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A Global Review of Metro Station Construction Projects

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ABSTRACT

Metro construction projects should technically and economically be optimized to achieve maximum efficiency. In this regard, selection of an excavation method is very important so as to not interfering available civil services and not imposing additional expenditures. Development of various new construction methods such as New Austrian Tunneling Method (NATM), Cut and Cover, Cover and Cut has provided a suitable environment for the design engineers to adopt the most appropriate excavation alternative. In this study, the most popular construction methods of underground metro stations are discussed. Also, different methods of ground pre-supporting systems for controlling instability of excavated underground space (convergence) and subsidence in urban area is explained.

KEYWORDS

Metro construction projects, NATM, Cut and Cover, Cover and Cut

1. INTRODUCTION

Metro with advantages such as high transportation capacity, low pollution, reasonable incurred resources, low energy consumption is a necessary infrastructure for metropolitan cities. It is also in conformity with the principle of sustainable development. At present, there are over 100 cities all over the world that have been operating metros.

The construction of metro in Iran is in a period of an unprecedented development in recent years. Large-scale metro constructions are ongoing in many cities such as Tehran, Isfahan, Mashhad, Shiraz, Tabriz and Ahvaz.

The method of construction of the metro stations is very sensitive to the surrounding area and therefore selection of the construction method is very important for such type of the projects. Figure 1depict the effect of metro construction operation on the surface traffic.

There are two basic elements of subway construction – constructing stations and their entrances, and constructing the tunnels running between the stations. Generally, there are three methods for metro station construction:

1. New Austrian Tunneling Method (NATM)
2. Cut and Cover method
3. Cover and Cut method

In this study, the above mentioned methods are discussed in detail in which advantages and disadvantages of each method are explained. Also, application of the NATM for excavating underground metro stations in difficult conditions is presented.

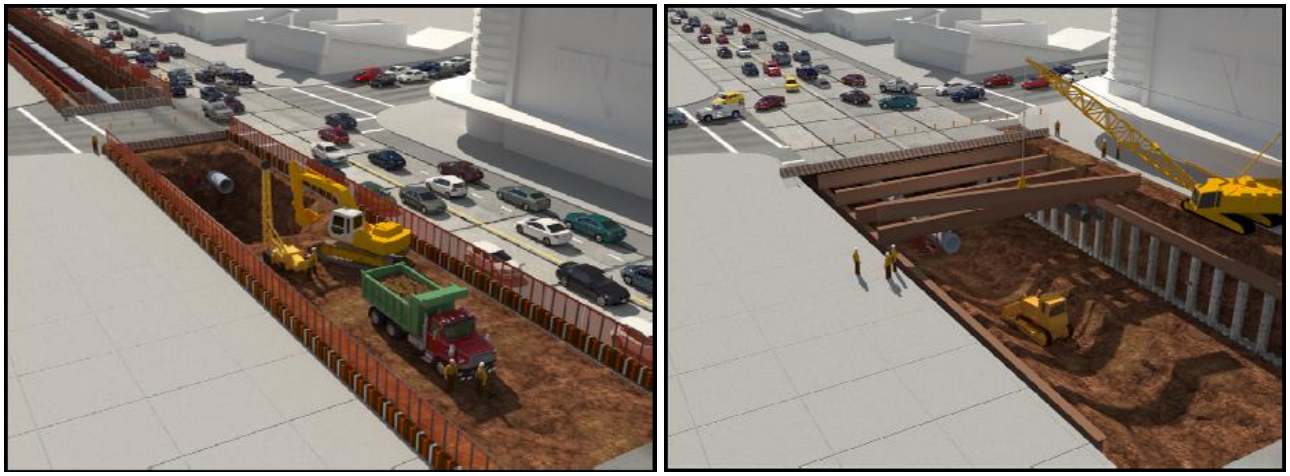

Figure 1: The effect of metro construction operation on the surface traffic.

2. UNFORESEEN GROUND BEHAVIOR

The risk of unforeseen ground behavior has been minimized by 1) performing an extensive site and laboratory investigation during the design phase and 2) by monitoring during the construction phase. In the construction phase, the technical monitoring is given a place within risk management. This new approach is very helpful to prevent risks resulting from unforeseen ground behavior [1].

2. 1. Site- and Laboratory Investigation

Site- and laboratory investigation is carried out to specify geotechnical, geological, geohydrological and environmental aspects. All investigations are focused on minimizing the underground risks by gaining as much knowledge as possible. Another goal is to determine design parameters for construction. Despite these efforts, still there may be some uncertainty in the collected information. The remaining risks of unforeseen ground behavior are covered by monitoring the behavior of the underground and surrounding structures during construction phase [1].

The determination of geotechnical parameters should somehow be in conformity with mathematical (analytical) models. The mathematical models are utilized to determine the geotechnical parameters. Advanced numerical methods with second order material models require different geotechnical parameters. The careful selection of mathematical models, the required level of safety (risk analysis) and site investigation is the start of the determination of the geotechnical parameters.

2. 2. Monitoring

During the design phase a very detailed program of monitoring specifications is prepared. The specifications form an integral part of the contract. Apart from the detailed monitoring specifications, a set of hazard warning levels is also introduced. These levels have to be used by the contractor to control the construction process. The levels can be differentiated into: 1) a warning level and 2) an intervention level. In the warning level, the contractor takes actions like increasing frequency of monitoring, informing the client and adjusting the construction process.

The warning levels also serve as a trigger of awareness for both contractor and client. After warning, the contractor has to immediately stop the activities and take necessary action to prevent possible hazards. Of course all parties like client, insurance and permitting parties have to be informed immediately. In Table 1 an overview is given of some of the most important types of monitoring [1].

Table 1: some of the most important types of monitoring with related hazard warning levels [1]

Object	Type of monitoring	Hazard warning levels	Aim
Metro tunnel	Tachymetric deformation	Based on rail track and tunnel deformation criteria	Prevention of tunnel damage and unobstructed exploitation of metro traffic
Surrounding buildings	Vibration and sound measurements	Based on hindrance and damage criteria from building codes	Preventing hindrance (where possible) and damage
Groundwater	Open standpipe piezometers	As dictated by groundwater extraction permits	Working within permits

3. DESIGN PHILOSOPHY

Design philosophy of the station structures is to determine an acceptable balance between the safety requirements and construction costs. The predicted deformations of the adjacent building foundations are used in the design phase. The deformations depend on the following factors:

a. Geotechnical behavior (parameters)
b. Calculation models (Numerical or Analytical)
c. Construction design

Knowledge of the optimal geotechnical parameters allows the soil behavior to be determined. Normally, it is not possible to exactly derive the geotechnical parameters from laboratory or in-situ tests hence a certain safety margin has to be introduced. The higher the safety margin the more the cost to be spent.

4. OVERVIEW OF DESIGN AND CONSTRUCTION METHODS

For construction of underground metro stations and tunnels, methods that ensure project safety and completion rapidness should be applied. The construction methods can be used either separately or in a combined form. Selection of the appropriate method should be in relation with geological and in situ conditions of the surrounding area.

- Use of the New Austrian Tunneling Method (NATM).
- Use of the Cut and Cover method.
- Use of the Cover and Cut method.

4. 1. Station Construction using the Underground Conventional Boring Method

The underground tunnel boring method using conventional means (known as NATM method or New Austrian Tunneling Method) is the second (in terms of preference) construction method applied internationally for the construction of tunnels using the underground boring method. The Tunnel Boring Machine (TBM) is the method, which is preferably used for the construction of tunnels. Because the size of station cross section is different from tunnel cross section, TMB is not suitable for excavation of underground metro station. Hence, it is necessary to use special method. On the other hand, for operating TBM, an entrance and exit shaft should be prepared. Therefore, the NATM method is widely used for excavating deep metro stations.

In urban areas, it is important to manage the project so as to make any disturbance. Using the underground construction methods, the occupation of areas at the surface (squares, streets, private plots, etc), the relocations of PUO pipes (water, power, telephone supply, etc) traffic diversions and archaeological excavations is avoided (Fig. 2).

NATM Construction Methodology

The basic principle of this method is to maintain the strength of the tunnel nearby surrounding surface. Controllable soil deformation with the use of flexible retaining has positive effect and safe advancement would be possible. The methodology of the project design/construction is the following:

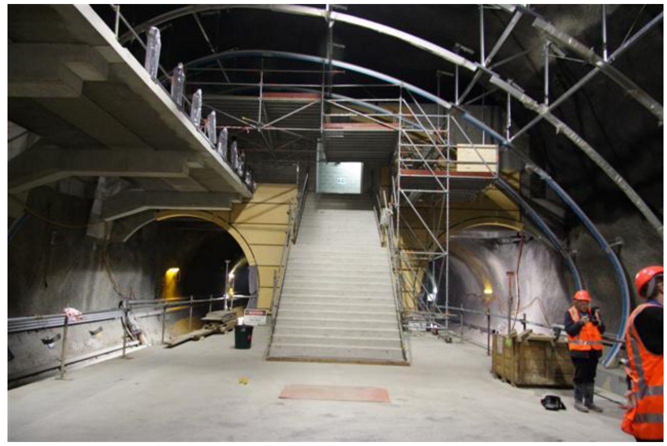

Figure 2: Using of NATM method for station construction

1. Geotechnical/geological investigations and tests are executed (on site and laboratory) for the identification of soil characteristics in the area where the tunnel has been planned to be bored. The design (calculations and drawings) of the excavation and the temporary retaining of the tunnel is under way based on the geotechnical characteristics of the soil, which resulted during the previous phase. Moreover, the design of the permanent (final) lining of the tunnel is prepared.

2. The excavation is executed using conventional mechanical means (road header, conventional excavator, etc) and sometimes the excavation front is directly retained at several phases, depending of the quality of the soil.

3. Upon completion of the excavation, which is gradually performed depending on the characteristics of the rocks and the project, there is a system of temporary retaining consisting of shotcrete lining, rockbolts, steel frames etc. In case of soil with poor characteristics, prior to the excavation, forepoling beams are installed in the entire area over the tunnel crown in the form of an umbrella providing protection to the excavation front. Frequently, excavation is performed in two phases, the upper semi-section (vault) and the lower semi-section (invert). Depending on the subsoil and the geometry of the tunnel the excavation can be performed in more than one phases. The time of installation of the initial retaining, as well as the completion of the full ring of the lining are important for the monitoring of deformations. The system of direct support, along with the soil surrounding the tunnel constitutes the bearing structure of the tunnel at this phase. Ground water systematic pumping should be performed during the construction.

4. Throughout the construction, the behavior of the subsoil and the temporary retaining are monitored on a systematic basis, i.e. the settlements at the soil surface and the adjacent buildings any convergence within the tunnel, the increase/decrease of ground water level, etc are measured. Safety of the buildings located adjacent to or over the alignment of the tunnel is a particularly crucial issue and it is

addressed via continuous monitoring by means of the appropriate instruments. The results of the measurements should be compared with the assumptions and the results of the design and, if needed, the necessary modifications to the support system and the time sequence of works are made. In addition, these data are used for the identification and/or the checking of the assumptions of the design of the permanent lining of the tunnel.

5. The final (permanent) lining of the tunnel is constructed when the system of the initial support has reached conditions of balance. The permanent lining provides increased safety as to the project lifetime creates a unified interior surface and improves its water tightness. The permanent tunnel lining is made of in situ cast reinforced concrete. Special segment metal forms, usually self-supporting. Figure 3 depicts some view of NATM construction method.

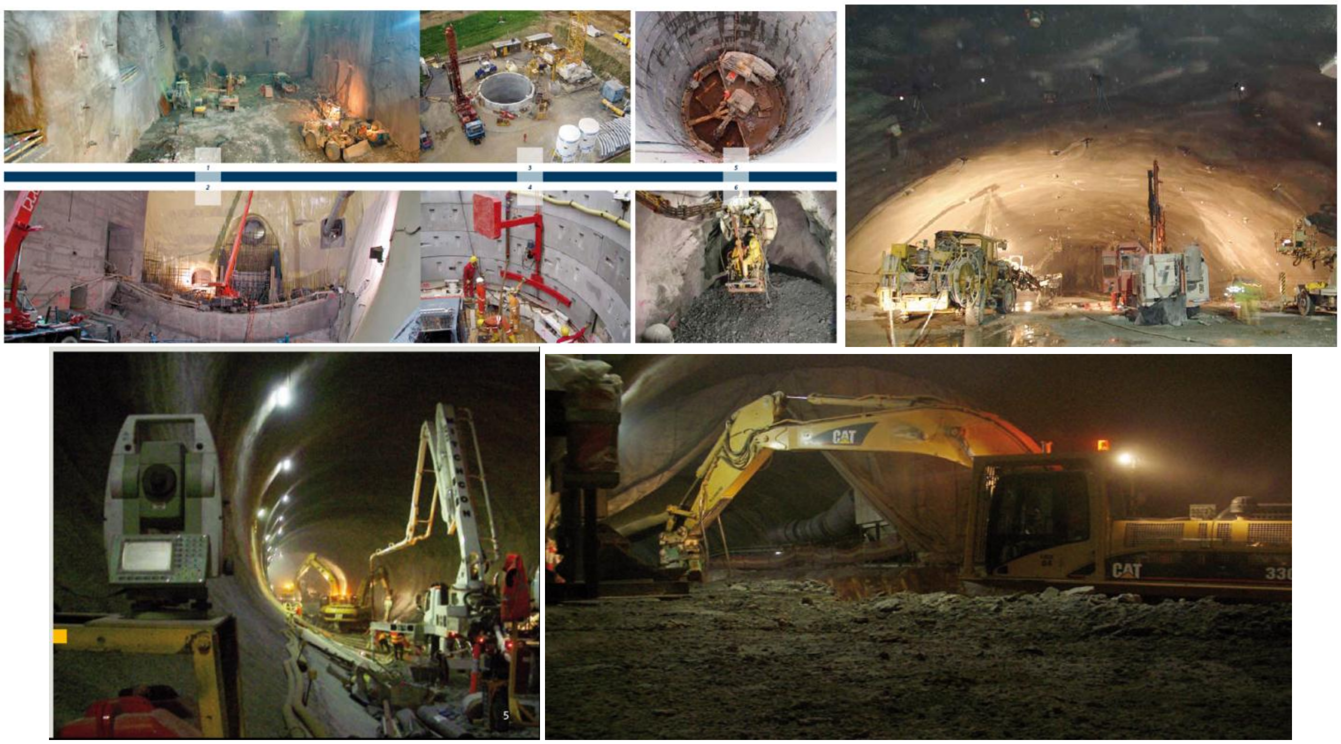

Figure 3: Some view of NATM construction method


Fig. 4: Cut and cover construction method

4. 2. Construction of Stations using the CUT & COVER Method

Despite the fact that the underground tunnel boring methods, are preferably used in central areas of the city, as moving away from these areas, the cut & cover method is replaced (Fig. 4). This method is also used in case there is enough space available. This happens because the cut & cover method is more economic, simple and safe.

The disadvantages of the method are as follows:

a) all PUO pipes located in the area where excavation works

are to be executed should be removed,
b) an archaeological investigation should proceed in order to identify any antiquities, especially in ancient cities, and
c) all required traffic diversions are affected.
Although the method is simply called "open cut", in fact it is a "cut & cover" method, since the structures upon their completion are backfilled.

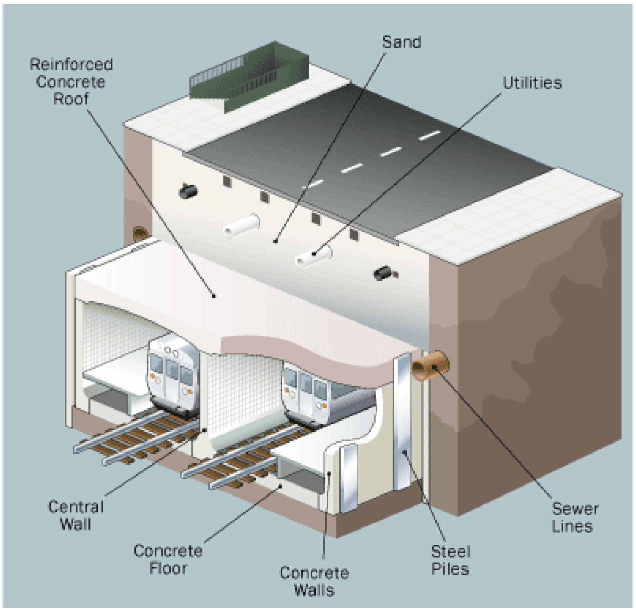

Fig. 5: In a cut-and-cover excavation, crews dig a trench and cover it with a temporary or permanent road surface.

Construction methodology

The cut & cover is simple in nature. First of all, a trench is excavated with vertical slopes. In the second step, a permanent bearing structure starting from the foundation upwards is built. Finally, the structure is backfilled up to the surface ground to initial position. The steps of the method are as follows:

1. A geotechnical/geological investigation and tests (on site and laboratory ones) are executed in view of identifying the soil characteristics in the area where our structure is to be constructed.
2. A design is prepared (calculations and drawings) related to the excavation and the temporary retaining, based on the geotechnical characteristics of the soil which resulted from the previous stage. Moreover, the design of the permanent bearing structure is carried out.
3. Prior to the commencement of the main works, the required archaeological excavations are carried out, all the PUO pipes (related to water supply, power supply, telephone connection etc.) and the eventual traffic diversions are executed.
4. The temporary retaining of the excavation usually consists of circular concreting piles, whose diameter is in the order of 0.80 – 1.00 m., spaced at 1.50-2.50m along the perimeter of the anticipated excavation. The pile row is connected at its pile cap by means of a strong concreting beam. The excavation is carried out using conventional mechanical means (excavators, hammers etc.) up to a fixed depth (e.g. 3.5m) and then anchors are placed at holes. These anchors are long enough (in the order of 15-25m) and are pre-stressed. Wire mesh is also applied along the perimeter of the trench thereafter shotcrete is performed. Subsequently, the excavation continues up to the next level and again some additional pre-stressed anchors are placed. This cycle continues up to the final level of the excavation. In case of water flowing in the trench wall, systematic drainage holes should be executed at a depth of 3-4m on the retaining structure/excavation.
5. The water proofing system of the structure, usually, is placed at the invert and at the peripheral surfaces at the perimeter of the trench and it consists of geotextile, waterproofing membrane and water stops.
6. The construction of the bearing structure is carried out in phases starting from the foundation, and then follows the walls, the roof slab in case of a underground station. As to the stations, the construction of intermediate flat slabs and walls. The construction commences with the installation of the steel reinforcement of the foundation slab (or general lean concrete slab), as provided for by the design. Subsequently, class C25/30 concrete is injected, in phases along the entire length of the construction with the provision of appropriate joints. The construction of the remaining elements of the permanent structure is made in a similar way. Figure 6 illustrate construction phases in cut and cover method.

4. 3. Construction of the Stations using the COVER & CUT Method

The Cover & Cut method (or "top-down" method) is contrary to the cut & cover method. The phases of these construction methods are as follows:

1. the vertical retaining panels (piles, diaphragm walls, etc.) along the perimeter of the excavation are excavated from the surface,
2. An excavation is initially carried out up to the level of the roof slab of the structure. Depending on the excavation depth, a light retaining of the slopes may be needed,
3. The roof slab on the excavation bottom is concreted. The slab is connected with the perimeter retaining ,
4. Backfilling is carried out over the slab and the surface of the soil is reinstated,
5. The excavation works for the station commence underneath the roof slab by means of a ramp which has been left for this purpose. The excavation is executed in successive phases, while the required retaining elements (e.g. anchors, struts) are installed gradually.

Upon completion of the excavation of the entire trench, operation related to the construction of permanent bearing structure elements is commenced. These elements usually consist in the foundation slabs and the lateral walls. In case diaphragm walls are used as a lateral retaining means, other permanent walls are not constructed. The advantage of this method is to reduce construction time. On the other hand, increasing costs and complicacy are the method disadvantages. Figure 7 illustrates construction phases in cover and cut method.

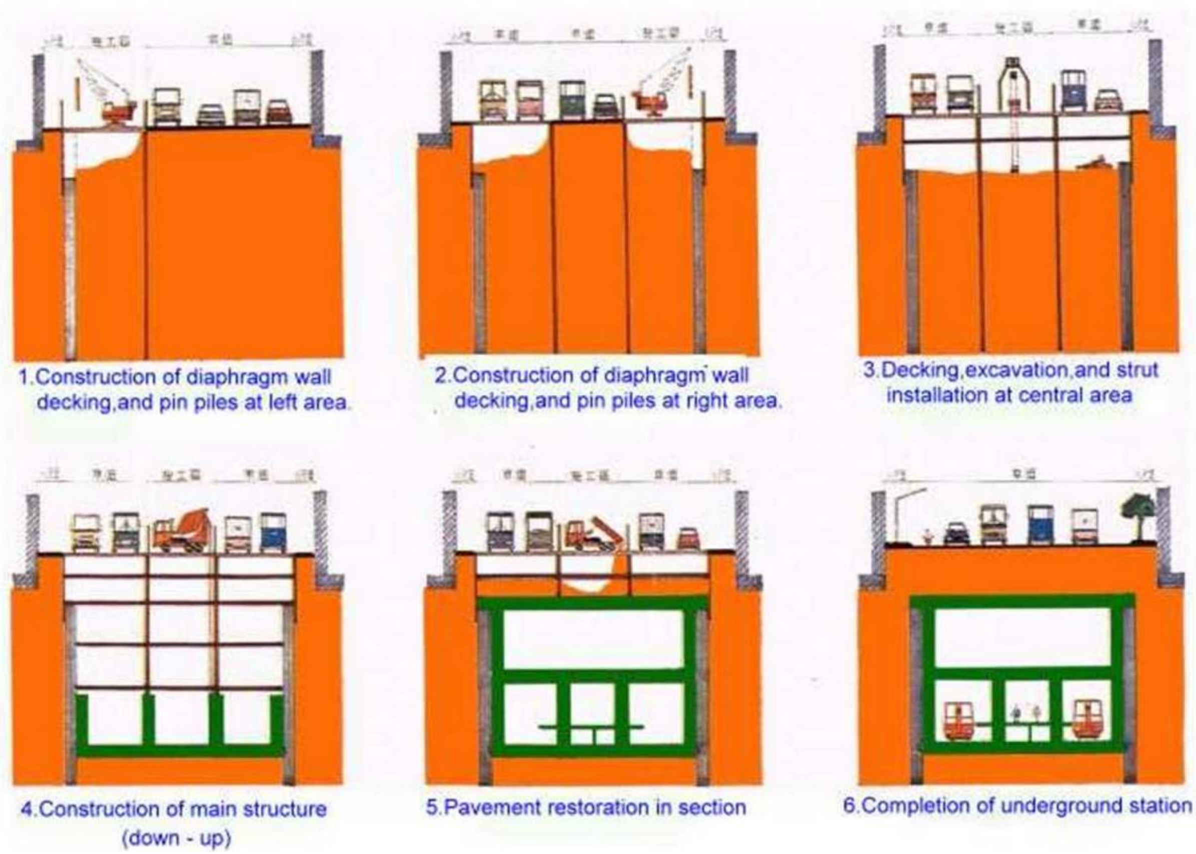

Figure 6: Illustration of construction phases in cut and cover method

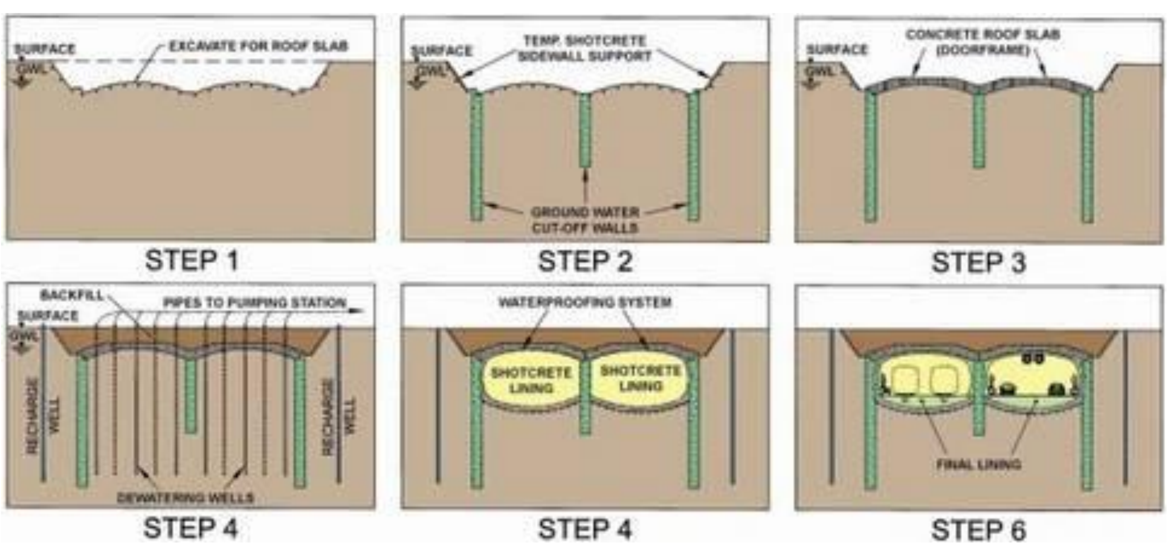

Figure 7: Illustration of construction phases in cover and cut method

5. CONSTRUCTION OF NATM UNDERGROUND STATION IN DIFFICULT CONDITIONS

The increasing population in metropolitan areas requires a concomitant upgrade of the infrastructure. The majority of the infrastructures are located subterranean congested urban areas. Due to the pre-existing structures on the surface, executing new projects is subjected to specific restrictions such as subsidence and/or noise limitations during construction. In urban areas, the ground generally consists of sedimentary soil and/or highly weathered rock masses. Both types of the grounds can be associated with major displacements during tunneling.

In these cases, the project limitations control the entire design process, as compliance with the design requirements may require time and cost intensive additional support systems including ground freezing, jet grouted columns or pipe jacking.

5. 1. Ground improvement

An alternative support system is the "Pipe Roof Umbrella" System, which is also referred to "Steel Pipe Umbrella" [2], "Umbrella Arch Method" [3], "Pipe Fore-Pole Umbrella" [4], "Long-Span Steel Pipe Fore-Piling" [5] or "Steel Pipe Canopy" [6]. Compared to this system the previously mentioned pre-support systems are stiffer but pipe roof systems are less time consuming and costly. These facts have led to increasing application of the pipe roof method.

A new pre-supporting system has been introduced for construction of large span metro underground stations in Iran.

5. 2. Some of underground metro station construction

1. Construction of NATM underground station tunnel by using the forepoling method in difficult conditions for Athens Metro.

This method was used in the Agios Savas underground complex which is a part of the new extension Line 3 of Athens' metro. The overburden thickness of the station's tunnel is approximately 18 m. The geological formation of the station tunnel consists of conglomerates and marl with small layers of sand and clay. The hydro- geological conditions are favorable for the project. The width of the top heading and bench is 20.2 m, the total height of the tunnel is 14.25 m (in the maximum enlargement), while the excavated height of the top heading exceeds 8 m (Fig. 8) [7].

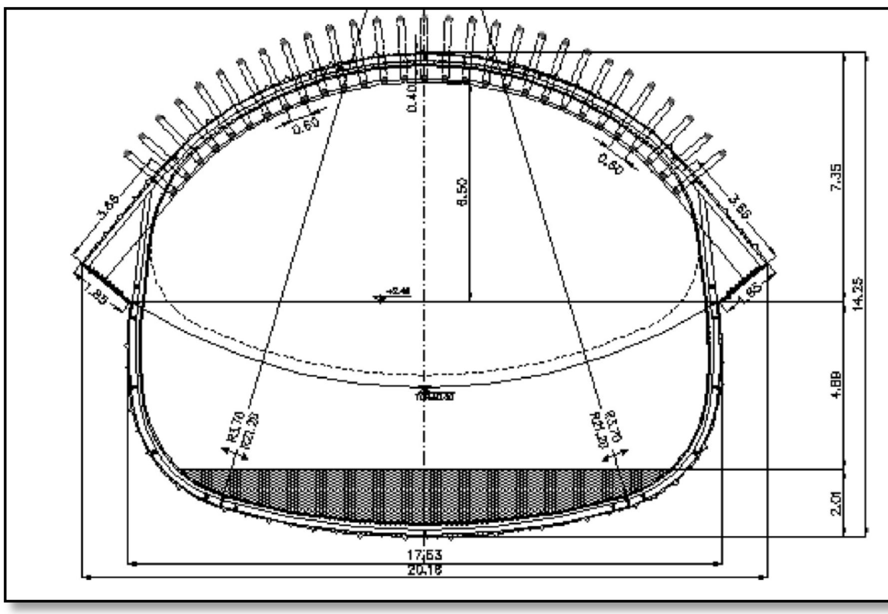

Figure 8: Excavation geometry of the typical cross section (maximum enlargement) [7]

The excavation and temporary support system is based on the following [7]:

- Top heading round length 1.00 m.
- Forepoling tubes St37, Φ193.7/179.5 mm, 12m length, placed at average axial distances of 0.60m per 6 round lengths of top heading.
- Shotcrete shell of 40 cm minimum structural thickness, C25/30. However, in the junction areas of temporary invert and elephant feet the structural thickness requirement increases for providing a better structural system with smooth geometrical corners and for avoiding stress concentrations.
- Steel sets placed at each round length, HEB 180, St37.
- Rock bolts of 6m length, S500, 25 mm in diameter, installed at a grid 1.00m × (each top heading round length) (cross × axial spacing) at the sidewalls of bench (except from the final and temporary invert) and pairs of rock bolts for steel sets secure.
- Reinforcement layers T188 mesh type, (external, intermediate and internal) are installed.
- Temporary invert with prefabricated steel reinforcement cages for faster installation and two layers of steel mesh T188 and shotcrete 35 cm thickness, C25/30.
- Reinforced final invert (with two steel meshes T188), shotcrete 40 cm minimum thickness C25/30.

Figure 9: Installation of the forepoling tubes at the top heading of the station tunnel [7].

Figure 10: Top heading excavation of the station tunnel. Installation of the HEB 180 steel arches [7].

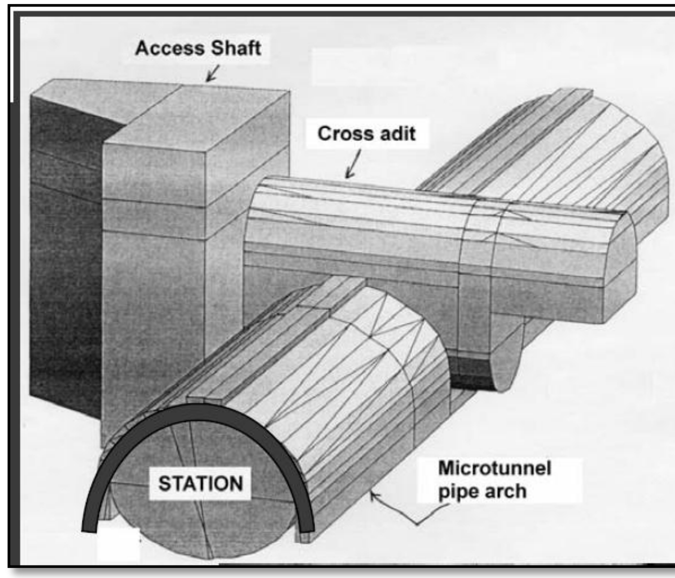

Figure 12: Sketch of Monastiraki Station, Athens Metro.

2. Construction of NATM underground station tunnel by using of pipe ramming method in difficult conditions for Athens Metro

Another method which was used in Athens Metro to improve the ground condition and to control the surface movement can optimize the cost and time of project. This method can also minimize the surface settlement. The diameter of pipe which ram in the ground in horizontal direction is about 1.2 m (figure 11). This method is also known as pipe ramming method which is able to ram high diameter pipe to maximum 120m. In this way, the pipes can be pushed in the ground approximately in all length of station.

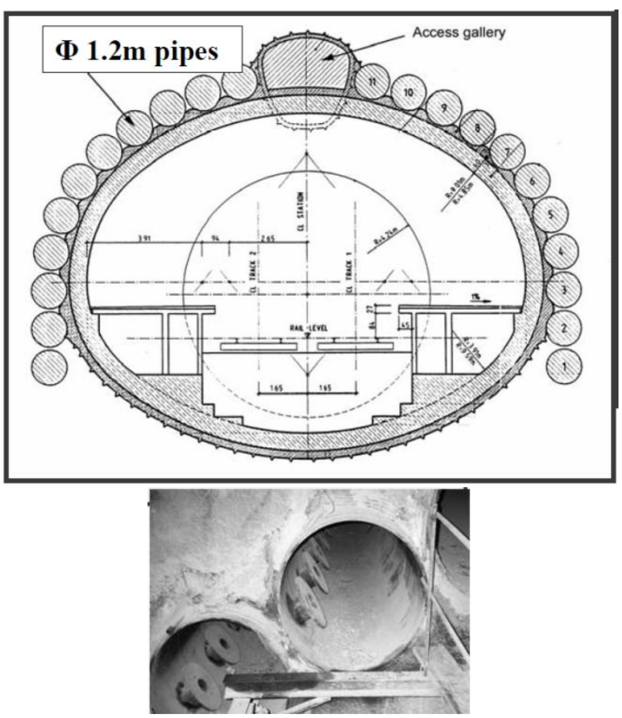

Figure 11: Athens Metro, Monastiraki Station (18m wide span), micro-tunnel pipe arch

3. Construction of NATM underground station tunnel by using of Concrete Arch Pre-supporting system (CAPS) in difficult conditions in Iran

Concrete Arch Pre-supporting System, CAPS is a rib shape ground pre-treatment system which can be used for increasing safety of large span underground constructions. This system is similar to Rib in Roc Pre-reinforcement System presented by Bengt and Stillborg (1979) [8]. This pre-supporting system has been applied in construction of Mt. Baker Tunnel in Seattle, USA, in which small horizontal tunnels were constructed prior to excavating of the main tunnel [9]. Construction method of CAPS is based on Iranian traditional water underground gallery so called "Kariz" which consists of wells and small semi-horizontal adits. CAPS consist of small vertical piles and arch beams in semi-horizontal and horizontal direction connected to galleries excavated manually around the large span underground station [10]. Figure 13 depicts the Rib-shape pre-supporting structure (CAPS).

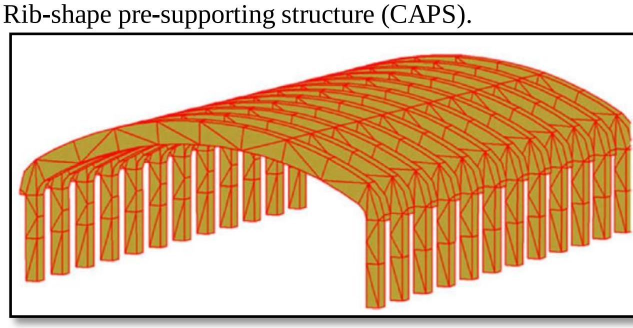

Figure 13: Rib-shape pre-supporting structure (CAPS) constructed prior to main excavation [10].

The aforesaid method suffers many technical disadvantages. The method is primitive with limited adaptation of technical automation and that is why workers are required for excavation with very rate of advancement. In this method also safety is unacceptable and there is no control over the quality of reinforcement concrete ribs.

6. CONCLUSION

Selection of the appropriate method of the excavation is a vital task in tunneling projects.

To minimize the risks building construction phase, a thorough site and laboratory investigation is required before commencing of any projects. In this investigation, different information such as geological, geotechnical, geo-hydrological and environmental aspects should be collected.

Monitoring of the deformation can be considered as an integrated part of tunneling projects.

Considering the fact that cross section of the metro stations is very large, application of the NATM is necessary especially in the poor geological ground conditions.

In very poor ground conditions, implementation of complimentary ground treatment measures such as grouting, fore-poling and pipe ramming should be considered while executing NATM.

In spite of being complicated in its implementation, cover and cut method is the right alternative for reducing construction time.

Cut and cover method can be replaced with underground boring method while moving away from congested area.

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