Indian Geotech J
https://doi.org/10.1007/s40098-024-01056-8

ORIGINAL PAPER

Pile and Concrete Arch Pre-supporting System (PCAPS) for Construction of Underground Subway Stations in Soft Grounds

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Received: 3 January 2023 / Accepted: 7 August 2024

Abstract One of the key parameters in the success of an underground project is the selection of the construction method based on the best scenario, which has strong effects on the host ground stability of the underground structures. This research introduces a construction method for double-deck underground subway stations in the soft ground, which is named *Pile and Concrete Arch Pre-supporting System* (PCAPS). This technique was originated from *Concrete Arch Pre-supporting System* (CAPS) for single-deck ones. This pre-supporting system for large span underground spaces is constructed by manpower-excavation method prior excavating the underground space in order to support the ground during the excavation of proposed underground cavity. PCAPS consists of concrete piles on the both sides of the underground cavity, arch beams (ribs) on its roof and final concrete lining inside the underground cavity, sequentially. State of the art of PCAPS is classified into four individual construction methods with various construction scenarios. The Molavi subway station (I7 station) belongs to line 7 of Tehran metro in Iran, was selected as a case study area to assessment the PCAPS construction method. The numerical simulation was employed to study the induced ground settlement of different PCAPS techniques, and then to select the optimal construction procedure under the same geotechnical conditions. The findings yield that the structural rigidity of the concrete piles and rib frames in PCAPS und upward/downward lining methods using different excavation sequences and staged constructions can control the ground deformations.

Keywords Pile and rib · Upward and downward lining methods · Surface settlement · Pre-supporting system · Large span tunnel

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Introduction

Tehran is the capital and largest city of Iran, which faces the traffic crisis and its consequences such as air pollution, fuel consumption, noise pollution, wasting time and accidents. Undoubtedly, construction of an efficient and high-capacity transportation system like subway will be the main solution to overcome this crisis in this metropolis. Underground subway lines usually pass right beneath the dense residential and commercial areas, so the construction of tunnels and stations should have the least effects on buildings and infrastructures. The induced ground settlement due to the construction of underground opening is capable to cause remarkable damages to the adjacent buildings [1]. There are different methods for construction of underground spaces such as subway stations, which can impose different risk levels during the construction. Various approaches have been proposed to predict ground settlement by some authors [2–5].

Each underground project has unique characteristics, so neither two host grounds are similar nor underground structures have the same behavior [6], as a result, the same construction methods and design assumptions cannot be used for two underground projects. Due to the large span of underground subway stations and the soft soil host ground in the urban areas, the subway stations need

Published online: 14 September 2024

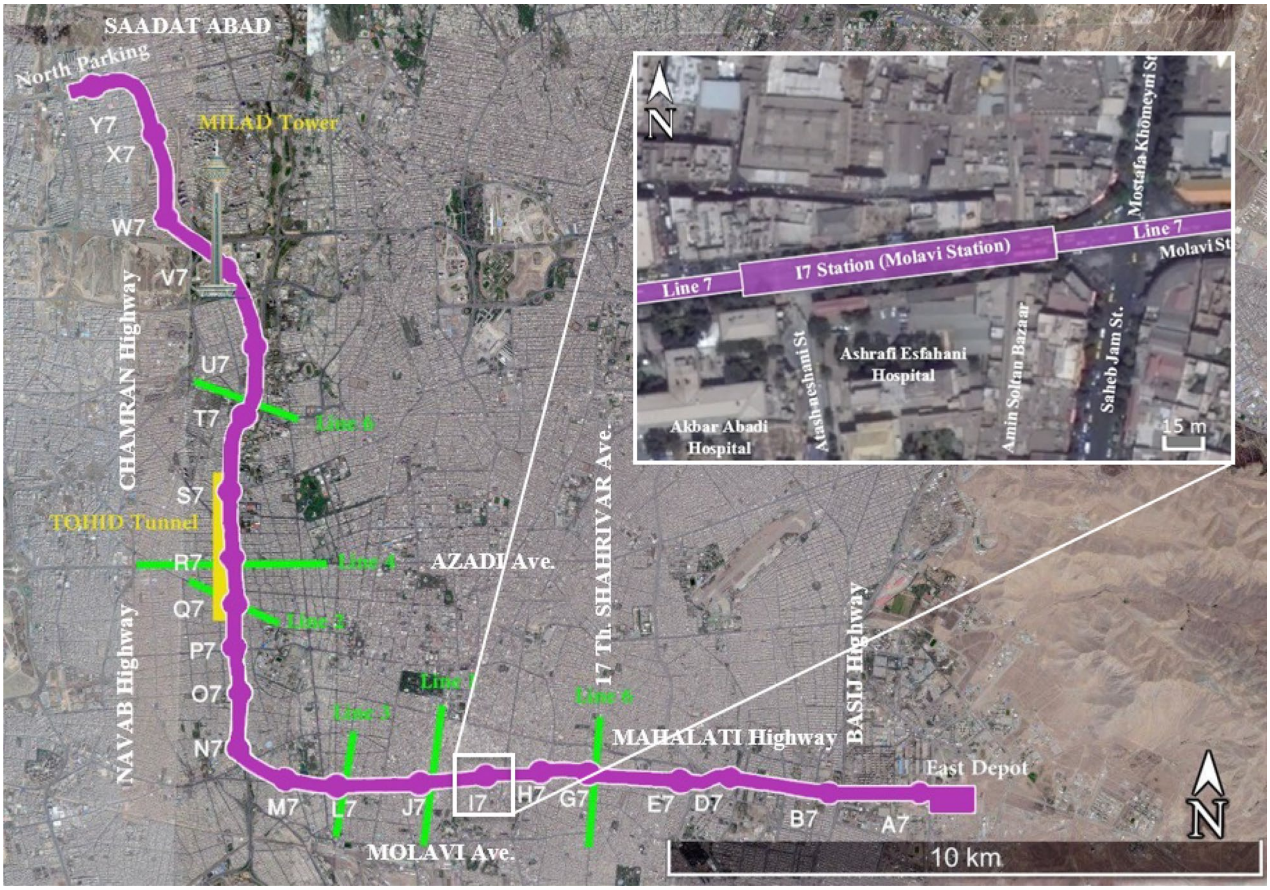


Fig. 1 Alignment of Tehran metro line 7 project and Molavi Station (I7 station) location

Table 1 Geological characteristics of Tehran Alluvium formations [26, 27]

Specification	Formation			
	A	B	C	D
Local name	Hezardareh Alluvial Formation	Kahrizak Alluvial Formation	North Alluvial Formation	Recent Alluvial Formation
Cementation	Cemented and hard	Variable, but usually weak cement	Cementation less than A and non-hard	Non-cemented
Grain size (mm)	Clay to 100–250	Very variable	Clay to 100–200	Clay to 1000
Dip layer (deg)	0–90	0–15	0	0
Thickness (m)	Maximum 1200	Maximum 60 (thickness decrease toward south)	Maximum 60	<10
Location of observation in Tehran	North area	North area	North and central area	Recent and old riverbed

special construction methods. In a usual classification, underground subway station construction methods are divided into two main categories:

(i) Cut and cover methods: the procedure is utilized for shallow subway station. In fact, the excavation is started from ground surface using soldier structures. The structure of station is built inside the excavation pit down to top and covered with backfill material when the construction of the station was completed [7]. The excavation and construction of stations are sometimes performed top to down [8, 9].

(ii) Underground excavation methods: these methods are appropriate for semi-deep or deep subway stations. These subway stations are constructed by sequential excavation method (SEM) and enlarging shield

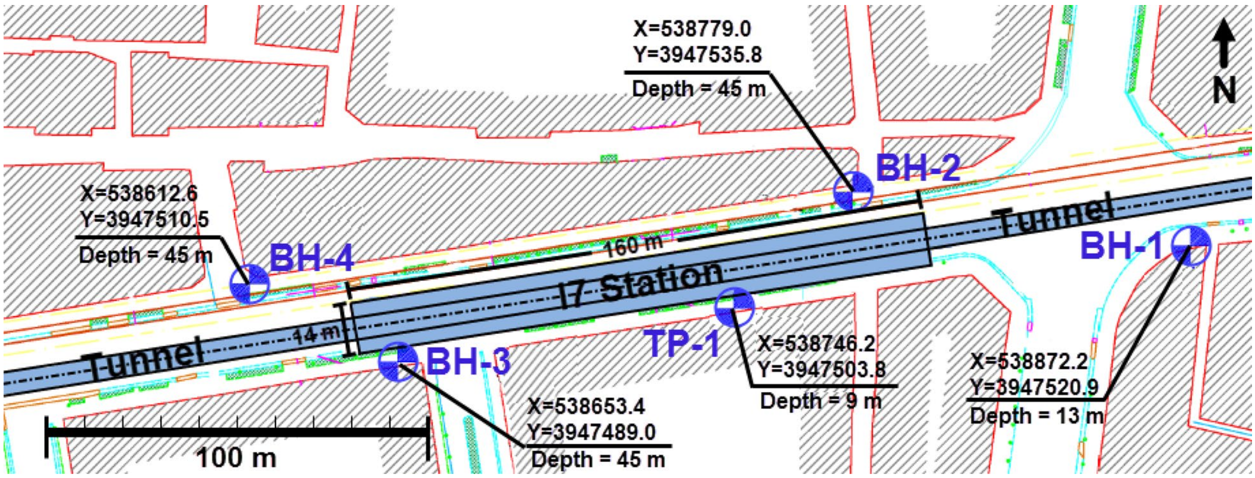


Fig. 2 Boreholes and test-pit location relative to Molavi Station (I7 Station) location on the site plan [28]

method [10, 11]. Also, the pre-supporting systems and methods such as ground grouting, ground freezing, pipe umbrella (e.g., pipe-roofing, pipe-jacking and forepoling) and structural elements (e.g., piles and arches) are implemented during the station construction [12–25].

The pre-supporting systems are performed prior excavating the underground space in order to support the ground during the excavation of proposed underground cavity. This means that before the underground space excavation, the support of the soil mass around the proposed underground space has been done. The pre-supporting systems can include soil improvement methods like ground grouting or structural elements installation like piles und pipe-roofing system. In this paper, the pre-supporting system for large span underground spaces such as underground subway station in shallow and soft ground will be introduced. This pre-supporting system consists of concrete piles on the both sides of the underground cavity, arch beams (ribs) on its roof and final concrete lining inside the underground cavity, sequentially. The current pre-supporting system is constructed by manpower-excavation method prior excavating the underground space. Subsequent to this pre-supporting system, the underground excavation can be executed in variety of methods.

In the current study, a brief overview of line 7 of Tehran metro and the selected case study area in the mentioned metro line, Molavi subway station, will be illustrated. Next, proposed construction methods for this underground subway station will be introduced in detail. Then, the 3D numerical analysis will be employed to compare different construction techniques by evaluating their ground surface settlement and design aspects of underground subway station construction.

Case Study Area: Molavi Station of Tehran Metro Line 7, Iran

Line 7 of Tehran metro is 27 km long and has 22 stations, which are named from A7 to Y7 stations (Fig. 1). This project is the deepest railway tunneling project in Tehran. Its utmost depth reaches 56 m, so it passes under other existed subway lines. The twin track tunnel was bored by two earth pressure balance machines (EPBMs) with 8.15 m internal diameter. The stations have been built by cut and cover (top-down/down-top) methods and underground excavation methods.

Among the stations of line 7 of Tehran metro, the *Molavi Station (I7 Station)* is selected as a case study area because of accurate network monitoring system for surveying the surface settlement. As shown in Fig. 1, *Molavi Station* located at the junction of *Molavi Street* and *Saheb Jam Street* in ancient urban context of Tehran with lose and soft ground conditions. The construction of this specific station is capable to cause remarkable damages to the adjacent buildings such as *Tehran Bazaar* as a historical market of Iran and several hospitals in this ancient context of city (Fig. 1). Due to the impossibility of excavation from the ground surface with the cut and cover (top-down/down-top) method in the *Molavi Street*, the underground method was selected for *Molavi Station* construction.

Tehran Alluvium is divided into four categories under the title of A, B, C and D, which A and D formations are the eldest and youngest deposits, respectively. The eldest one, i.e., A, has the most cohesive and cemented alluvium, while the youngest one, i.e., D, lacks cohesion.

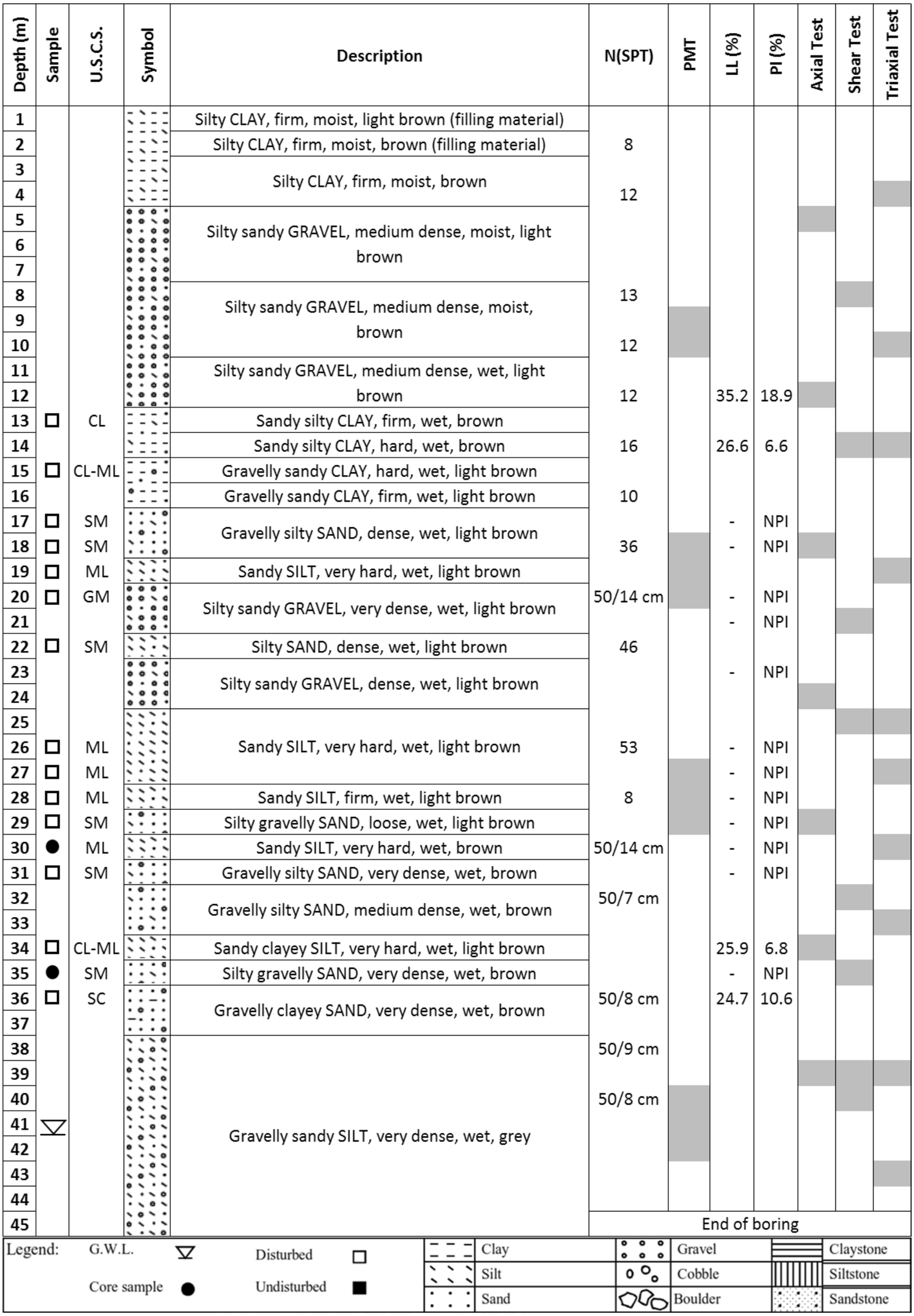


Fig. 3 Borehole log data (BH-4) around Molavi Station (I7 Station) [28]

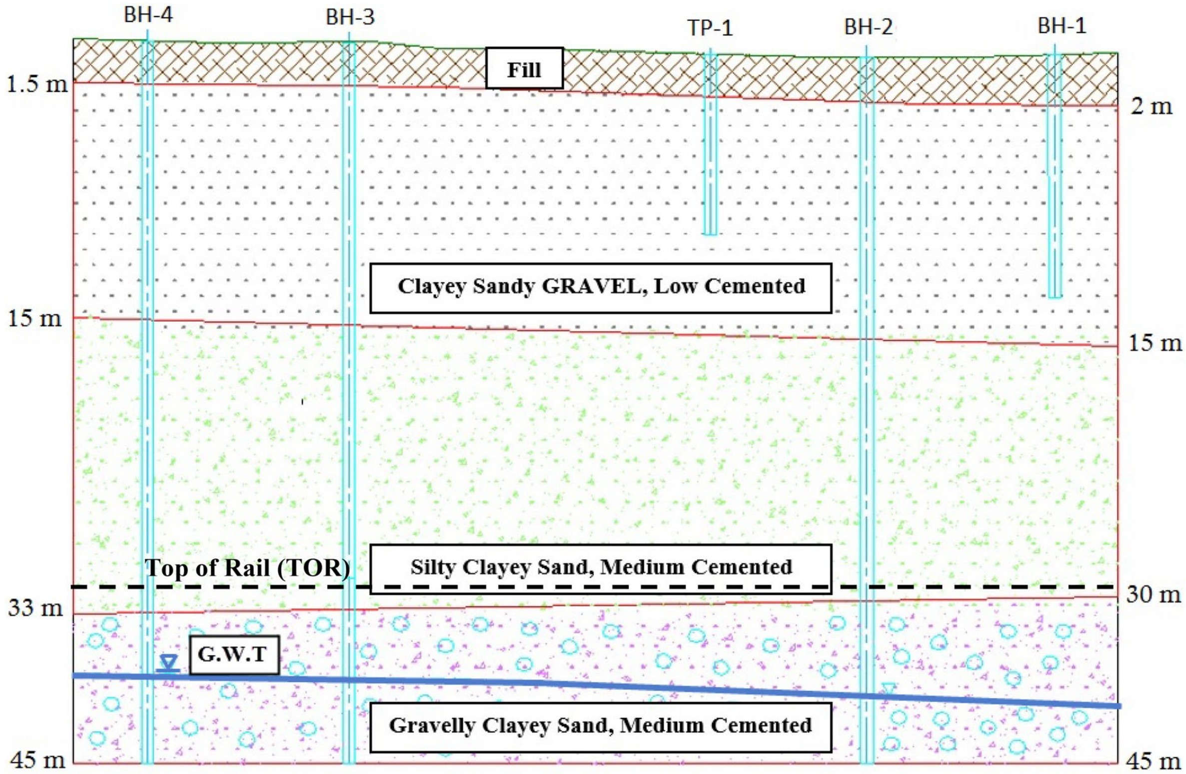


Fig. 4 Geotechnical longitudinal profile and ground water table along Molavi Station [28]

Table 2 Geotechnical parameters of soil layers [28]

Layer thickness(m)	Wet density, γ_t(KN/m^3)	Friction angle, φ (deg)	Cohesion, C (KN/m^2)	Elastic modulus, E (MN/m^2)	Poisson ratio,ν	K_0=1-sinφ
0–2	18	22	10	15	0.40	0.63
2–15	19.2	29	12	18	0.35	0.52
15–30	20.5	28	17	32	0.35	0.53
30–45	21	33	18	45	0.35	0.46
45 <	21	33	20	60	0.35	0.46

Fig. 5 Mellat single-deck station (N2 Station) of Tehran metro line 2 using CAPS method for the first time

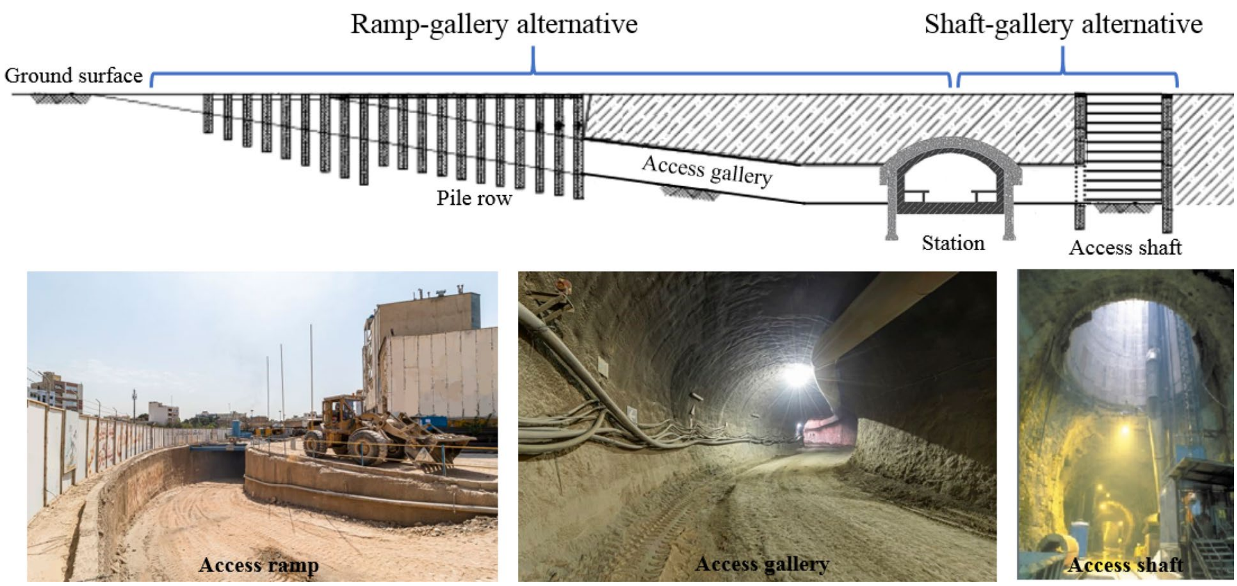


Fig. 6 Access way alternative from the ground surface to the underground space

The deposit C is moderately cemented and B has weak and variable cohesion [26]. The route of the line 7 consists of the entire Tehran Alluvial units. Table 1 shows the specifications of the whole deposits. The *Molavi Station* located at the "Recent Alluvial Formation" of "Tehran Alluvial." To survey the geological and geotechnical characteristics of subsurface soil layers along *Molavi Station*, four Boreholes (BH) with depths ranged 13–45 m were bored for SPT (standard penetration test) and PMT (pressure meter test) and a test-pit (TP) with 9 m depth was dug for PLT (plate load test) and in situ density test [28]. Figure 2 shows the boreholes and test-pit location relative to the Molavi Station (I7 Station) location on the site plan.

Typical engineering parameters were measured by field tests (e.g., SPT, PMT and PLT) and laboratory tests for soil characteristics (e.g., classification, physical, chemical, mechanical and strength parameters) to employ in the numerical model. Figures 3 and 4 illustrate the borehole log data (BH-4) and longitudinal profile of geology and ground water table (GWT) along *Molavi Station*, respectively. The soil layers composed of clayey sand and also silty sand. The ground water table is lower than the station location, and it is at the level 40 m. The geotechnical parameters of soil layers along the *Molavi Station* are given in Table 2.

Construction Method

The final choice of the method to be used for an underground opening construction in urban area depends upon the complex interaction of a number of factors such as safety, cost and schedule considerations [29]. Engineering judgment

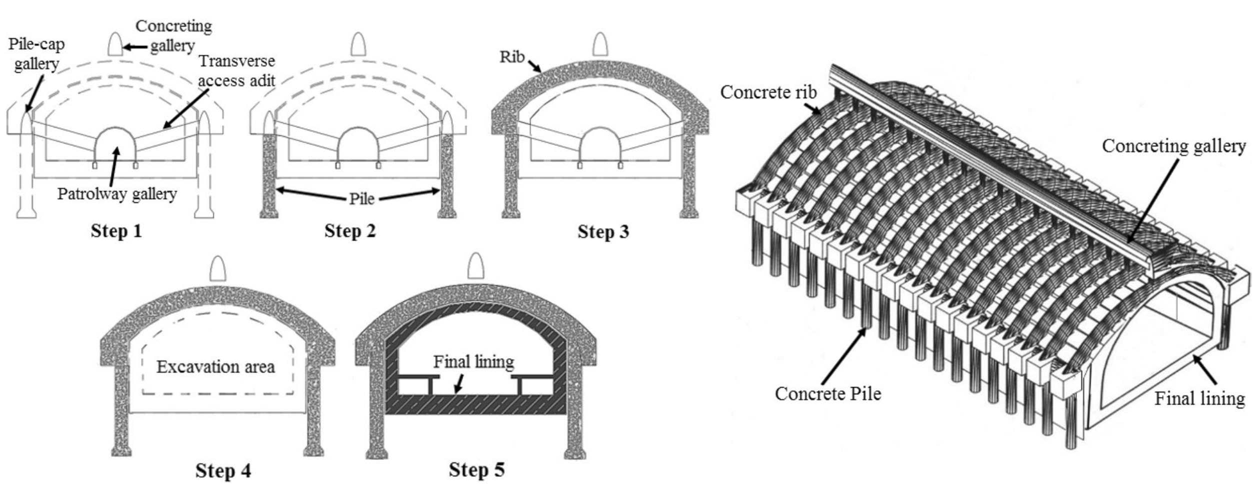


Fig. 7 Construction processes of CAPS technique (left figures) and 3D view (right figure) [32]

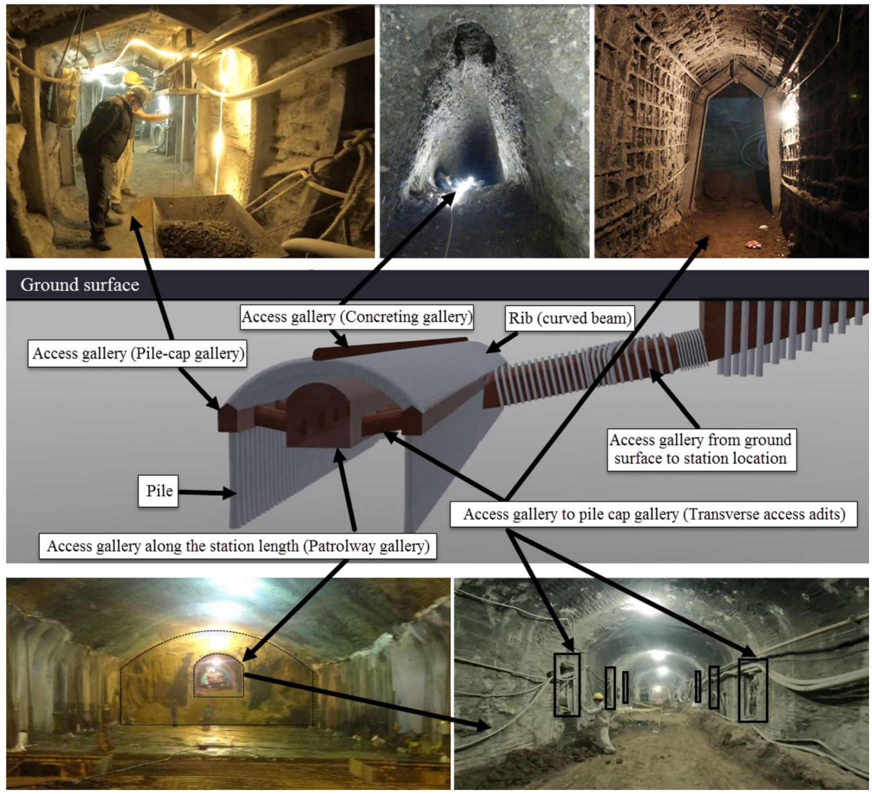


Fig. 8 Introduction of access galleries for CAPS construction

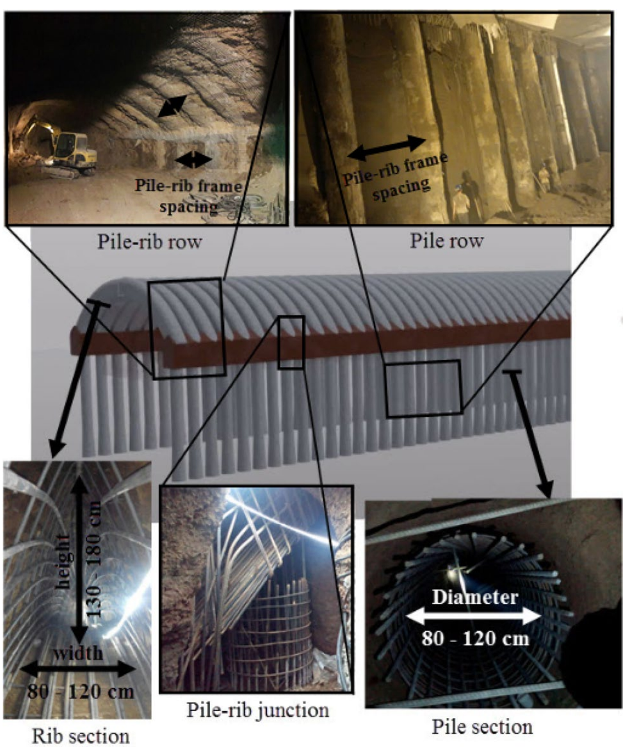


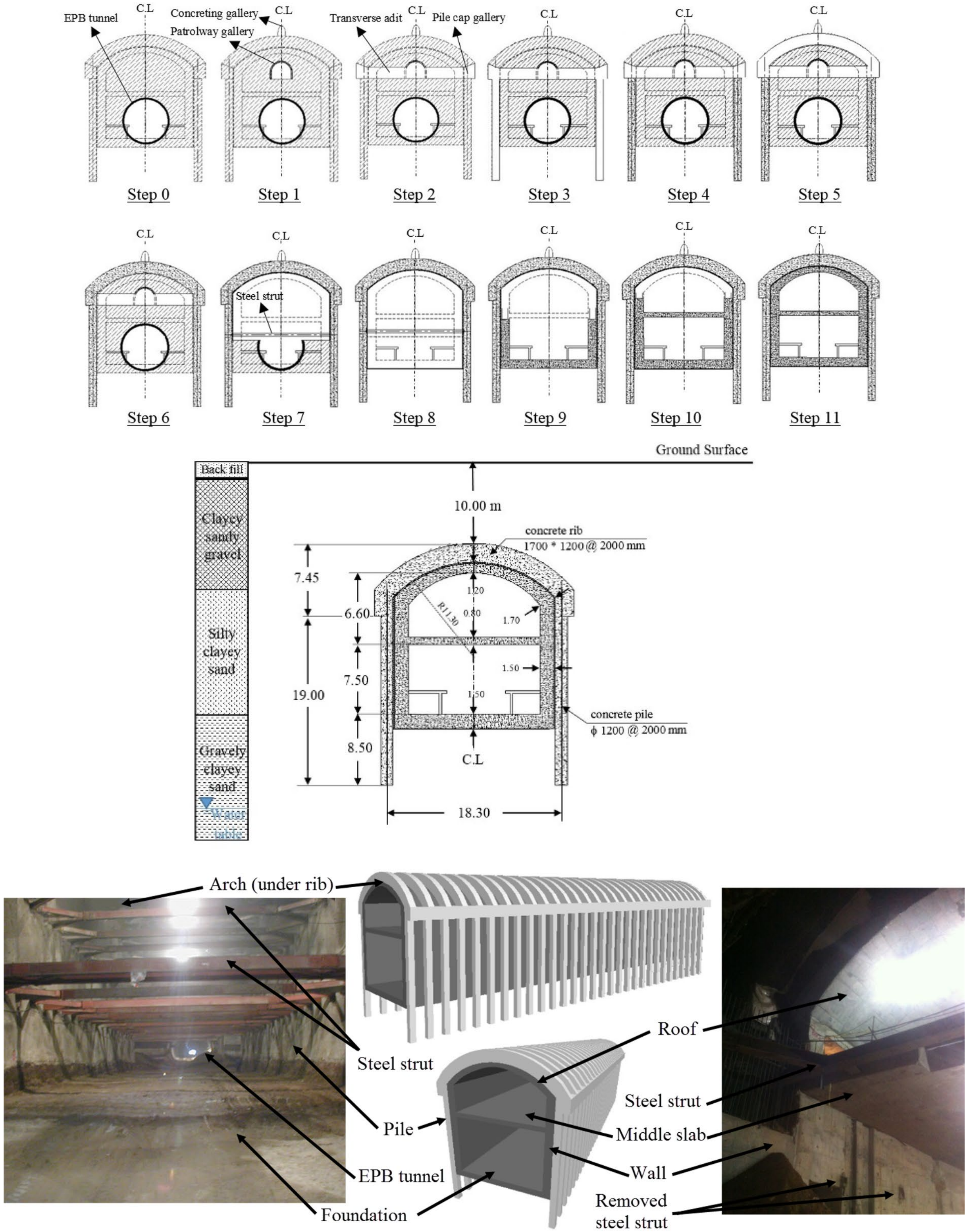
Fig. 9 Geometry and dimension of piles and ribs

certainly plays a major role in many real-life projects, so engineers should combine the engineering judgment with theoretical calculations for any underground project. The majority of the underground subway stations have been built by pre-supporting systems as a common construction technique in Iran. The procedure requires structural elements around the proposed station or large span underground opening in order to improve the host ground stability.

Concrete Arch Pre-supporting System (CAPS)

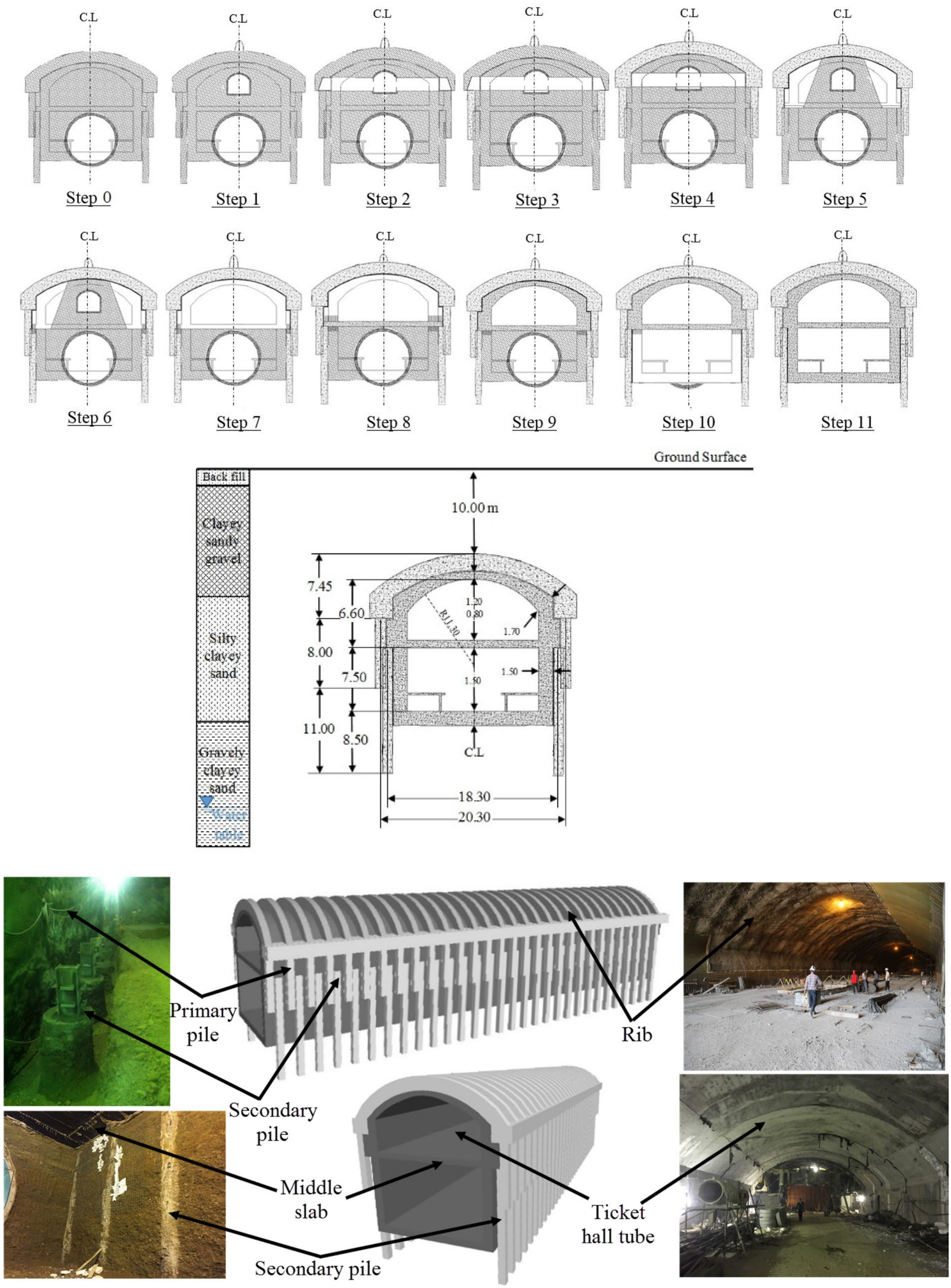
The most traditional and widespread Iranian technique for construction of large span underground spaces is Concrete Arch Pre-supporting System (CAPS). This method was first introduced by Sadaghiani and Gheysar in 2003 for construction of *Mellat Station* in 2002 (Fig. 5), which belongs to line 2 of Tehran metro [30]. This pre-supporting system is constructed by manpower-excavation method prior excavating the underground subway station [14, 31].

An access way from the ground surface to the desired underground space (e.g., underground subway station) is required for construction of any underground space using underground methods such as CAPS technique. Access way uses as a regular means of worker access to underground spaces and tunnels under construction. In a usual classification, access way to the underground spaces is divided into two main categories: (1) Access ramp-gallery and (2) Access



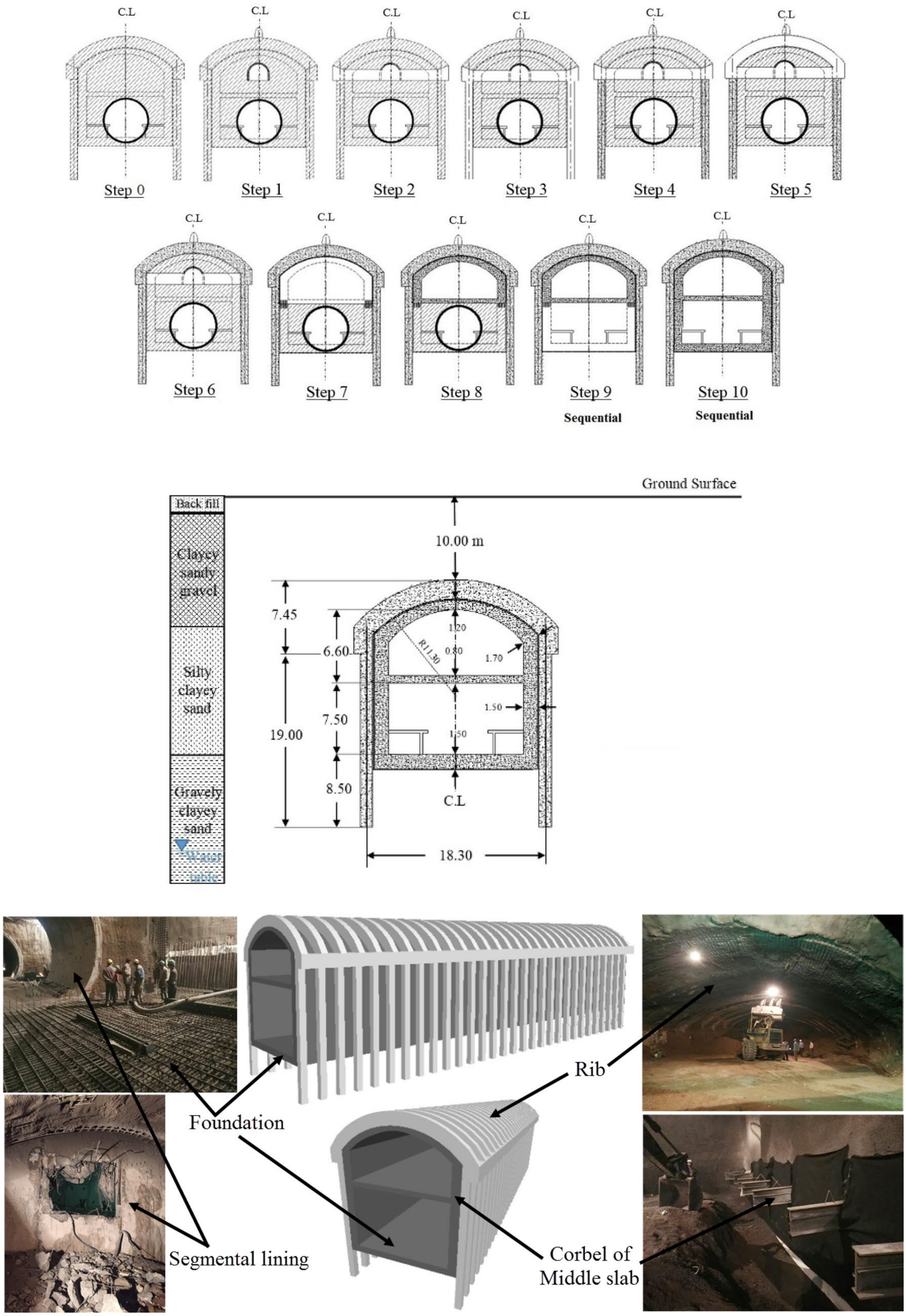
(a) PCAPS 1 (PCAPS with steel strut)

Fig. 10 Construction processes of different PCAPS technique in real-life project and the typical design cross section. **a** PCAPS 1 (PCAPS with steel strut) **b** PCAPS 2 (PCAPS with double piles) **c** PCAPS 3 (PCAPS with soil mass supporting) **d** PCPAS 4 (PCPAS with horse-saddle rib and concrete slab)



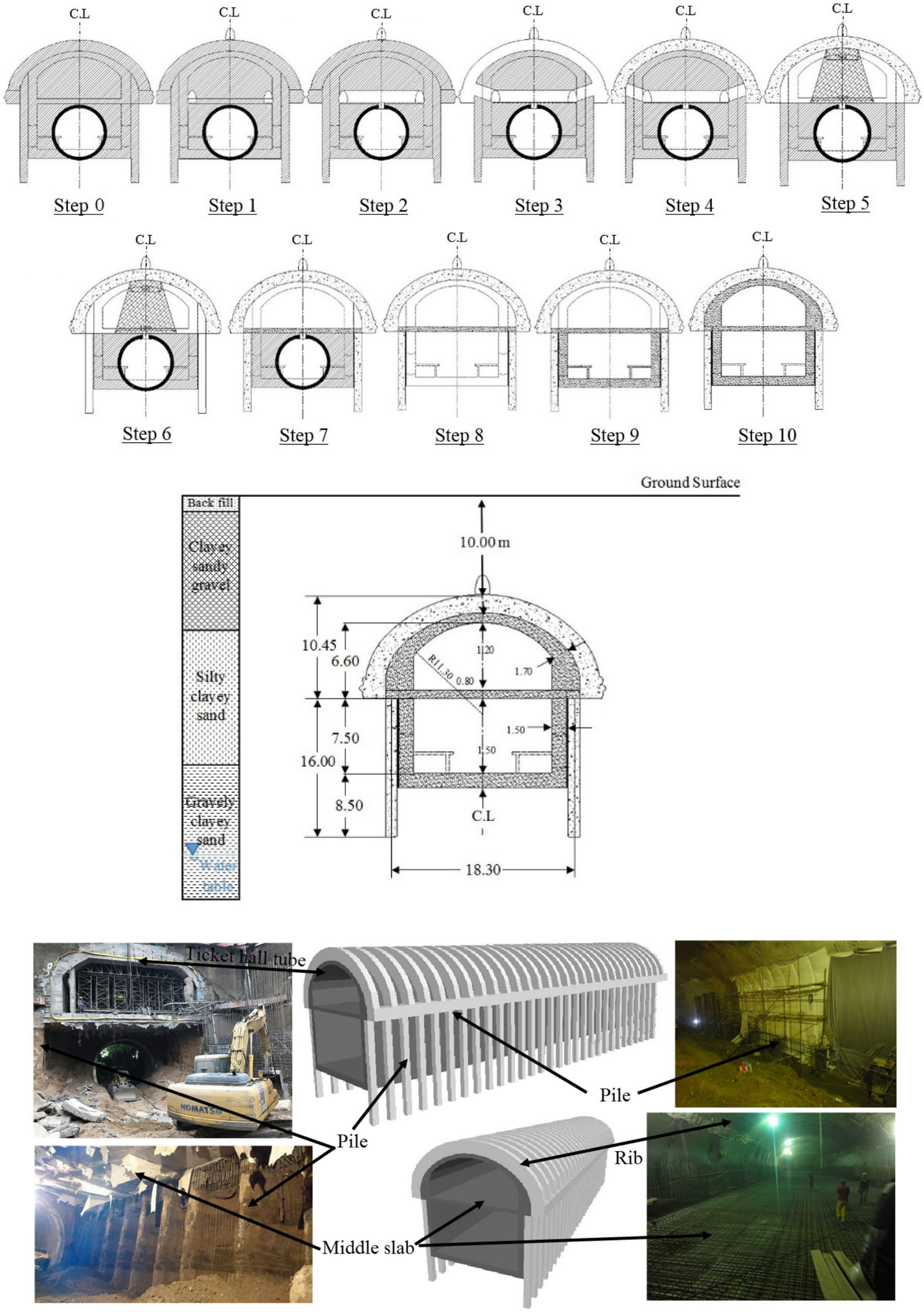
(b) PCAPS 2 (PCAPS with double piles)

Fig. 10 (continued)



(c) PCAPS 3 (PCAPS with soil mass supporting)

Fig. 10 (continued)



(d) PCPAS 4 (PCPAS with horse-saddle rib and concrete slab)

Fig. 10 (continued)

shaft-gallery (Fig. 6). Thus, constructing an access way to the station location is the first step for current construction method.

In order to construct underground subway station using CAPS technique, should be carried out in five steps. These steps of construction in cross-sectional steps and 3D view are illustrated in Fig. 7 as follows [32]:

- Step 1—an access gallery is excavated along the length of the station, which is commonly called *Patrolway gallery* (Fig. 7—Step 1 and Fig. 8). This gallery has the least dimension as possibly, which is of 3–4 m width and of 4.5–6 m height, generally. From this gallery, the multiple manually excavated transverse access adits are bilaterally made in certain distances to excavate the pile-cap galleries at the both sides of the station, longitudinally (Fig. 7—Step 1 and Fig. 8). A longitudinal gallery is further manually excavated at top of the station along the length of the station, whose vulgar name is *concreting gallery* (Fig. 7—Step 1 and Fig. 8),
- Step 2—from pile-cap galleries, multiple wells are excavated in a queue at the both sides of the proposed station to be used as the piles. The piles are constructed with reinforced concrete inside the wells (Fig. 7—Step 2 and Fig. 8—see pile-cap gallery). The diameter of piles is usually ranged 80–120 cm (Fig. 9),
- Step 3—multiple manually excavated curved adits are made between each bilateral pile, which is called rib (Fig. 7—Step 3). The reinforced ribs and reinforced pile-cap galleries at both sides of the station are concreted through concreting gallery, gravitationally (Fig. 7—Step 3 and Fig. 9). The ribs have half-oval cross section, which is of 80–120 cm width and of 130–180 cm in height (Fig. 9). The optimal centrally distance between two set of pile-rib frames depends on the pile diameter, which is ranged from 2 to 3D (D is pile diameter).
- Step 4—subsequent to the pile-rib fames as a pre-supporting system, the underground excavation can be executed (Fig. 7—Step 4 and Fig. 9),
- Step 5—the final lining of the station is constructed inside the excavated space (Fig. 7—Step 5).

Pile and Concrete Arch Pre-supporting System (PCAPS)

Owing to the lack of sufficient area in dense urban contexts, it is hard to possess the lands for project, thus the underground subway stations are built in two or more floors. Generally, the first floor is allocated to platform and train passenger boarding, the second one is assigned to ticket hall and plant rooms, while the remaining floors are considered for public applications like common concourse, parking and shopping center and so on. The CAPS

Table 3 Access phase and pre-supporting construction phase procedure for different PCAPS types based on Fig. 10

PCAPS type	Access phase		Pre-supporting construction phase			
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
PCAPS 1	Patrolway and concreting galleries construction	Transverse access adits construction, then pile-cap galleries construction	The piles excavation	The piles construction	The ribs excavation	The ribs and pile-cap construction
PCAPS 2	Patrolway and concreting galleries construction	Transverse access adits construction, then pile-cap galleries construction	The short (primary) piles construction	The ribs and pile-cap construction	The side drifts excavation in ticket hall level	The long piles construction between the short ones
PCAPS 3	Patrolway and concreting galleries construction	Transverse access adits construction, then pile-cap galleries construction	The piles excavation	The piles construction	The ribs excavation	The ribs and pile-cap construction
PCAPS 4	Patrolway and concreting galleries construction	Transverse access adits construction, then pile-cap galleries construction	The ribs excavation	The ribs and pile-cap construction	The side drifts excavation in ticket hall level	The piles construction in front of ribs

Table 4 Staged construction phase procedure for different PCAPS types based on Fig. 10

PCAPS type	Staged construction phase				
	Step 7	Step 8	Step 9	Step 10	Step 11
PCAPS 1	Station cavern excavation part 1 using steel struts installation	Station cavern excavation part 2 by segmental lining destruction	The final lining construction upwardly by removing steel struts	The upward lining construction	The upward lining completion
PCAPS 2*	The ticket hall space excavation	The ticket hall slab construction			
	The ticket hall lining construction downwardly	The platform space excavation by segmental lining destruction	The downward lining completion		
PCAPS 3	The ticket hall space excavation	The ticket hall lining construction downwardly	The platform space excavation by segmental lining destruction	The platform lining construction downwardly	–
PCAPS 4**	The ticket hall space excavation and the concrete slab of ticket hall construction	The platform space excavation by segmental lining destruction	The station lining construction downwardly	The downward lining completion	–

* Ticket hall level construction and EPB-tunnel construction can be done simultaneously in PCAPS 2

** The final lining of station can be constructed downwardly in PCAPS 4

technique is used to construct one deck subway stations just having platform structure. To clarify the scope and novelty of the study, the CAPS technique for one deck underground subway stations was revised for double-deck underground subway stations by considering Pile and Concrete Arch Pre-supporting System (PCAPS) (Fig. 10, Tables 3 and 4). Thus, a new style for construction of

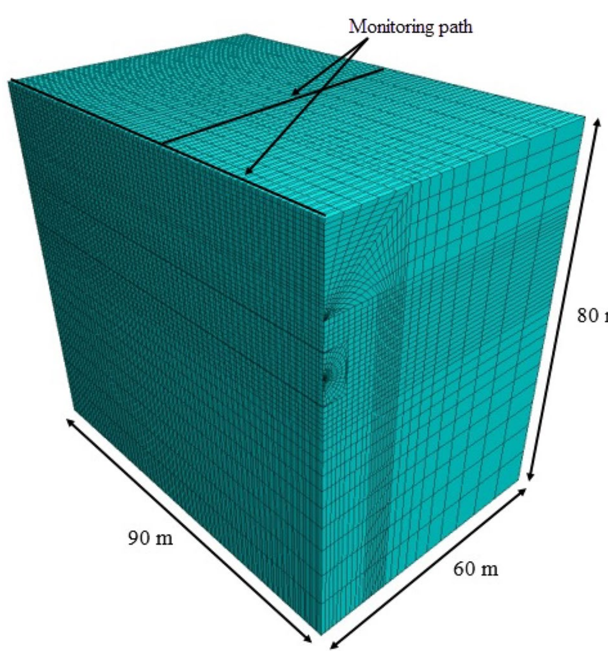


Fig. 11. 3D FDM model for station construction using PCAPS technique

double-deck underground subway station is introduced on the basis of PCAPS. The PCAPS method for double-deck underground subway station is a combination of "pile and rib frames with different style" and "upward and downward lining methods for each floor of station as a concrete tube." The current study is in the analysis of construction phases (or techniques) of PCAPS method and in describing the lessons learnt from line 7 of Tehran metro as a real-life project with adequate details. Thus, four different PCAPS techniques (e.g., PCAPS 1, 2, 3 and 4) have been introduced in cross-sectional steps (Fig. 10) and are explained in Tables 3 and 4. The access ways to proposed underground subway station introduced in Sect. "Concrete Arch Pre-supporting System (CAPS)" are the same for PCAPS technique. In order to construct a double-deck underground subway station using PCAPS technique, should be carried out in different steps in three phases (e.g., access phase, pre-supporting phase and staged construction phase) based on Fig. 10 and Tables 3 and 4.

Simulation of Station Construction using PCAPS

The Numerical Model Definition

Numerical methods are widely used for analysis of tunnels and underground spaces construction. A three-dimensional model of FDM code was handled to analyze the deformations and stress distributions. To simulate the PCAPS technique for the construction of underground subway station, FLAC 3D software was applied in such

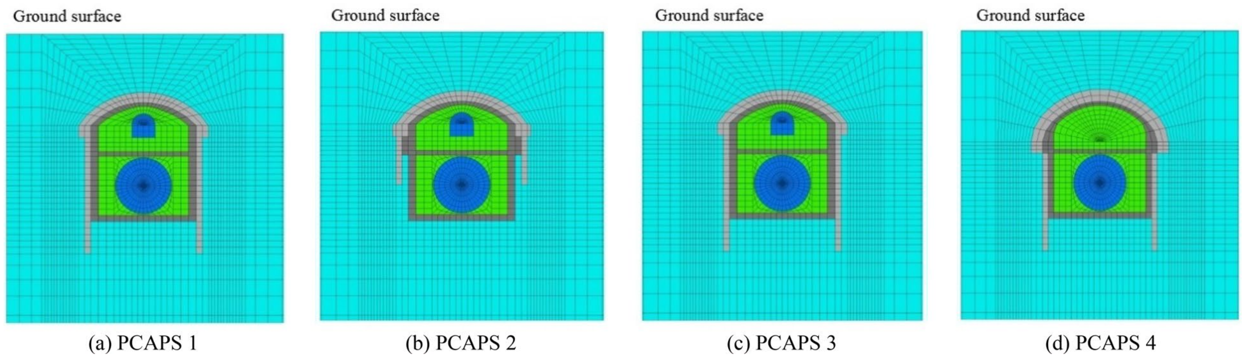


Fig. 12 PCAPS mesh generations for Molavi double-deck station of Tehran metro line 7. **a** PCAPS 1 **b** PCAPS 2 **c** PCAPS 3 **d** PCAPS 4

way as step by step assessment. As obviously seen in Fig. 11, the model geometry is 60 m in width, 80 m in height and 90 m in length, so no effect is imposed on the analysis by boundary conditions. The model bottom boundaries, both in vertical and horizontal directions, were set as fixed, as well as the lateral boundaries were set as fixed in the horizontal direction, whereas the top boundary was set free. With regard to the symmetry governing the geometry, excavation sequences, surface load and pile-rib frames, half of model was applied to the analysis for reducing the calculation time. Considering the constitutive modeling, the soil layers were modeled as Mohr–Coulomb material based on Table 2. The linear elastic behavior was adopted for structural elements by assigning the concrete properties to piles, ribs, final lining, tunnel segmental lining and shotcrete lining and steel properties to strut and TBM (tunnel boring machine)'s shield according to Table 6, respectively. These support structures were modeled as volume elements (clusters) and structural elements in numerical model. To monitor the surface settlement in transverse and longitudinal directions, monitor points were selected on the middle of the model (see monitoring path in Fig. 11) to validation and outcome.

Figure 12 depicts various mesh generations based on four cases of PCAPS. Mesh/grid size and its convergence were performed based on the mesh independence; mesh convergence is achieved when further mesh refinement does not significantly alter the solution. To simplify the numerical model, instead of sections with circular and half-oval shapes, the square and rectangular sections were adopted for piles and ribs, respectively, granted that the same axial and bending stiffness are considered. In order to obtain a better comparison of PCAPS and excavation schemes, same station dimension, overburden depth and site condition were employed in the numerical simulation.

The steady-state solution or numerical convergence is typically considered reached when the system response or behavior stabilizes over time, and there are no significant changes in the key parameters of monitoring points. For a steady-state simulation, the numerical solution was satisfied the following three conditions: (1) residual RMS error values have reduced to an acceptable value (typically 10^{-4} or 10^{-5}), (2) monitor points for our values of interest have reached a steady solution, and (3) the domain has imbalances of less than 1%.

The Calculation Phases in the Numerical Model

The details of the numerical model like input phase, calculation phase and output phase are shown in Fig. 13. The calculation phase is as follows: (0) initial condition phase, (1) access phase, (2) pre-supporting construction phase and (3) staged construction phase based on Tables 3 and 4. The staged construction phase of the numerical model based on Sect. "Construction Method" (construction method) is as follows:

Step 1—Traffic load: Applying traffic load and existing two-story buildings load at the model surface (the load is uniformly distributed 20 kPa based on [33] at the model surface),

Step 2—Reset displacement: Reset displacement to zero after applying the traffic and building loads in model,

Step 3—Tunnel construction simulation using EPBM: In the current step, the face pressure is applied to the tunnel face in the numerical model during each excavation step based on Table 5. In the meantime, the shield is modeled by deactivating the soil inside the tunnel with the over cut around the shield (Fig. 14). When the model in each step of the tunnel excavation to a steady state reached, the segmental lining of the tunnel is activated as a structural element. Then, grouting pressure is implemented in the numerical model behind the erected segments to model the filling process of the annular gap based on Fig. 14. The EPBM specifications are given in Table 5.

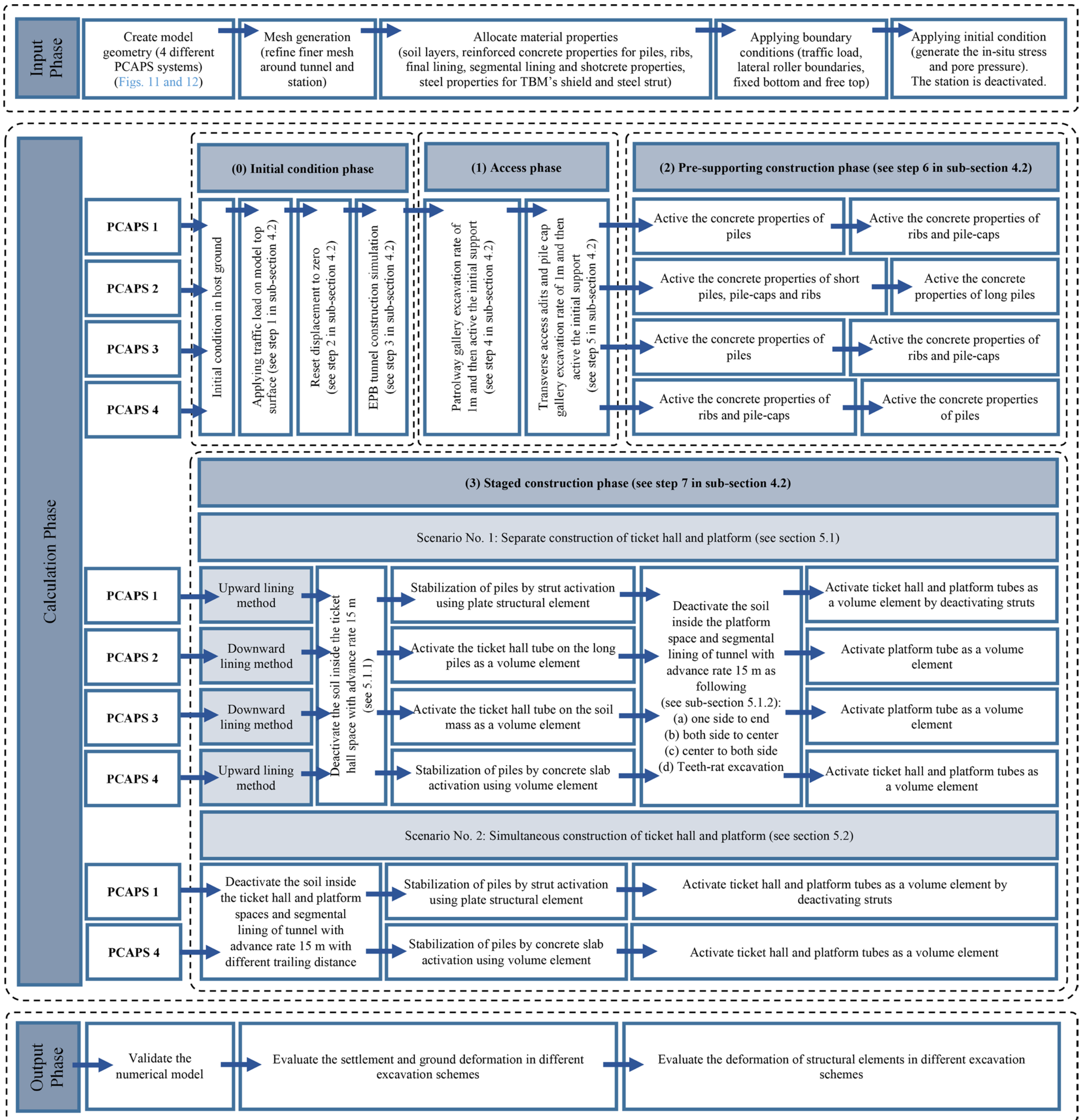


Fig. 13 Numerical simulation procedure for PCAPS analysis

Table 5 Specifications of EPBM in line 7 of Tehran metro [34]

Type of machine	Excavator diameter, (m)	Over cut, (m)	Length of shield, (m)	Excavation round, (m)	Face pressure, (KN/m^2)	Grout pressure, (KN/m^2)
EPB	9.16	0.02	10.5	1.5	70	150

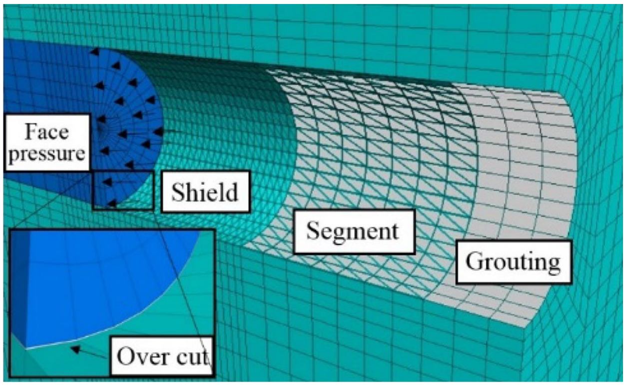


Fig. 14 EPB process in the numerical model

Step 4—Patrolway gallery construction simulation as an access gallery along the station: After tunnel simulation, the station construction simulation is started with *Patrolway gallery* construction simulation. *Patrolway gallery* has a length of about 75 m along the station length and its overburden depth is about 16 m in the numerical model. The thickness of the shotcrete tubing is 0.30 m based on Table 6. So, this access gallery was excavated with full-face excavation method with 1 m advance rate. In order to gallery simulation, the soil inside the tunnel was firstly deactivated with 1 m advance rate, and then the structural elements as a shell element were activated around the gallery based on Figs. 8 and 15 and step 1 of Fig. 10.

Step 5—Transverse access adits and pile-cap gallery construction simulation: Based on step 2 of Fig. 10 and Fig. 8, the soil inside these galleries was deactivated with full-face excavation method in the numerical model with advance rate of 1 m and then reinforced elements such as Patrolway gallery were activated in the model. Their reinforced elements (e.g., shotcrete and frame) are applied to numerical model by shell structural element. The structural elements' specifications in the numerical model are given in Table 6. Patrolway gallery section and transverse access adits in the numerical model and real-life project are demonstrated in Fig. 15.

Step 6—Pile and rib construction simulation: Based on step 3–6 in Fig. 10 and Fig. 13, pile and rib system for each PCAPS technics are applied in the numerical model by changing the properties of soil in the pile and rib elements to the concrete properties based on Table 6.

Table 6 Material parameters of structural elements for EPB tunnel and station [34]

Structural elements	Type of material	Model behavior	Thickness, (m)	Elastic modulus, E (GN/m^2)	Poisson ratio, ν	Density, γ (KN/m^3)	Compressive strength, σ_c (MN/m^2)
Shield and strut	Steel	Elastic	0.05	200	Rigid	–	–
Segment	Concrete	Linear elastic	0.35	30	0.20	25	40
Pile and rib	Concrete	Linear elastic	Variable	23.5	0.20	24	25
Station lining	Concrete	Linear elastic	Variable	26	0.20	25	30
Access gallery	Composite	Linear elastic	Variable	21	0.2	25	20

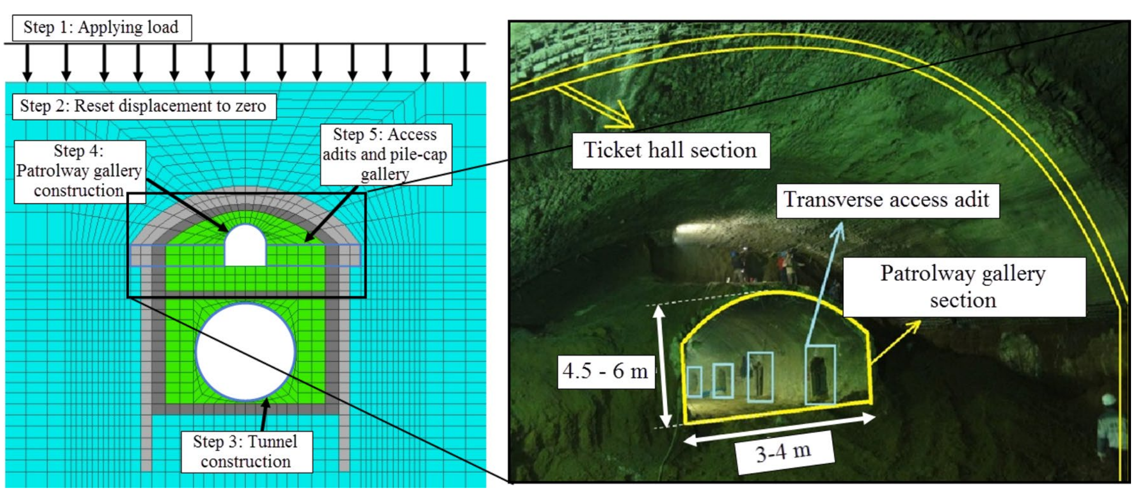


Fig. 15 Access way construction simulation in the numerical model

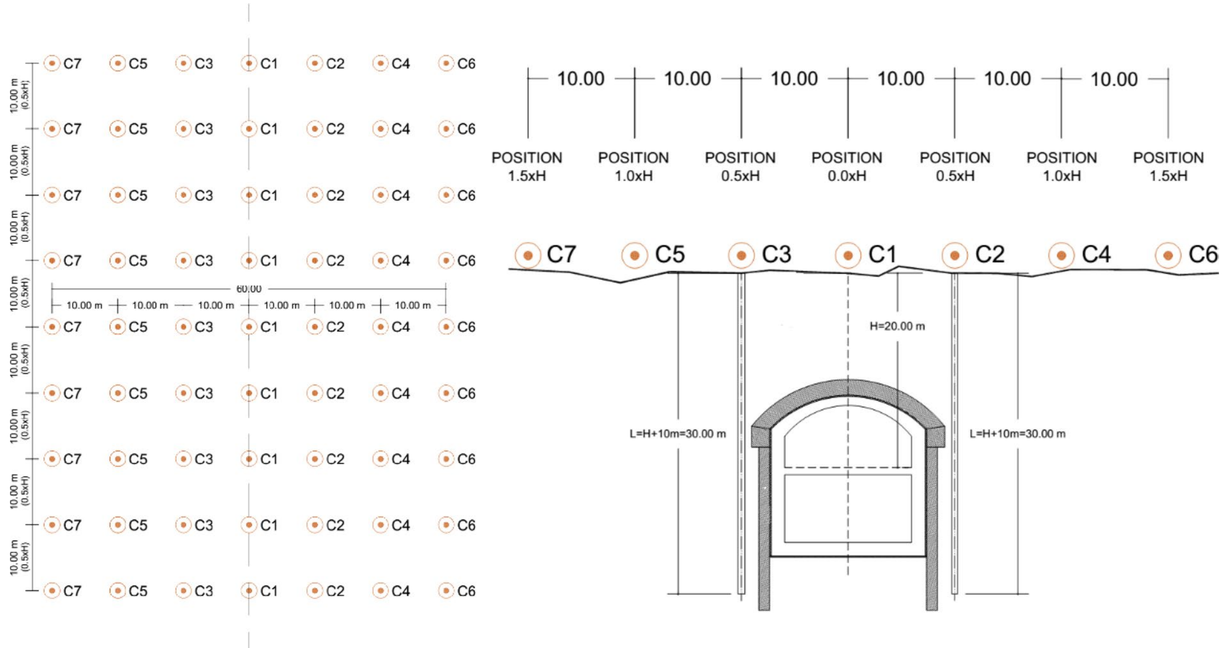


Fig. 16 Layout of benchmarks in plan (left figure) and in cross section (right figure)

Fig. 17 The result of the surface settlement in numerical model and field measurement of Molavi Station

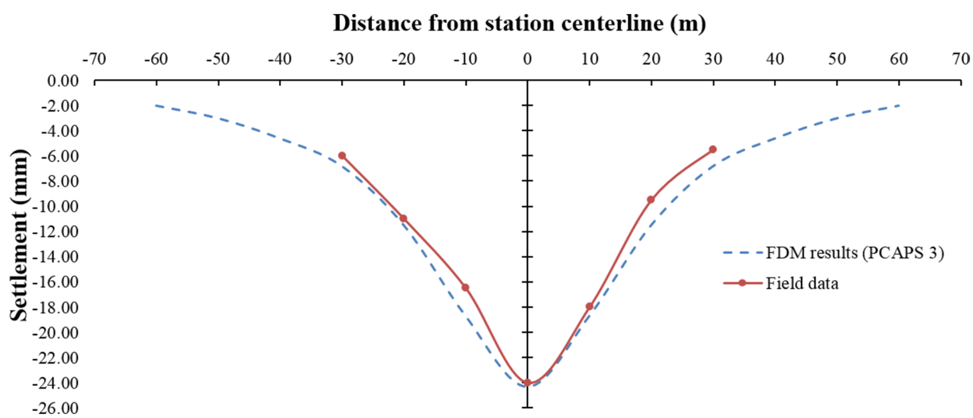
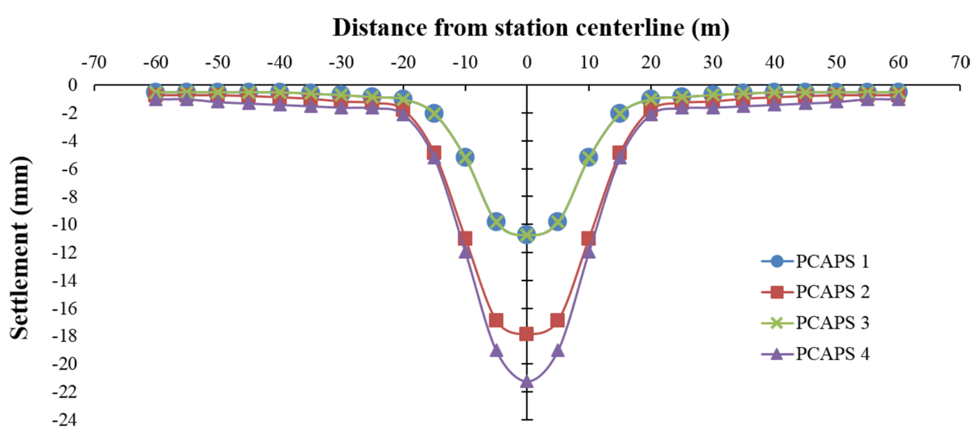


Fig. 18 Transverse surface settlement profiles for ticket hall excavation (to step 7 in all PCAPS in Fig. 10)



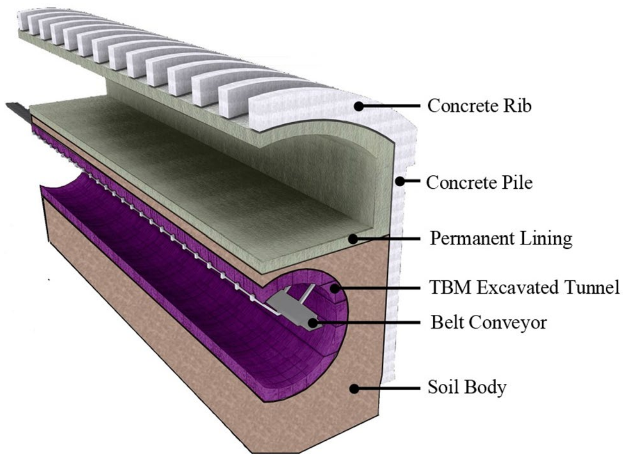


Fig. 19 Tunnel construction before station construction strategy in PCAPS techniques

Step 7—Station construction simulation (soil excavation inside the station and final lining construction upwardly/downwardly simulation): Based on step 7 to the end step in Fig. 10 and Fig. 13, the soil excavation inside the station and the final lining construction were modeled with deactivating the mesh elements inside the station area and with activation of the volume elements inside the station with concrete properties based on Table 6, respectively. Different construction scenarios and sequential construction procedures for station construction will be discussed in section "Selection of Appropriate Construction Method Using PCAPS" (see Fig. 13 as a numerical simulation procedure for PCAPS analysis).

Verification of the Numerical Model

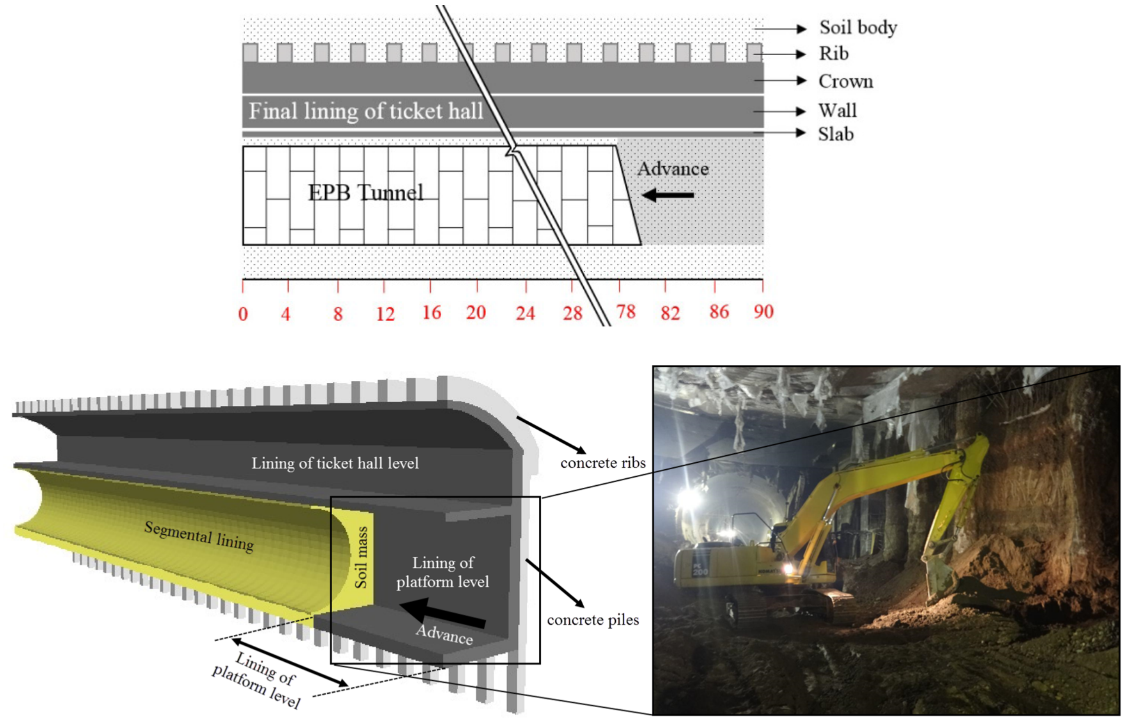
The field data were measured during the *Molavi Station* construction to verify the numerical model. The current station was constructed using PCAPS 3 method. The monitoring points for surveying the surface settlement included topographic measurements based on a network of benchmarks. These benchmarks were arranged on a network in both longitudinal and transverse directions (seven benchmarks per cross section) as depicted in Fig. 16. The topographic measurements of the settlement area were monitored during the station construction [34]. Given the station depth (H), monitoring instruments were transversely installed to the route at distances, 0.0 H (exactly on axis), 0.5 H, 1.0 H and 1.5 H away from axis. The longitudinal spacing of monitoring instruments was set 0.5 H. It is worthy to mention that the depth of the *Molavi Station* (H) is 20.0 m [34].

Based on Fig. 16, the settlement pins as a monitoring system were monitored the surface settlement in all sequence of the construction process of *Molavi Station*. The field data have been acquired at the final sequence of the construction process based on step 10 of Fig. 10c. The results of the surface settlement were acquired by numerical model and the monitoring system are rendered in Fig. 17. Time-dependent settlement was not considered in the FDM analysis and the results of the surface settlement caused by the construction process without considering the time factor have been compared with the numerical model. The results imply good accordance, proving the model validity and pave the way to apply the numerical model for analyzing different procedures of station construction.

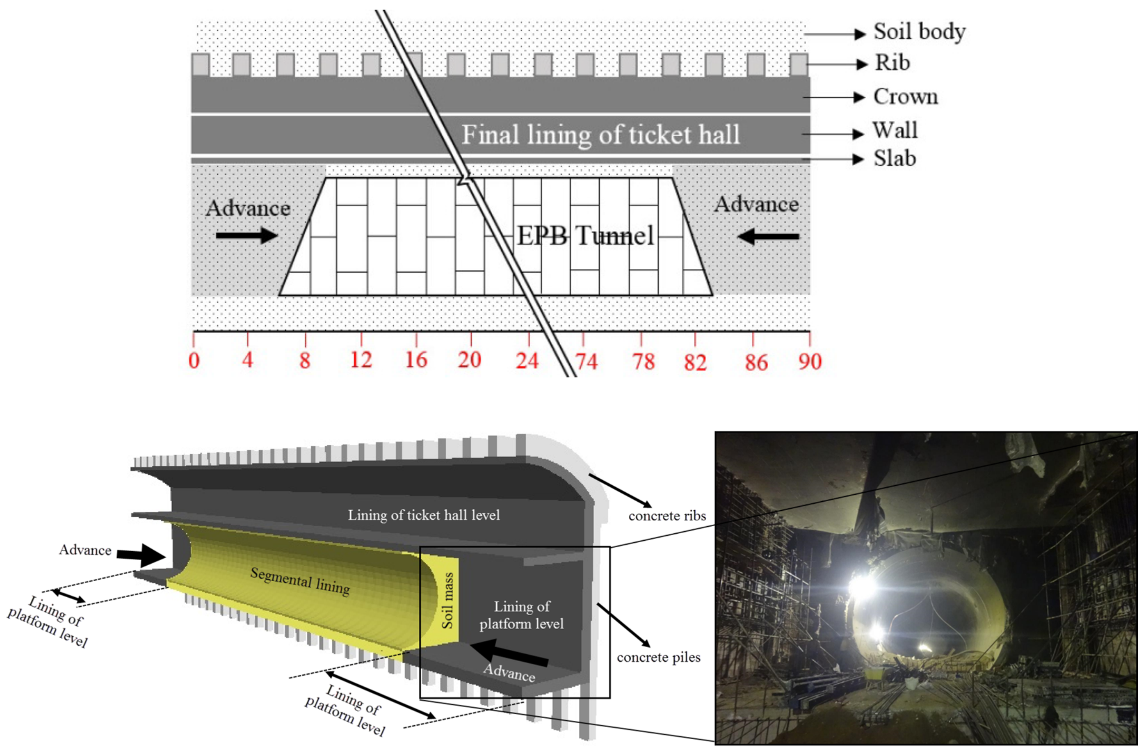
Selection of Appropriate Construction Method Using PCAPS

Choosing a suitable construction method for underground spaces is always among the key parameters for successful construction of the tunneling projects [35]. Furthermore, choosing the optimal support system for tunnel and the suitable excavation sequences exert strong effect on the host ground stability of the tunnel and its deformations. In the most crucial factors influencing on the underground subway station construction method, the following can be mentioned: station depth, station dimension, traffic condition of the site plan, soil properties, ground water level, time and costs [36, 37].

Depending on the project completion and its advance rate, various scenarios are practically proposed for the construction of the double-deck underground subway station using PCAPS techniques. In the current study, two different construction scenarios were proposed, one, separate construction of ticket hall and platform level (see 5.1 subsection) and the other, simultaneous construction of ticket hall and platform level (see 5.2 subsection). In order to choose the adequate construction scenarios using PCAPS method, finite difference method was employed by considering the ground surface settlement (Figs. 11 and 12).

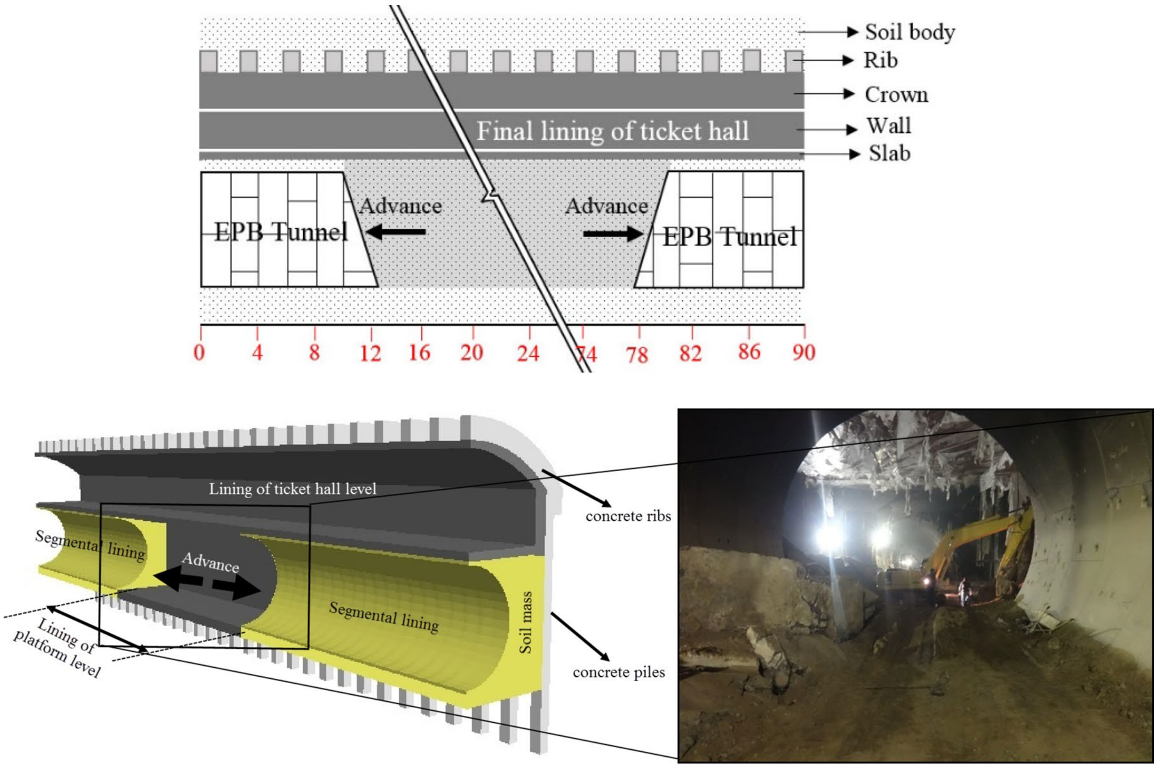


(a) Platform excavation from one side of the station (one face)

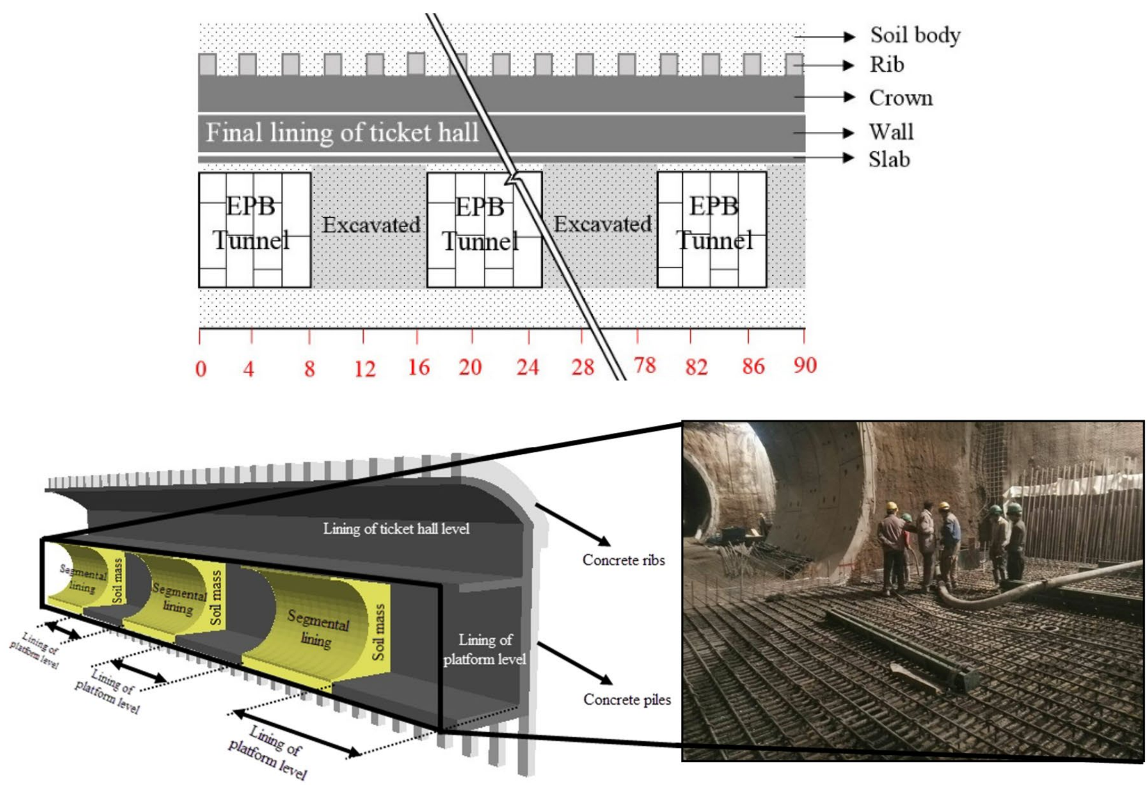


(b) Platform excavation from both sides to center (two faces)

Fig. 20 Different scenarios for platform excavation from existence EPB tunnel. **a** Platform excavation from one side of the station (one face) **b** Platform excavation from both sides to center (two faces) **c** Platform excavation from center to both sides (two faces) **d** Platform excavation by rat-teeth excavation (several faces)



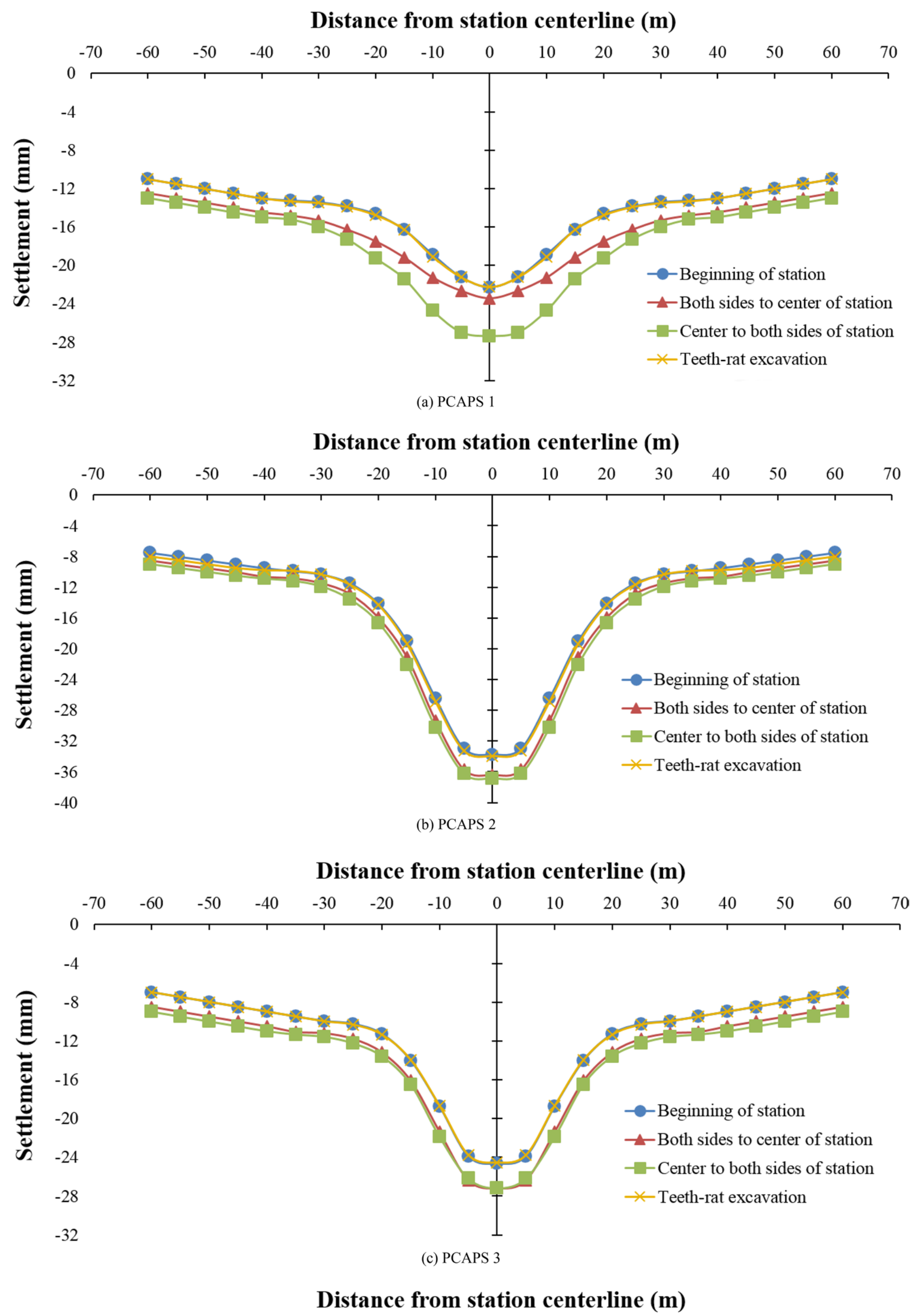
(c) Platform excavation from center to both sides (two faces)



(d) Platform excavation by rat-teeth excavation (several faces)

Fig. 20 (continued)

Fig. 21 Transverse surface settlement profiles for final step of station construction in all PCAPS. **a** PCAPS 1 **b** PCAPS 2 **c** PCAPS 3 **d** PCAPS 4



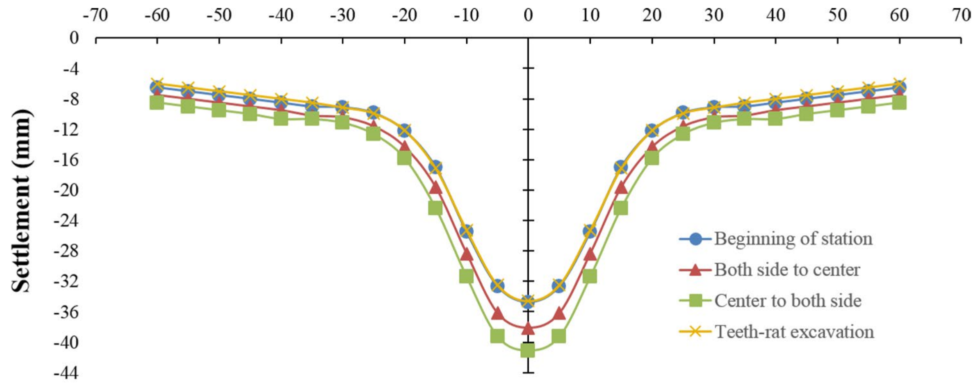
Separate Construction of Ticket Hall and Platform Scenario

The ticket hall and platform level can be constructed separately, in a way that the ticket hall is constructed at first, followed by the platform constructed. So, two types of lining methods are considered for PCAPS as follows:

(i) Upward lining method for PCAPS 1 and PCAPS 4, which means that the entire length of the station in both floors is firstly excavated and then station liner is placed from down to top sequentially,

(ii) Downward lining method for PCAPS 2 and PCAPS 3, which means that the upper floor of the station is sequentially excavated and lined and then the lower floor of the station will be constructed.

Fig. 21 (continued)



(d) PCAPS 4

In the following, the optimum construction method for ticket hall and platform level will be selected by considering the ground surface settlement.

Optimum Construction Method for Ticket Hall Level

The transverse surface settlement profiles based on the ticket hall excavation are seen in Fig. 18. As clearly seen, the maximum surface settlement over the station centerline in PCAPS 1, PCAPS 2, PCAPS 3, as well as PCAPS 4 is about 10.75 mm, 17.85 mm, 10.75 mm and 21.25 mm, respectively. Based on the modeling results, due to the presence of the two type of piles in PCAPS 2, i.e., short and long piles (Fig. 10b), the embedded depth of the piles and their total load bearing capacity decrease as compared with PCAPS 1 and 3, thus it shows more surface settlement. On the one hand, due to the lack of rigidity at the joint between concrete piles and ribs in PCAPS 4 (Fig. 10d), and on the other hand, since the pile-cap as a rib foundation is directly rested on the soil mass, thus more surface settlement is induced in PCAPS 4 as compared with PCAPS 1, 2 and 3. Therefore, PCAPS 1 and PCAPS 3 were preferred over the PCAPS 2 and PCAPS 4 for ticket hall construction.

Optimum Construction Method for Platform Level

In subway projects, due to the limitations imposed by railway infra-super structures, the tunnel excavation is preferably done prior to the construction of stations. As mentioned in Fig. 10, the tunnel was bored by EPBM earlier than the station construction in line 7 of Tehran metro. The profits of this strategy are as follows (Fig. 19):

(i) a large volume of the soil allocated in the platform level is excavated by EPBM before the station construction gets started,
(ii) no need for breakthrough structure at both sides of the station for EPBM passage,
(iii) more convenience and easiness in getting access to the entire length of the platform level for excavation.

Granted that the tunnel is excavated prior to the station construction, it is feasible to get access along the length of the platform of station. As a result, the platform excavation can be done anywhere arbitrarily. The main parameter in the selection of optimal excavation schemes is to limit the ground deformation, so it is essential to fully understand the effect of face advancing [38, 39]. Thus, four various scenarios were proposed for platform excavation. Platform excavation sequences which were used in the numerical model are shown in Fig. 20 as follows: platform excavation with one face (Fig. 20a), platform excavation with two faces (Fig. 20b and c) and platform excavation with several faces (Fig. 20d); the latter one is so-called rat-teeth excavation. Figures 19 and 20 show PCAPS 3 method which are generalized and extrapolated for PCAPS 1, 2 and 4.

Transverse surface settlement profiles for four platform excavation sequences based on Fig. 20 are illustrated in Fig. 21. According to Fig. 21, when the platform is excavated by two faces, more settlement induces than one-face and multiple-faces case for all PCAPS. The same surface settlement trend is shown for one-face and multiple-faces. Remember that in multiple-faces case, there are lots of faces under excavation simultaneously.

When the platform is excavated centrally to lateral (Fig. 20c), the induced surface settlement over the station centerline reaches 27.38 mm for PCAPS 1 and 41.10 mm for PCAPS 4 according to Fig. 21a and d in the case of upward lining method, respectively. These values of settlements are more than the case which excavation is done laterally to central (Fig. 20b), whose values according to Fig. 21a and d are 23.47 mm and 38.13 mm, respectively. By drawing a comparison between centrally to lateral and laterally to central cases in PCAPS 2 and PCAPS 3 (Fig. 21b and c), the same trend was found for surface settlement profiles in the case of downward lining method. The reason may be raised as follows: (1) The ticket hall lining bears more loads from ground, because it was constructed in previous step and (2)

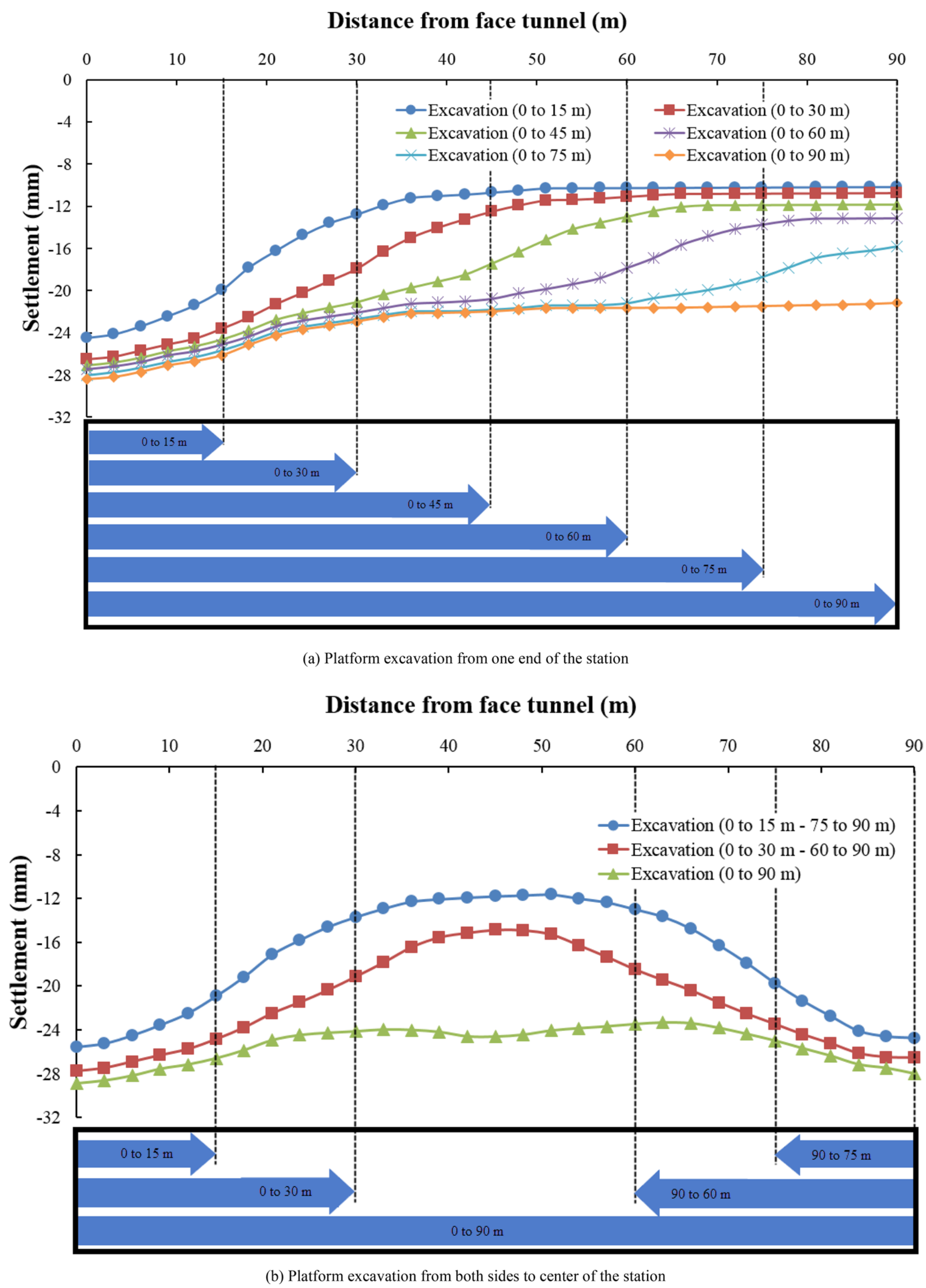
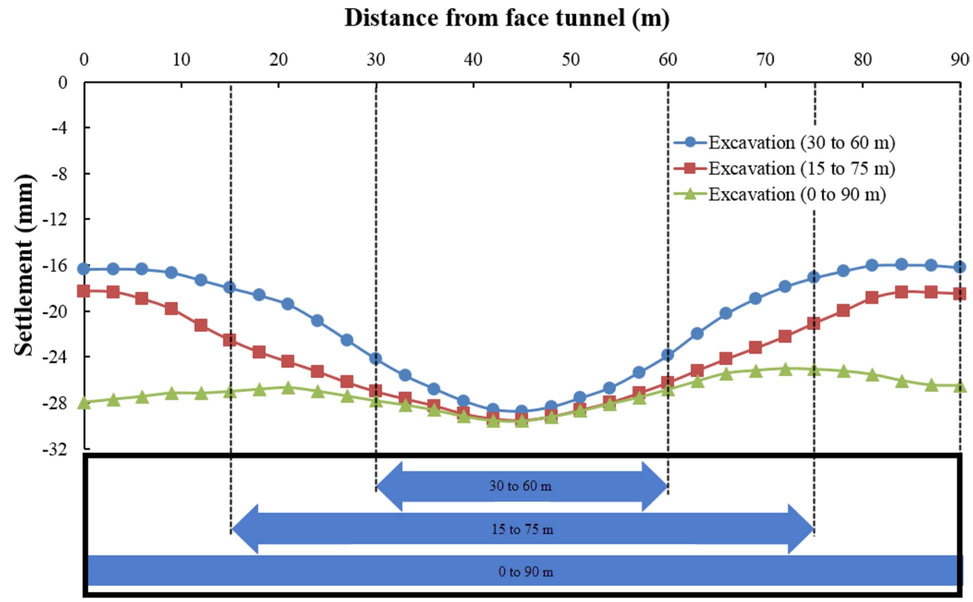


Fig. 22 Longitudinal surface displacement profiles for final step of station construction in PCAPS 3. **a** Platform excavation from one end of the station **b** Platform excavation from both sides to center of the station **c** Platform excavation from center to both sides of the station **d** Platform excavation by rat-teeth excavation

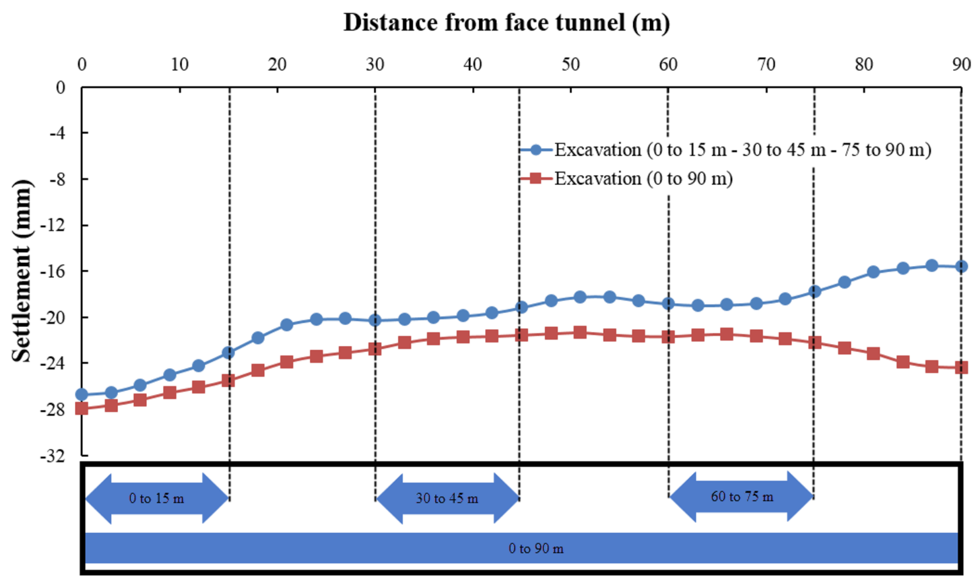
Limitation of the excavation zone in cross section, because half of the station in cross section was constructed. Based on the numerical modeling results (Figs. 18 and 21), PCAPS 1 (upward lining method) and PCAPS 3 (downward lining method) with multiple-faces (Fig. 20d) or one face (Fig. 20a) for platform excavation had the lowest surface settlement value. Although computed settlements from PCAPS 1 and 3 (Figs. 21) are almost the same, the settlement expansion on the ground surface in PCAPS 3 is less than PCAPS 1. PCAPS 3 was selected as the optimal construction method in this case.

The longitudinal displacement profiles (LDP) along the station centerline for PCAPS 3 are seen in Fig. 22 as an optimal case. They imply that the maximum and minimum surface settlement along the station length begets depending on the four platform excavation sequences (Fig. 20). According to Fig. 22a, when the excavation gets started at one point, the maximum settlement occurs at that point itself. According to the deductions acquired from Fig. 22b and c, when the

Fig. 22 (continued)



(c) Platform excavation from center to both sides of the station



(d) Platform excavation by rat-teeth excavation

Fig. 23 Trailing distance in simultaneous excavation of ticket hall and platform level in PCAPS 1 and 4

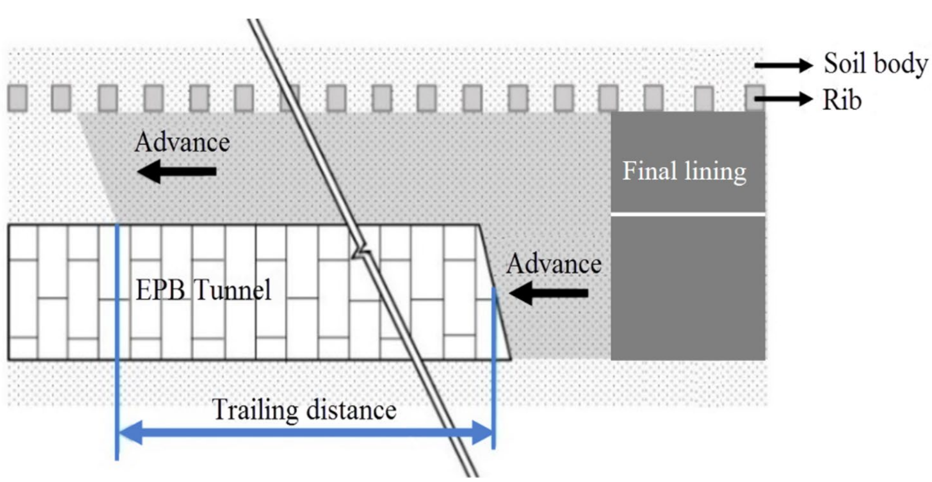
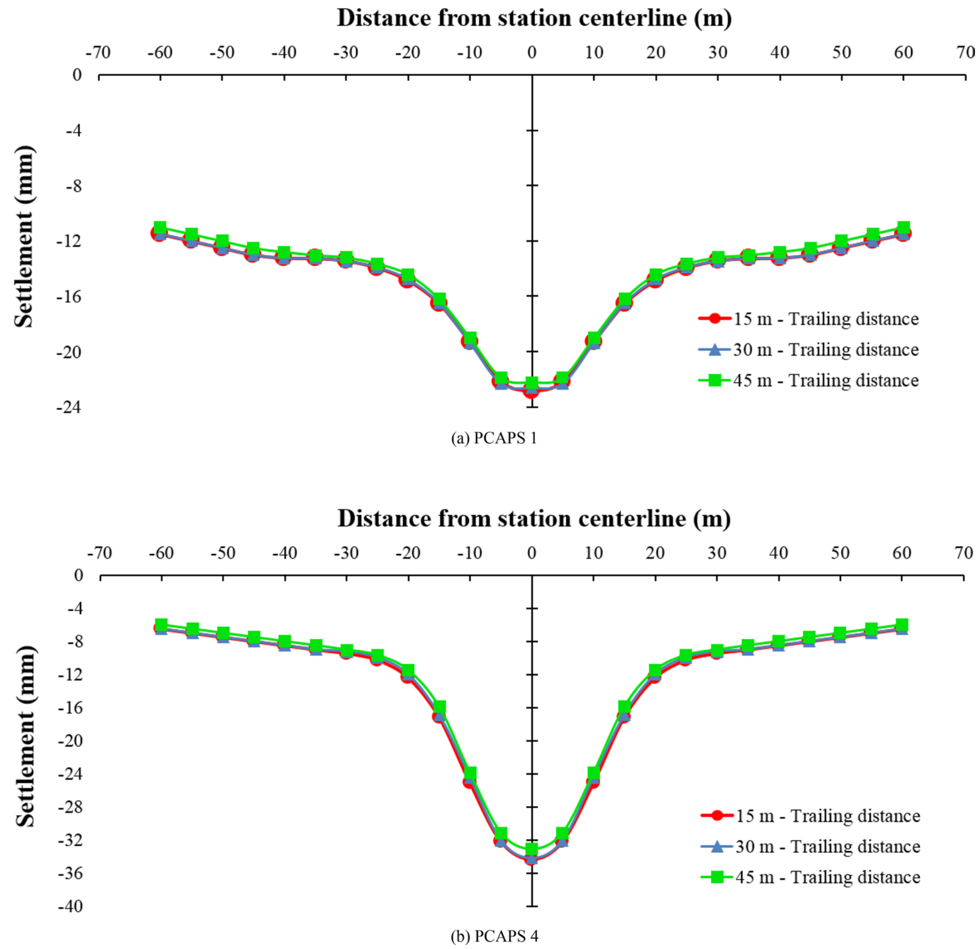


Fig. 24 Transverse surface settlement curves for different trailing distances between the ticket hall and platform faces. **a** PCAPS 1 **b** PCAPS 4



excavation started laterally to central and centrally to lateral in two faces, the maximum deformation occurs at both sides and center of the station, respectively. The multiple excavations scenario (Fig. 22d) shows uniform settlement profile, which is formed along the station centerline.

Simultaneous Construction of Ticket Hall and Platform Scenario

The ticket hall and platform level can be constructed simultaneously in PCAPS 1 and PCAPS 4 (case of upward lining method), in a way that the ticket hall and platform face is excavated with a trailing distance, and when the excavation of the station was finished, the final concrete liner in both floors will be placed sequentially. According to Fig. 23, the excavation procedure and upward lining method in PCAPS 1 and 4 are similar to the top heading and bench excavation method in tunneling.

The distance between excavation stages in sequential excavation method plays a prominent role in surface settlement reduction [7]. In order to understand the effect of trailing distance between ticket hall and platform faces while applying PCAPS 1 and PCAPS 4, the excavation of ticket hall face was simulated at trailing distances of 15 m, 30 m and 45 m in front of the platform face. The transverse surface settlement and longitudinal surface settlement curves for different trailing distance between ticket hall and platform faces are illustrated in Figs. 24 and 25, respectively. Figure 24 reveals that due to the pre-supporting system like PCAPS used around the opening prior excavation, any change in distance between ticket hall and platform faces shows no effect on the surface settlement. As shown in Fig. 25, any change in trailing distance shows about a significant effect on ground displacement ahead of the stations.

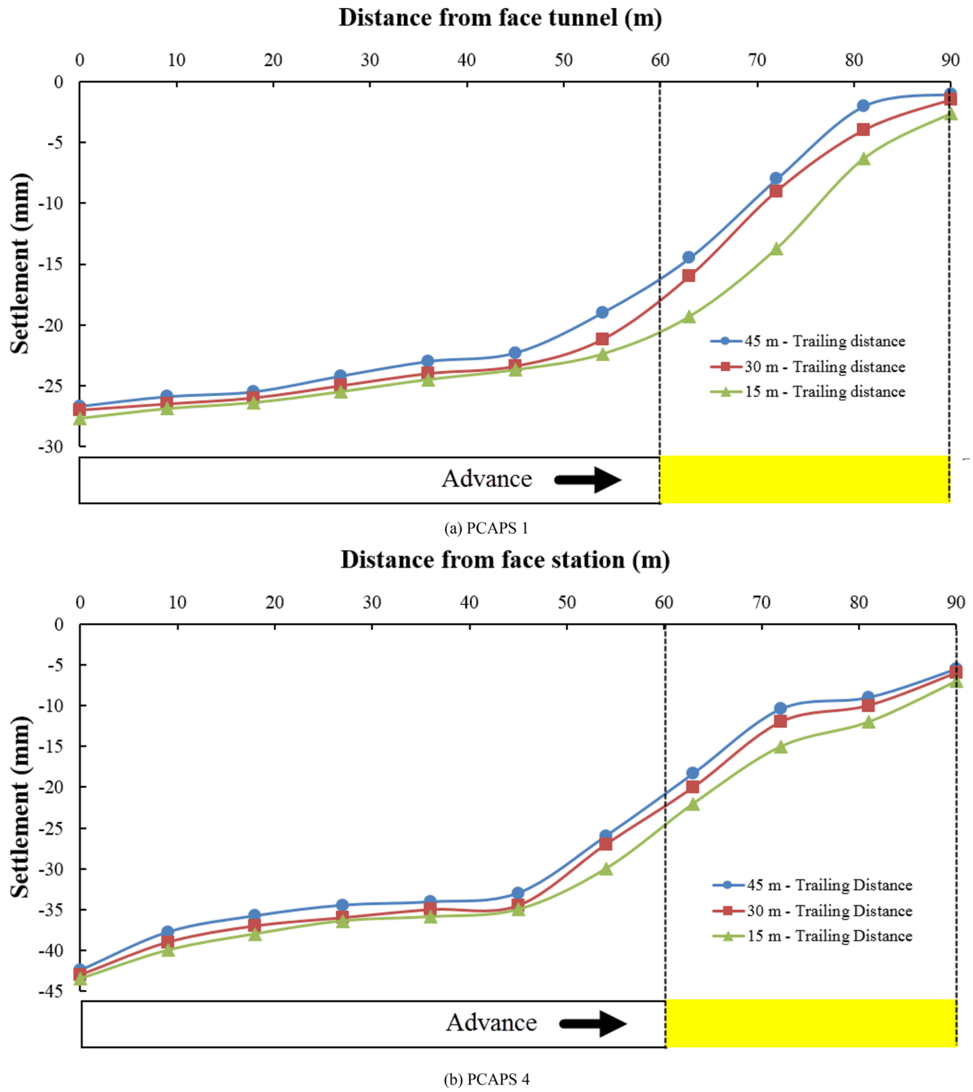


Fig. 25 Longitudinal surface settlement curves for different trailing distances between the ticket hall and platform faces. **a** PCAPS 1 **b** PCAPS 4

Conclusion

Selection of a construction method for the biggest underground spaces in urban areas, for instance, the underground subway stations, is a key factor in analysis and design procedure. The study surveys proposed PCAPS construction method for double-deck subway stations. PCAPS was originated by revising the CAPS method used for one deck subway stations. To choose the optimal technique for PCAPS application as well as the optimal sequential excavation, a 3D FDM model was developed for the *Molavi Station*, a station which is located at the route of line 7 of Tehran metro. The numerical modeling results are in well accordance with field data acquired by monitoring system. The main results are as follows:

1. The structural elements are used to get the ground improved and stabilized in PCAPS method before the underground station is excavated.
2. Rigidity between piles and their correspondent ribs is crucial to maintain the stability and reduce the settlements as well as the damages to the buildings.
3. Based on the numerical modeling results, PCAPS 3 with multiple excavation faces at platform level had the

lowest surface settlement and expansion on the ground surface.

4. PCAPS is categorized in two classes: the downward lining method and upward lining method. For PCAPS 1 and PCAPS 4, the final lining is done upwardly, contrary to them, for PCAPS 2 and PCAPS 3, the lining is done downwardly. For PCAPS 2 and PCAPS 3, the upper tube is constructed prior to the lower one, for this reason, these methods demonstrate less settlement.
5. Since the PCAPS method is used for the construction of *Molavi Station*, as for the case of simultaneous excavation of ticket hall and platform scenario, no specific effects could be mentioned on the surface settlement in final step with changing in distance between ticket hall and platform faces.

Acknowledgements Authors would like to dedicate their special thanks to Amirkabir University of Technology (Tehran Polytechnic) for their valuable efforts and cooperation to let authors get access to software and facilities for the study. The authors also express their gratitude to the Tehran Urban and Suburban Railway Company (TUSRC) for granting aid and allowance to authors to get access to the required data needed for the research completion.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

General information about line 7 of Tehran metro

The tunnel of line 7 of Tehran metro was excavated by two EPBMs with the length of about 23.4 km with the excavation diameter of 9.13 m (Fig. 26). Figure 26 shows two lots of this project; south–north lot and west–east lot. The remaining tunnels were excavated by new Austrian tunneling method (NATM).

According to Table 7, the stations have been built by cut and cover (top-down/down-top) methods and underground excavation methods using PCAPS 1 to 4 approaches.

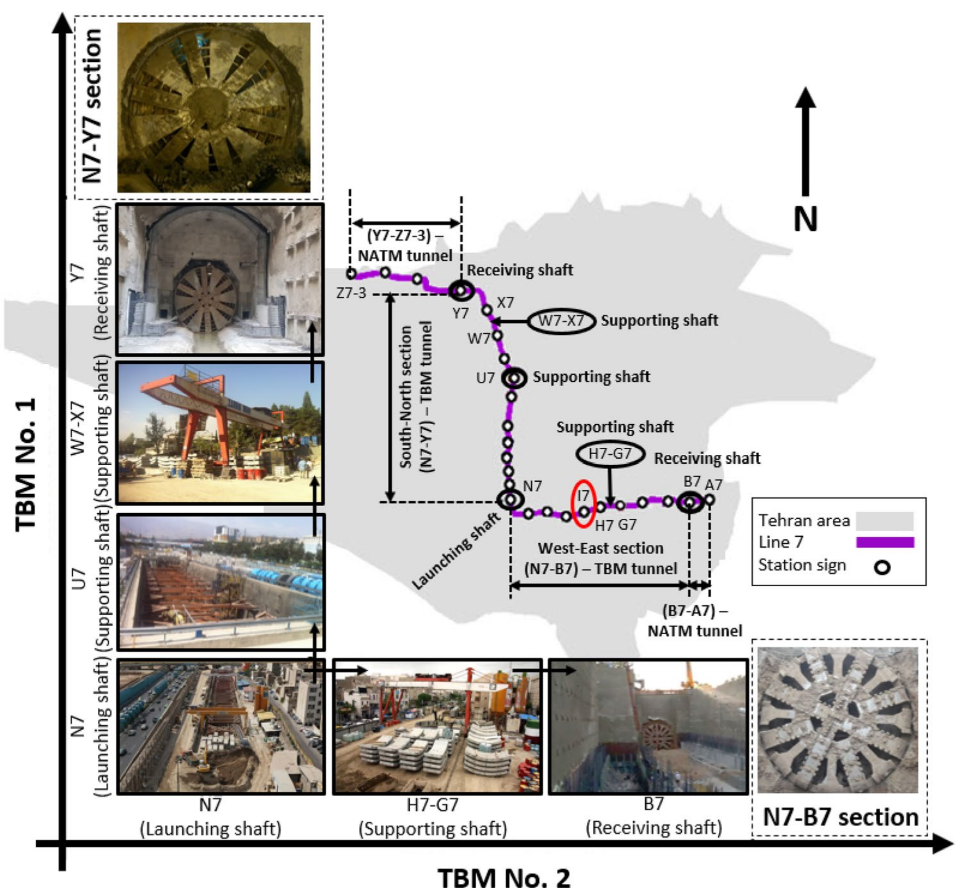


Fig. 26 Tunnel construction process of Tehran metro line 7 [40]

Table 7 Construction method of stations in line 7 of Tehran metro

Construction techniques	Station label
Cut and cover methods (top-down/down-top)	B7, N7, W7
PCAPS 1 (Underground excavation methods)	E7
PCAPS 2 (Underground excavation methods)	G7, O7, P7, Q7, S7, T7
PCAPS 3 (Underground excavation methods)	A7, H7, I7, J7, L7, M7, V7, X7, Y7
PCAPS 4 (Underground excavation methods)	R7, D7, U7

Due to revising in a part of the tunnel rout, C7, F7 and K7 stations located in eastern lot were relinquished

References

1. Franzius JN (2003) Behaviour of buildings due to tunnel induced subsidence. PhD thesis, Department of Civil and Environmental Engineering of Imperial College of Science, Technology and Medicine London, pp. 21–22.
2. Peck RB (1969) Deep excavation and tunneling in soft ground, State-of-the-art report. In Proc 7th int conf soil mechanics and found engineering, Mexico, pp. 225–290.
3. Sagaseta C, Moya JF, Oteo C (1980) Estimation of ground subsidence over urban tunnels. In: Proceeding of 2nd Conference on Ground Movement and Structure, Cardiff, pp. 331–344.
4. Migliazza M, Chiorboli M, Giani GP (2009) Comparison of analytical method, 3D finite element model with experimental subsidence measurements resulting from the extension of the Milan underground. Comput Geotech 36:113–124
5. Li XG, Yuan DJ (2012) Response of a double-decked metro tunnel to shield driving of twin closely under-crossing tunnels. Tunn Undergr Space Technol 28:18–30
6. Hoek E (2014) The development of Rock Engineering. Lecture Series, Rocscience Inc, Toronto, Canada.
7. U.S. Department of Transportation Federal Highway Administration (FHWA) (2009) Technical Manual for Design and Construction of Road Tunnels Civil Elements.
8. Pakbaz MS, Imanzadeh S, Bagherinia KH (2013) Characteristics of diaphragm wall lateral deformation and ground surface settlements: Case study in Iran-Ahwaz metro. Tunn Undergr Space Technol 35:109–121
9. Lentini V, Castelli F (2019) Numerical modelling and experimental monitoring of a full-scale diaphragm wall. Int J Civ Eng 17:659–672
10. Fulcher B, Menge S, Grillo J (2013) New York City-second avenue subway: MTA's 72nd street station and tunnels project construction of a large span station cavern, running tunnels, crossover and turn-out caverns, shafts and entrances. SME.
11. Cao L, Fang Q, Zhang D, Chen T (2018) Subway station construction using combined shield and shallow tunnelling method: Case study of Gaojiayuan station in Beijing. Tunnelling and Underground Space Technology.
12. Fang Q, Zhang D, Wong LNY (2012) Shallow tunnelling method (STM) for subway station construction in soft ground. Tunn Undergr Space Technol 29:10–30
13. Ocak I (2008) Control of surface settlements with umbrella arch method in second stage excavations of Istanbul Metro. Tunn Undergr Sp Technol 23:674–681
14. Sadaghiani MH, Dadizadeh S (2010) Study on the effect of a new construction method for a large span metro underground station in Tabriz-Iran. Tunn Undergr Sp Technol 25:63–69
15. Valizadeh Kivi A, Sadaghiani MH, Ahmadi MM (2012) Numerical modeling of ground settlement control of large span underground metro station in Tehran Metro using central beam column (CBC) structure. Tunn Undergr Space Technol 28:1–9
16. Abdi Cherlo M, Hashemolhosseini H, Cheraghi M, Mahdevari S (2013) Feasibility evaluation for excavation of Naghshe Jahan Square subway station by underground methods. Rock Mech Geotech Eng 5:452–459
17. Liu J, Wang F, He S, Wang E, Zhou H (2015) Enlarging a large-diameter shield tunnel using the pile–beam–arch method to create a metro station. Tunn Undergr Space Technol 49:130–143
18. Kang Y, Liu Q, Cheng Y, Liu X (2016) Combined freeze-sealing and New Tubular Roof construction methods for seaside urban tunnel in soft ground. Tunn Undergr Space Technol 58:1–10
19. Grigson R, Voorwinde M (2017) Achieving Column-Free Platforms—Design and Construction of Large Span Station Mezzanines on the Second Avenue Subway Project. Structures Congress, ASCE, Denver, Colorado.
20. Zhang M, Liu Y, Fan L, Li P (2017) Performance of constructing a double-deck subway station by combining the shield method and cavern–pile method. Tunn Undergr Space Technol 67:120–131
21. Yang X, Li Y (2018) Research of surface settlement for a single arch long-span subway station using the Pipe-roof Pre-construction Method. Tunn Undergr Space Technol 72:210–217
22. Li B, Wang ZZ (2019) Numerical study on the response of ground movements to construction activities of a metro station using the pile-beam-arch method. Tunn Undergr Space Technol 88:209–220
23. Yu L, Zhang D, Fang Q, Cao L, Xu T, Li Q (2019) Surface settlement of subway station construction using pile-beam-arch approach. Tunn Undergr Space Technol 90:340–356
24. Guo X, Wang Z, Geng P, Chen C, Zhang J (2020) Ground surface settlement response to subway station construction activities using pile–beam–arch method. Tunn Undergr Sp Technol inc Trenc Technol Res. 108:103729
25. Huang C, Li S, Yang Y, Liu Y, Li J, Qi W (2023) Model experiment and support optimization analysis of primary support arch cover excavation of large-section metro station in sandy mudstone stratum. Eng Fail Anal 149:107286
26. Rieben EH (1966) Geological Observation on Alluvial Deposits in Northern Iran. Geological Organization of Iran, Report, pp. 9–39.
27. Fakher A, Cheshomi A, Khamechiyan M (2007) The addition of geotechnical properties to a geological classification of coarse-grained alluvium in a pediment zone. Q J Eng GeolHydrogeol 40:163–174
28. P.O.R. Consulting Co (2009) Geotechnical Investigations & Foundation Report for I7 Station, Tehran Metro Line 7 Project (In Persian).
29. Hoek E (2001) Big tunnel in bad rock. J Geotech Geoenviron Eng 127(9):726–740
30. Sadaghiani MH, Gheysar Y (2003) Study on the effect of construction sequence of a large underground on the ground behavior in Mellat Station, Tehran Metro. In: Proceedings, Fourth National Civil Engineering Conference, Tehran, Iran, pp. 287–294 (In Persian).

31. Eslami B, Golshani A (2017) Performance of CAPS method considering its interaction with adjacent structures-the Q7 station of tehran metro line 7. Int J Geoeng Case histories 4(3):147–161
32. Mohammadi D, Parsapour D (2023) Structural response of large span underground spaces due to adjacent excavation. Geotech Geol Eng J. https://doi.org/10.1007/s10706-023-02618-y
33. National Iranian code for building construction (2020) Issue 6-loading (In Persian).
34. SELI Co (2008) Shape and detailed geometry of the segments and statical verification in the foreseen geology and steel reinforcement. Report for Tehran Metro Project-Line 7 north-south section.
35. Sharifzadeh M, Kolivand F, Ghorbani M, Yasrobi SH (2013) Design of sequential excavation method for large span urban tunnels in soft ground – Niayesh tunnel. Tunn Undergr Sp Technolc 35:178–188
36. UITP (2018) Transport and traffic strategic framework in Tehran, Iran.
37. Isaksson T, Stille H (2005) Model for estimation of time and cost for tunnel projects based on risk evaluation. Rock Mech Rock Eng 38:373–398
38. Karakus M, Fowell RJ (2003) Effect of different tunnel face advance excavation on the settlement by FEM. Tunn Undergr Space Technol 18:513–523
39. Farias MM, Moraes AH, Assis AP (2004) Displacement control in tunnels excavated by the NATM: 3-D numerical simulations. Tunn Undergr Space Technol 19:283–293
40. Mohammadi D, Shahriar K, Moarefvand P, Farrokh, E (2023) Discussion of cutter-head opening design for earth pressure balance machines (EPBMs), Proceedings of the Institution of Civil Engineers – Geotechnical Engineering,, ICE publishing, https://doi.org//https://doi.org/10.1680/jgeen.22.00254.