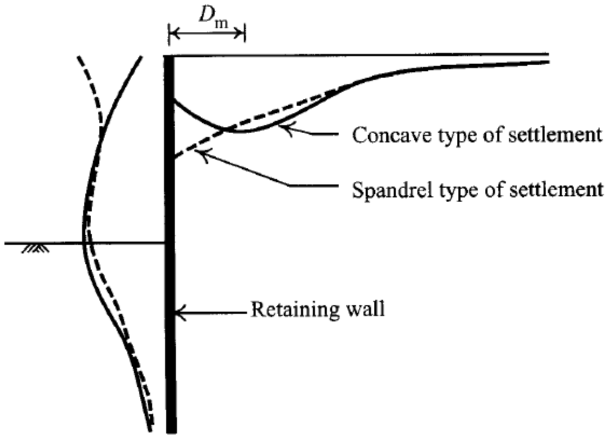


Fig. 1 – Types of ground settlement (Ou et al. 2006) [29]

Besides, in recent decades, numerical simulation has quickly become the dominant method for solving engineering problems, including stability analysis and predicting system behavior. Numerical modeling, such as the finite element method, is a functional tool for stability analysis of underground spaces in sequential construction and determining the influence of effective parameters [30-32]. In this research, the Cut-and-Cover top-down method and construction sequences and width and depth of diaphragm wall influences are measured using numerical modeling of the Naghshe-Jahan metro station.

2 Study site geological specification

Isfahan is a large city in central Iran, with near 2 million populations. Metro construction began in 2002 in this city, and in 2015 part of the first line from the north to southern Isfahan was put into use. The second line was supposed to connect the eastern Isfahan to western parts and started in 2015. Twenty-three kilometers length with 22 stations, the second line will establish from the city's east side, and its crossover with line one is located on the west side. Line two continues its way to Sepah Street and beneath the north side of Naghshe-Jahan Square in Hafez Street and then goes to Zainabiye Street. The connection between two stations (Khorram to Zainabiyya) needs two parallel tunnels excavating by mechanized drilling. Two tunnel boring machines (TBM) are used; however, the excavation operation from Shohada square to Khorram Street is done by a Non-mechanized drilling method.

Fig. 2 – The location of Naghshe_e Jahan Station in Isfahan City

Fig. 3 – The location of Naghshe_e Jahan Square to Zayanderood River

That most parts of this line are located beneath the historical areas of Naghshe Jahan Square, a vitrine of the most beautiful artworks from the Safavieh era, became a UNESCO World Heritage site in 1979, makes the situation extremely critical that careful consideration must be done for preventing damages to surrounding structures. According to the surveys, intermediate stations' construction is under operation before the end of the tunneling process, so this can play a crucial role in determining the underground conditions. Furthermore, due to the lack of high-tech equipment to control the settlements and the shallow depth of the station, the cut-and-cover approach is used instead of the underground drilling method. Besides, since scrutiny of drilling sequence is necessary for such conditions, this method has been designated. However, Cherlo et al. (2013) evaluate the excavation of Naghshe Jahan Square subway station by underground methods. The ground settlement is estimated to be 6 to 8 cm and 9 cm relative to the centerline, which is unacceptable in this area [33].The studied case, Naghshe-Jahan station, which is intended to be constructed as an island station 100 meters long, is shown in Figure 3, and figure 4 shows an overall picture of Naghshe-Jahan station or M2 station.

In geological terms, the Isfahan province extended sequences of sedimentary deposits, metamorphic and igneous rocks exposed at different levels. Groundwater levels vary throughout the year, according to the recent droughts. The studied area is located in the north of the Zayanderood river and floodplain sediments.

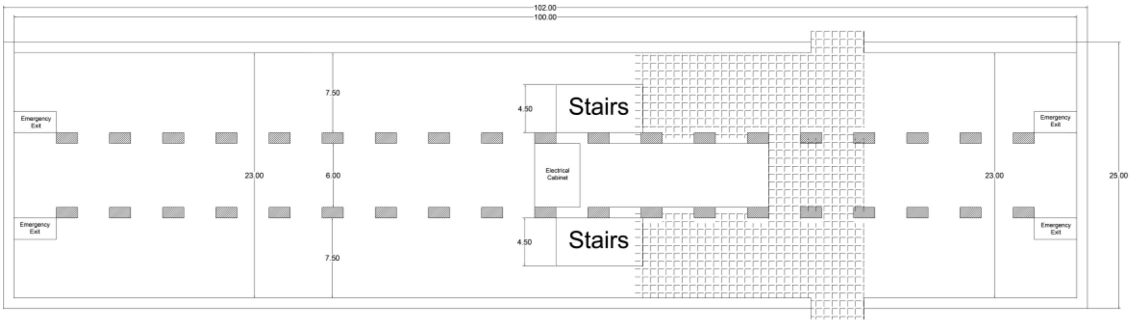


Fig. 4 – Plan of Naghsh_e Jahan Metro Station

Since the urban train line two passes from some old urban areas, manufactured soil depths manually in some boreholes were observed. The borehole drilling process did not collide with bedrock along line two; consequently, line two tunnel is constructed in soil formations. Geotechnical investigations have been done for the studied area by Isfahan's subway and suburban operation. Forty-four boreholes with depths of 30 to 40 meters were dug to identify the geotechnical characters. Various tests on borehole samples were carried out to account for the geotechnical profiles, which generally include three layers of surface fine-grained, coarse-grained, and bottom fine-grained. The depth of groundwater based on geotechnical reports of Pajoohesh Consulting Company depends not only on seasonal changes but also on the average of Zayanderood River flow, and its estimated level is 17.5 meters from the surface.

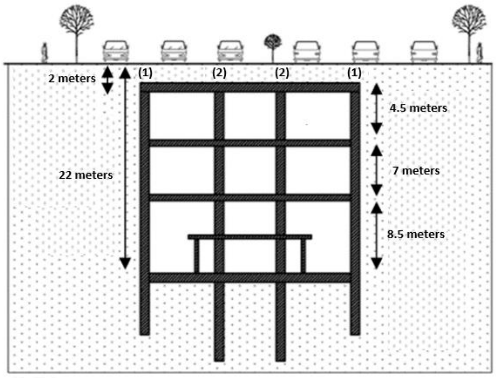


Fig. 5 – The shape of the station from the front side

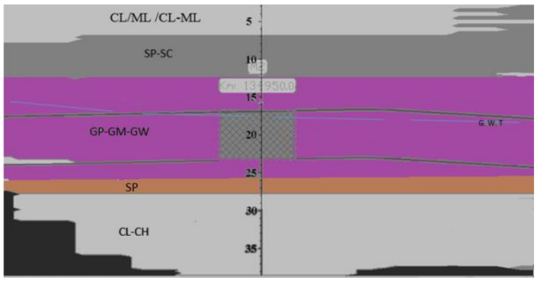


Fig. 6 – Longitudinal profile of line 2 and the situation of the station

3 Construction method

Because of the lack of the opportunity to control the ground conditions during excavation, the underground excavation procedure did not apply to this case; the need to complement the station in the shortest possible time and control underground water's flow to the excavation station almost obliterates the chance of using this method. In addition, the station's shallow depth and shortage of advanced features for drilling were other reasons for choosing Cut-and-Cover top-down method instead.

As already mentioned, cut-and-cover excavation with top-down method benefits diaphragm walls operated as reinforced concrete elements around the station's scope and interval piles dictated by the station's architectural design. These piles are implemented to withstand loads of different levels of the station before the excavation begins. Hence, after installing these elements, the station is ready to be constructed.

This method was used in Sanat square station, Tehran metro line 7, and Kargar Station in Ahvaz urban train. Furthermore, this method was used in Kargar Station in Ahvaz urban train, and induced settlement was investigated. The measured settlement was compatible with first and second Pack curves; the excavation impact on adjacent buildings was in the range: "negligible effect" [34].

An essential benefit of this approach is the potential to control the ground settlement compared to underground excavation. Moreover, permanent floor slabs bring about continuous strut action that is much superior to isolated struts at discrete locations; also, the need for additional bracing and extensive falsework is significantly reduced. It can lead to substantial savings in time and expenses. Large amounts of backfill can take place much earlier and help isolate the environment from the effects of subsequent excavation. Moreover, impervious diaphragm walls can prevent the groundwater flow into the excavation, and by working undercover of the roof slab, the adverse effects of construction under exposure to severe weather conditions are largely eliminated. Finally, and in the end, noise and dust pollution is significantly reduced. Finally, the top surface is freed, and any construction activity aboveground can be performed concurrently with the construction activity below the surface.

3.1 Construction of top-down method with diaphragm walls and inside Piles

As shown in Figure 7, at first, facilities and existing buildings on the surface are erased where the diaphragm walls are installed. Then, the soils on the station's roof will be excavated for two meters to prepare the required platform for installing diaphragm walls.

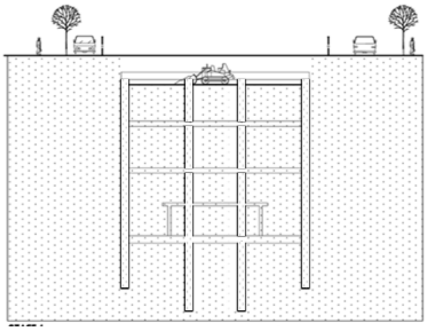


Fig. 7 – Eliminating the surface loads and the surface soils on the top of the diaphragm walls

At this stage, reinforced concrete diaphragm walls presented continuously along with the station's depth should be dogged down around the station. Then inside piles between the diaphragm walls should be constructed with regards to the predetermined architecture criteria. The diaphragm walls and inside piles installation are shown in Figure 8. After digging the diaphragm walls and before concreting, Bentonite, as a prevalent type of drilling mud, should be injected for stabilizing the excavated places.

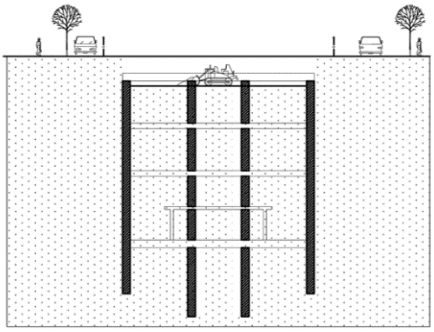


Fig. 8 – Installation of diaphragm walls and inside piles

The next step is to install the roof slab on diaphragm walls and inside piles. Piles and diaphragm walls' thickness varies due to the surface loads values incurred after the reconstruction. Once the installation is done, embankments will get started. When reconstruction of the surface area of the territory is finished, the surface street will be reopened again, and its loads will be applied. The installation step of roof slab and soil remediation, and ground levels are shown in Figure 9.

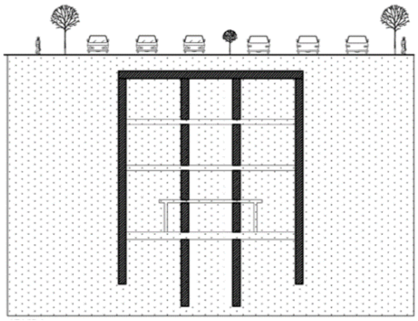


Fig. 9 – Instruction of roof slab and embankment on it

At this point, excavation continues step-by-step to reach the Middle slab position. Then the Middle slab will be instructed, and parts of the load caused by the excavation equipment and inside walls will be applied to it. Then the digging process will continue down to the next slab. Once the excavation reaches the depth of 17.5m, where the underground water is present, the underground water's toehold is exclusively the bottom of the excavation. In such a situation, the water can be disposed of with assembled pumps. Water flow direction and its amount should be numerically modeled for each stage. According to this model, the underground water effect on ground settlements and incurred forces is considered every step. The digging stages down to reach the floor slab are shown in Figure 10.

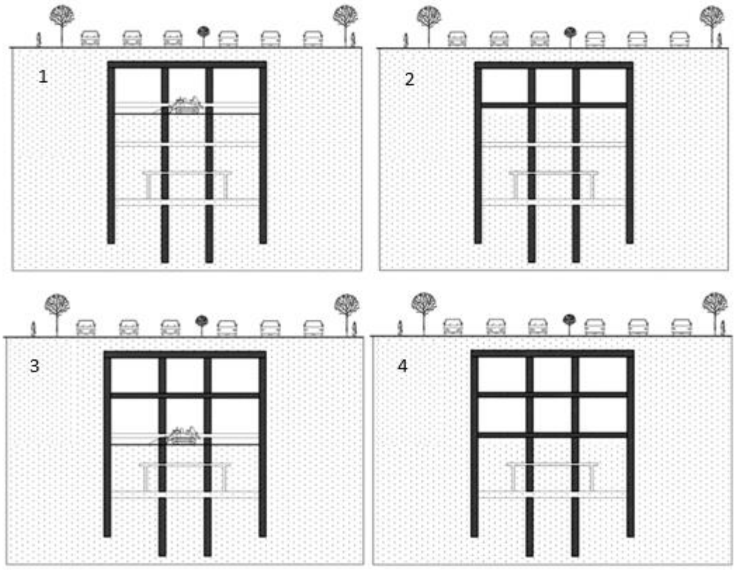


Fig. 10 – Systematic excavation until middle slabs and instruction of middle slabs

In this step, when the excavation reaches the station floor and the groundwater is ridden, the impervious base slab should be assembled, as is shown in Figure 11; afterward, infrastructure loads will be applied to the base slab. After installing the train rails, all the station loads, including ticket hall equipment and other forces, will be applied to the base and other slabs. Finally, in Figure 12, there is a 3D view of the completed station's layout.

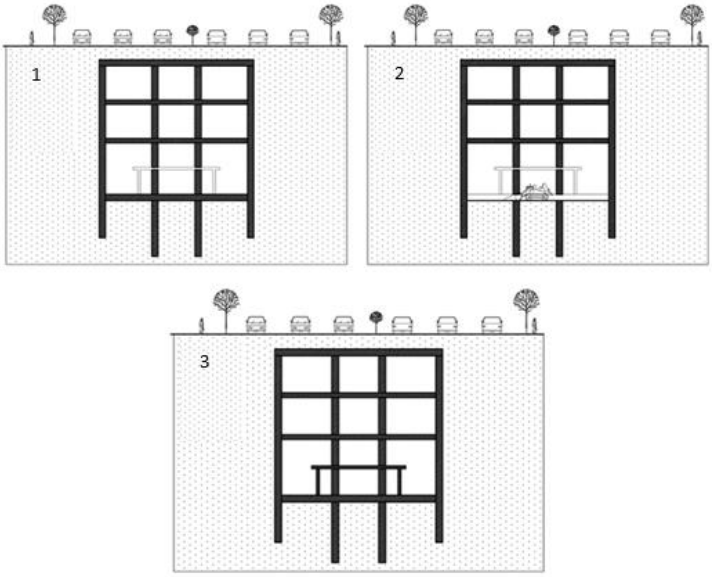


Fig. 11 – Construction of base slab and allocation of the loads

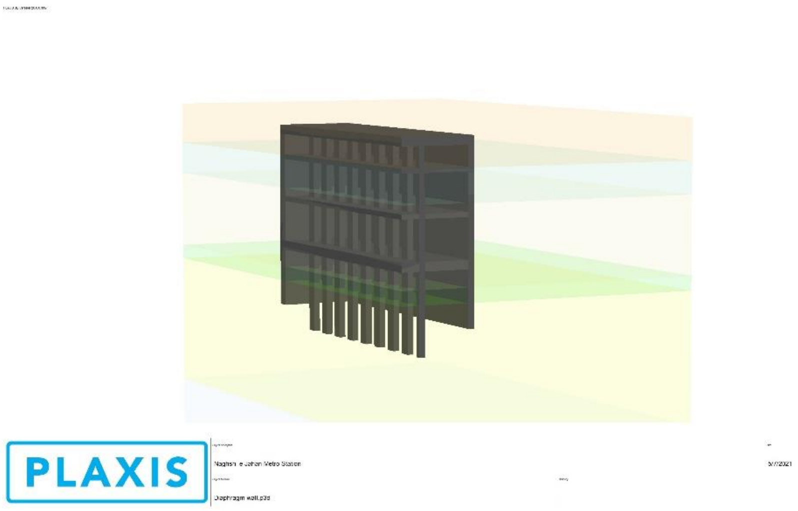


Fig. 12 – 3D view of the completed station's layout

Table 1 - Structural parameters of M2 Station

Element name	Width (cm)	spacing (m)	Elasticity (GPa)	Poisson ratio	Density (KN/m^3)
Diaphragm walls	100	-	20	0.2	25
Floor-Roof slabs	150	-	20	0.2	25
Middle Slabs	80	-	20	0.2	25
inside piles	100 200	6	20	0.2	25

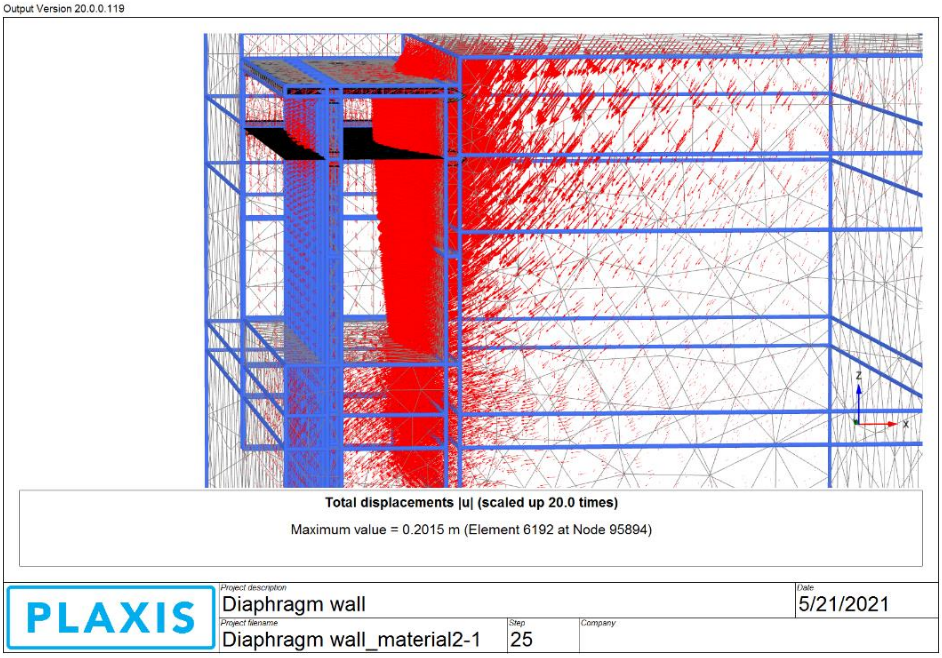
4 Numerical modeling of M2 station

In order to get a comprehensive insight into system behavior and ground-support interaction, a series of numerical modeling using the finite element method was conducted to forecast the surface settlement, stress distribution, and other ground behaviors. A reliable model of ground behavior needs a series of 3-D finite element modeling. Plaxis 3D-Foundation code was used to perform these analyses. Construction stages according to the cut-and-cover top-down method as well as excavation steps were modeled. Modeled design stages include 13 steps, and two-meter excavation was at first considered as a single stage. Figure 13 presents a general model of the station; a quarter of the station was modeled due to the symmetry. With regards to the values obtained from the 3D model of Reverse Analysis, the maximum model size, which does not make any differences in the settlement were chosen in 120 m width (x-direction), 170 meters long (y-direction), and 70 meters in depth (in the direction of z). The boundary conditions are as follows: vertical borders cannot move in the X direction, yet the movements are ceaseless in other directions. The station floor is fixed to any orientations.

Table 2 - Soil parameters around M2 Station for MC model

Layer name	Depth	Unsaturated density (KN/m3)	Saturated density (KN/m3)	Cohesive (KN/m2)	The angle of friction (degree)	Elasticity (KN/m2)	Poisson ratio	Permeability (M/day)
CL/ML/CL-ML	0-7	20.5	-	13	27	1.5e4	0.35	9.43e-5
SP-SC	7-12.5	21.2	-	5	32	3e4	0.27	1.98
GP-GM-GW	12.5-25.6	20.9	-	5	32	4.5e4	0.27	1.98
SP	25.6-28	21.2	22.3	5	32	3e4	0.27	1.98
CL-CH	28-40	20.1	21.2	10	29	1.9e4	0.35	9.43e-5

As mentioned in the previous section, the construction of diaphragm walls and an impermeable soil layer on the trench floor allow a few water values into the excavation, which can be prevented by permissive drainage equipment. This practice will be performed once the excavation process reaches depths below the groundwater level. Concrete elements, diaphragm walls, inside piles, elements of floors, and roofs of the station, are specified with a linear elastic model, and soils confirmed to the Mohr-Coulomb model. Geotechnical parameters are obtained from In-situ geotechnical tests (Table 1). As the primary excavation proceeds after maintaining elements' concrete reach a sufficient strength, the elastic modulus used for concrete elements is 18 GPa for pre-supporting elements, 12 GPa for shotcrete, and 25 GPa for the final lining. Besides, due to the traffic flow on the surface, the stress values according to traffic flows on the Earth's surface are deemed 24 KPa.At a distance of about 3D- D is the station width- from the station's center, shown in figure 12, the settlement will decline to zero. The Settlement distribution can also be seen in figure14.


Output Version 20.0.0.119

Total displacements |u| (scaled up 20.0 times)

Maximum value = 0.2015 m (Element 6192 at Node 95894)

Project description: Diaphragm wall
Date: 5/21/2021
Project filename: Diaphragm wall_material2-1
Step: 25
Company:

Fig. 13 – Model of the diaphragm wall and main struts of M2 station in total displacement

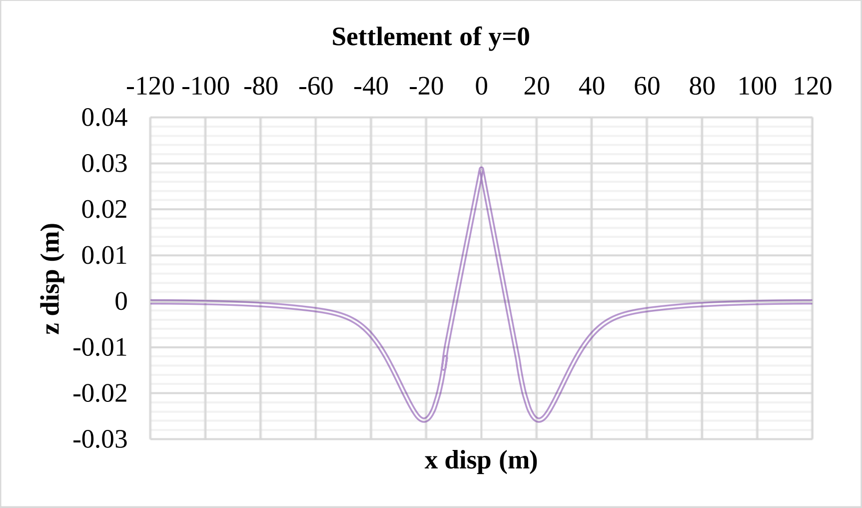


Fig. 14 – Settlement after final construction of the station

Figure 14 shows the distribution of vertical surface displacements, which have been acquired from PLAXIS 3D, using Surfur software modeling.

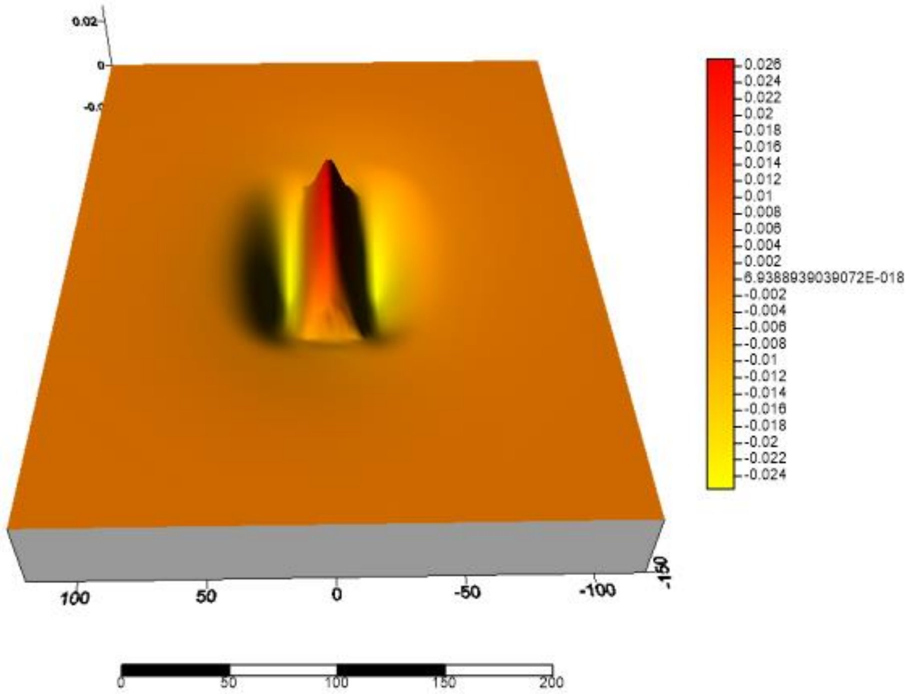


Fig. 15 – Settlement overview of the ground around the station from Surfer software

Ground settlement for various stages of excavation at the station's cross-section and longitudinal section are shown in Figures 16 and 17. These figures show that in the early stages, settlements are spandrel and maximum settlements occur close to the diaphragm walls. As excavation continues, similarly to Ou et al. (2005), ground surface settlements become concave, and the maximum surface settlements occur at a bit of distance from the diaphragm walls. This phenomenon is presented in Figure 17.

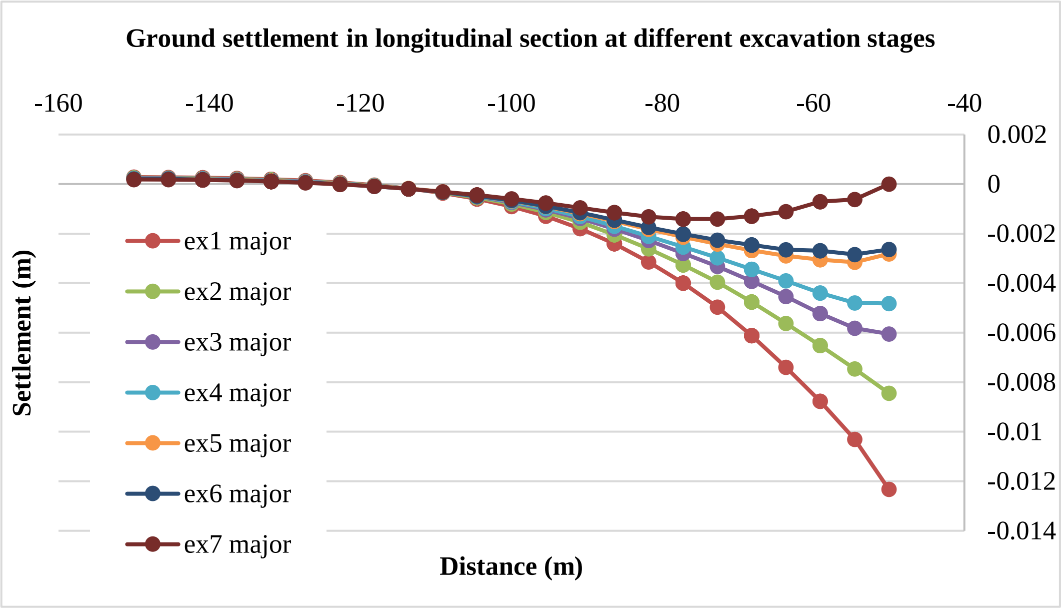


Fig. 16 – Settlement of ground surface in various stages of excavation at the longitudinal section

After the Final excavation in the seventh step beneath the groundwater level, the settlements reach up to 17 mm, which is an acceptable value at this location. It occurred at a distance of about 9 meters from the wall. It should be noted that after the completion of the station's excavation and floor slabs construction and other manufacturing processes, the final amount of settlement is almost 25.8 mm. The rest of this study will discuss the diaphragm wall root's thickness and its impact on the Earth's surface settlements and base floor uplift of excavation and diaphragm wall horizontal displacements.

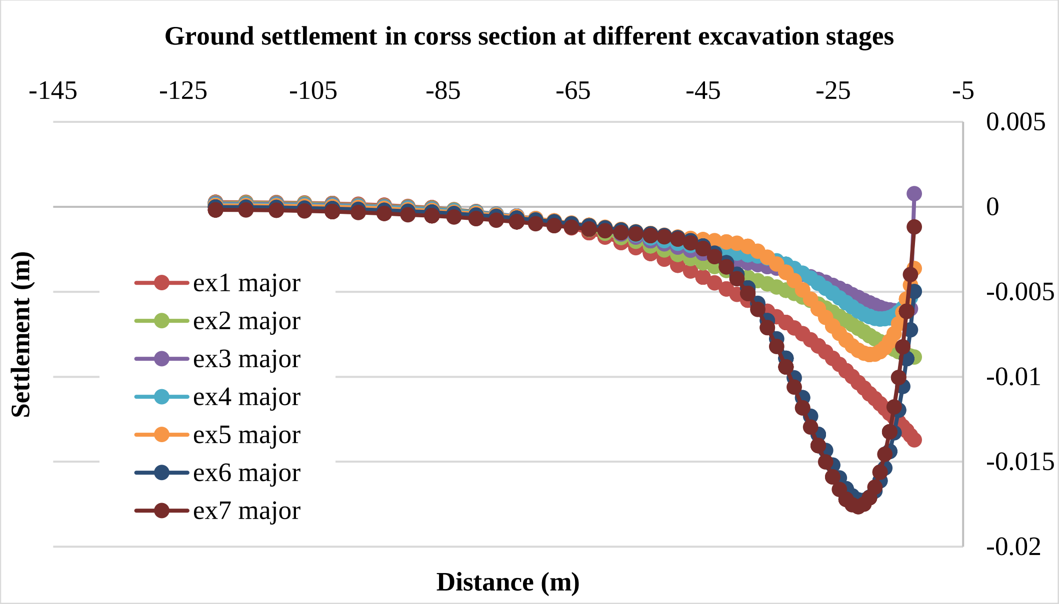


Fig. 17 – Settlement of ground surface in various stages of excavation at the cross-section

In the proposed model by the project consulting firm, a depth of 29 meters for diaphragm walls (7 meters below the platform level) is suggested. By changing the depth of diaphragm walls to 26 and 31 meters (the length of roots will be 4 and 9 meters Respectively below the platform level) and remodeling the station by applying new parameters, an increase in the roof's length influences the absolute values of surface settlement, uplift on the base floor of excavation and horizontal displacement of the diaphragm wall. Figure 18 shows that by increasing root length from 7 to 9m, slope displacement is reduced. These values remain almost constant for the uplift of the base floor.

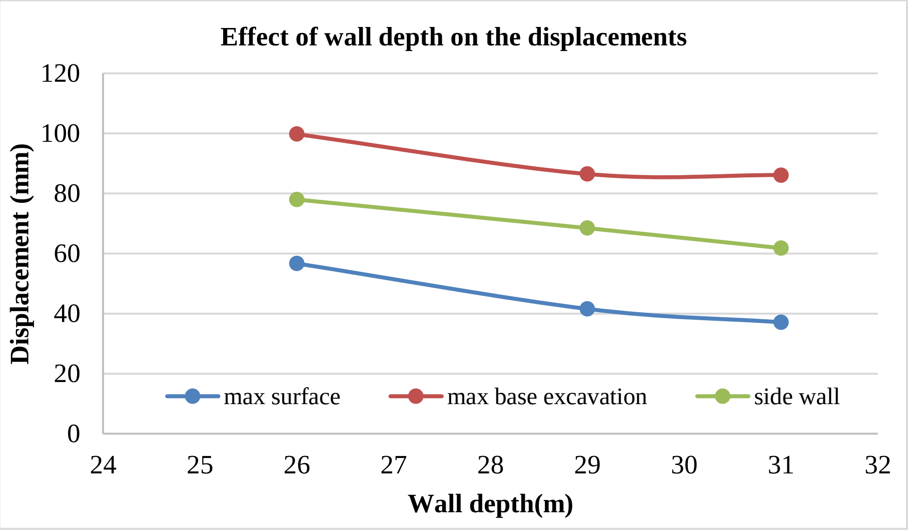


Fig. 18 – Charts the absolute displacement value changes due to change of diaphragm wall depth

Furthermore, in the proposed model of the diaphragm wall's thickness is intended to be 100 cm. When this value fluctuates between 80 and 120 cm, the absolute changes in land surface settlement, uplift of the base floor, and horizontal displacement of diaphragm wall decrease with thickness increase. As shown in Figure 19, with increasing the thickness to 100 cm, the distribution slope for all three cases almost turns zero; hence, the displacements remain constant, and as a result, the thickness of 100 cm of diaphragm wall is recommended for optimum values.

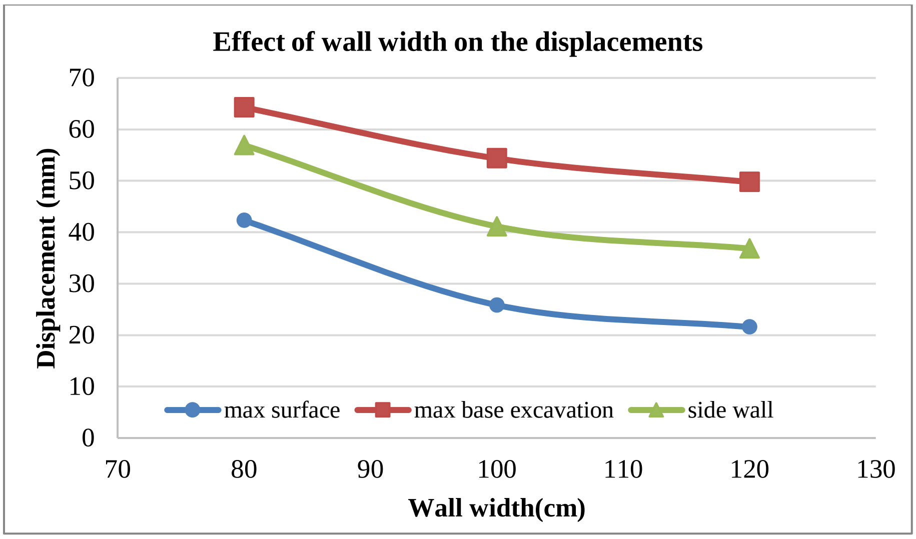


Fig. 19 – Effect of wall width on the displacements

A monitoring system was used to ensure the safety of adjacent buildings or properties during excavation. Steel nails were used to measure the ground, to make a foresight to a fixed point and back sight to the nails using a level to obtain the ground settlement at the points where the nails were driven in. The fixed point is the datum point outside the influence range of excavation. A particular position of a building with the pile foundation is assumed to be a fixed point either. Thus, the settlement nails were driven through the pavements so that the settlement of the nails represented the actual settlement of the soil. The measurement of the settlement of buildings was the same as that of ground settlement except that the settlement nails were to be set on the buildings themselves, on the wall, or the columns, for example. In the primary excavation of the metro station, monitoring confirmed the software outcomes above in a reasonable range.

5 Conclusion

Large span Underground spaces excavation method using a top-down approach and capped by middle column for Naghsh-e-Jahan station, Cut-and Cover approach is introduced in this research. The Cut-and-Cover method was preferred over other procedures to achieve a new floor for streets and traffic with sufficient strength and minimum settlement and an economically effective method. This method that has also been used for Ahvaz Metro station benefits inside piles for handling different floors of Naghshe-Jahan station. This study utilizes nonlinear finite element software for modeling and estimating the impact of some parameters because of the significant condition of the Naghshe-Jahan metro station. The Numerical Modeling results indicate the excavation steps effects on the Earth's surface settlement level, displacements of floor and diaphragm walls, and uplift of the base floor of excavation. The impact of changing the diaphragm wall roots' thickness on the surface settlement, uplift of the base floor, and horizontal displacement of diaphragm walls has been investigated. The results of the different stages of excavation on the surface settlement are compatible withOu et al. 2005. After Final excavation at the station's cross-section in the seventh step beneath the groundwater level, the settlements reach up to 17 mm, at 9 meters from the wall. The underground method's settlement is estimated by Cherlo et al. (2013) on the ground close to 6 to 8 cm and around 9 cm relative to the centerline, which is considerably more than the cut-and-cover excavation method estimated in this research.

Absolute values of base floor uplift and horizontal displacements of diaphragm wall increase when root length is reduced, but it must be kept in mind that after a specific rate, the diaphragm wall's root thickness increases, the values would reach a constant rate. A significant increase in thickness and length of the roots of diaphragm walls will contrive a small amount of displacement. However, it can lead to operational costs, speed of execution, and operation of the station concerning financing issues due to the considerable amount of concrete required to complete the station. Consequently, an increase in thickness without a reservation cannot guarantee the ideal conditions for the station construction; based on the above conditions, the optimum value for the roots' thickness is 100 cm, which is economically practical and reliable for achieving the minimum surface subsidence.

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