Chapter 12
Underground Space for Sustainable Urban Development: Experiences from Urban Underground Metro Constructions in India

T.G. Sitharam and S.D. Anitha Kumari

Abstract For thousands of years, underground has provided humans refuge, useful resources, physical support for surface structures, and a place for spiritual or artistic expression. More recently, many urban services have been placed underground. Over this time, humans have rarely considered how underground space can contribute to or be engineered to maximize its contribution to the sustainability of society. Tunneling works and other forms of underground construction have been taken up recently in India as part of urban mass transit operations. The experiences from the various underground metro constructions in India are consolidated along with the technologies used for the tunneling procedure. For this, case studies of the four underground metro constructions in India are presented. The different methods of tunneling and its procedure with their suitability in different situations are also looked into. From the stability point of view, tunneling can be a significant cause of settlement resulting in huge damages to surface structures in densely populated cities. This paper also focuses on the development of computational procedures including DEM and FEM to model the soil stresses and deformations that develop as a consequence of underground construction and underground space creation. Methods are being developed to access the risk of settlement-induced damage of these openings.

Keywords Sustainability • Tunnels • Tunneling methodology • Case studies • Numerical modeling • Seismic response

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12.1 Introduction

Thirty-two percent of Indian population is presently residing in its urban areas. This population is set to go higher and higher as rapid urbanization takes place and is expected to reach around 590 million by 2030. This has led to the fact that the urban infrastructure should be developed by keeping in mind the future growth of the existing cities. For any country to keep its pace of growth, adequate transport facilities are a must. The explosive growth of personal vehicles in the roads due to lack of efficient public transport systems has forced the governments to think about the introduction of alternate fast, affordable, safe, sustainable, and comfortable public transport modes. In this context, mass rapid transit system, MRTS, has significance as it reduces energy consumption and pollution, thus making it eco-friendly, provides more space occupancy, and above all is a cheap mode of transport. This has led to the introduction of metro rails, which are considered one of the most important modes of urban transport, in various cities in India. Even though the challenges associated with the metro rail at various stages starting from its planning to inception are considerably high, the long-term benefits associated with those rapid transit systems have forced the governments to implement them in ever-growing cities of India. Currently, the metro rails are operational in five cities, viz., Kolkata, New Delhi, Bangalore, Gurgaon, and Mumbai. Hyderabad Metro is also under construction, and it is in its testing stage, which is mainly over ground. Of these, Delhi Metro has the maximum operational length of 190.03 km with 48.06 km running underground. The timely execution and the huge operational success of Delhi Metro are a big boost to the metro systems in India. The expansion of the operational metro systems is under way. Four metro systems are under construction in Chennai, Hyderabad, Jaipur and Kochi. Around 11 cities have been identified for future metro systems in India.

Due to the fast growth of the cities, the amount of surface space available for the introduction of these metro systems at grade is less. Hence in congested urban cities, where space is scarce, the construction is either overground and/or underground. The underground systems help to reduce the cost and project completion time when the acquisition of land is nearly impossible or moving surface utilities which are expensive. Moreover, the harmful surface emissions from the vehicles can be avoided by collecting these within the underground and cleaning it thus making it eco-friendly and sustainable. In this paper, the urban underground metro construction in India with case studies of Delhi, Bangalore, Mumbai, and Kolkata is presented along with the different methods of tunneling adopted. As it is difficult to estimate the underground conditions and the behavior of these structures through experiments, numerical modeling has gained significance in analyzing the behavior of these structures. Hence, this paper also focuses on the development of computational procedures using DEM and FEM to model the soil stress deformations due to underground construction. The behavior of twin tunnels during seismic loading is also numerically modeled using FEM.

12.2 Methodology of Tunneling/Tunnel Construction

There are different tunnel construction methods adopted depending on the geological and hydrological conditions, cost and time considerations, limits of surface settlements/disturbance, and many other factors. Some of the common construction methods are:

(Ref: http://miningandblasting.wordpress.com/2011/07/27/tunnel-construction-methods-and-their-comparison/)

(a) Cut and cover tunneling
(b) Drill and blast technique
(c) Bored tunneling by TBM

12.2.1 Cut and Cover Tunneling

Cut and cover tunneling is generally preferred for shallow tunnels. This type of tunneling is done when excavation from the surface is possible economically. In this method, the tunnel is built inside the excavation, and once the structure is completed, the excavation is covered with backfill material. There are two methods adopted in cut and cover tunneling: (i) bottom-up construction and (ii) top-down construction.

In bottom-up construction, the tunnel is completed before it is covered up and the surface reinstated as shown in Fig. 12.1. The advantage of bottom-up construction is that the inside of the excavation is easily accessible for machinery and materials, and drainage systems can be installed outside the structure. However, it has the disadvantage that the surface cannot be reinstated to the final stage until the construction is completed. Moreover, temporary relocation of utilities is also required at times.

In top-down construction, the tunnel walls are constructed first and the final structural walls act as the excavation support. In case water is present, dewatering should be done. The first stage will be to excavate till the bottom of top slab of tunnel. Immediately after this, the roof is constructed and tied to the support of excavation walls. Once this is done, the top is backfilled and the ground is reinstated. The advantage here is that the obstruction on the surface can be minimized and can be opened to public use much before the complete construction. Figure 12.2 shows the various stages in top-down construction. This also has the advantage of reducing the total time taken for construction by overlapping various activities. However some disadvantages are also associated with this method. It provides limited space for the construction of the interior slabs. The accessibility to the tunnel will be limited unlike the bottom-up construction.

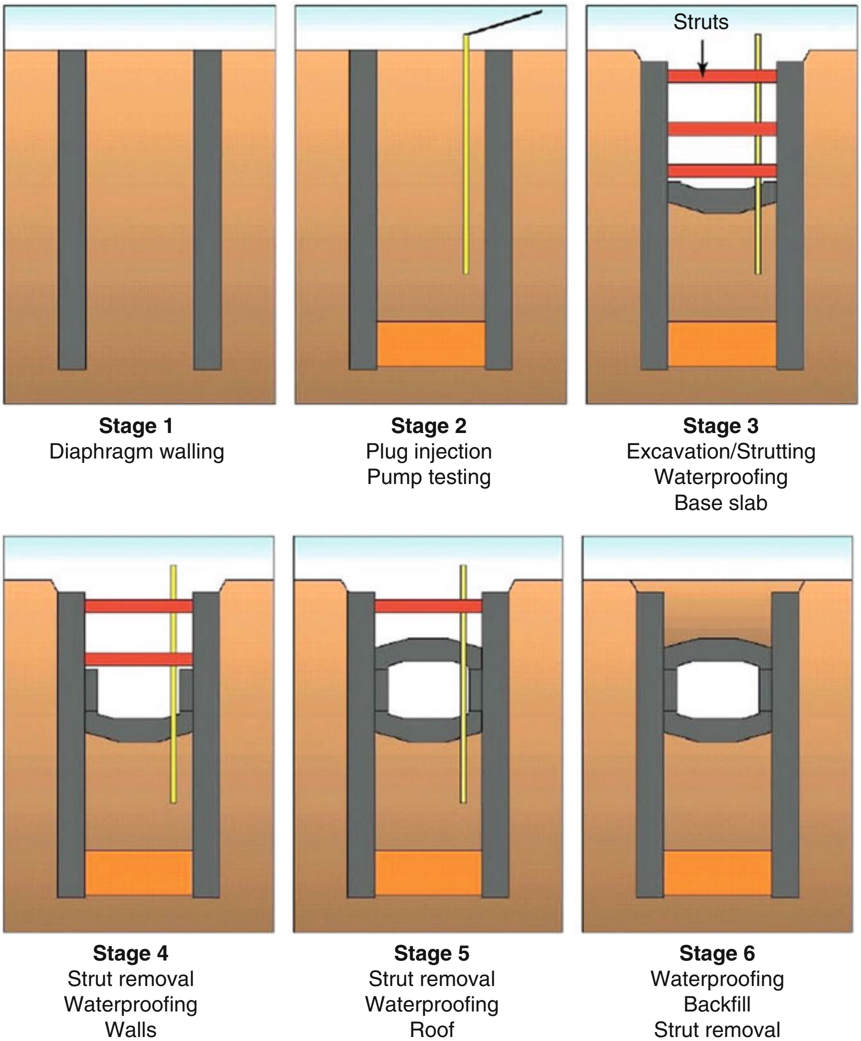


Fig. 12.1 Conventional bottom-up sequence of construction (Ref: http://www.scribd.com/doc/27950632/Tunnel-Construction)

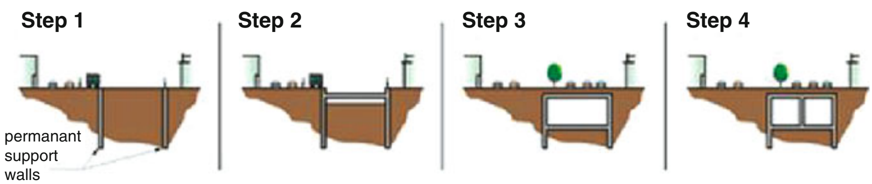


Fig. 12.2 Stages of top-down construction of tunnels (Ref: http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/05.cfm)

12.2.2 Drill and Blast Technique

In this method, explosives and detonators are placed on a large number of blast holes drilled at designated tunnel surfaces. The detonation of explosives results in the collapse of the rocks. The debris of each blasting is carried to the surface and the new tunnel surface is reinforced before further blasting. Generally drill and blast technique is preferred in areas where shorter tunnels in hard rocks are required. In order to obtain an approximately circular cross section, it is necessary to have controlled blasting by knowing the amount of explosives in properly positioned and drilled holes. In order to direct the energy from the explosives for a proper alignment, various factors like the geological condition of the rock bed, the spacing, size, depth, and angle of the drill hole have to be precisely determined. The construction sequence followed in drill and blast technique is shown in Fig. 12.3. Some of the major disadvantages associated with drill and blast technique are the safety risks like production of poisonous gases and high volumes of dust and noise pollution. Moreover, due to continuous blasting, there is possibility of weakening of rocks around the tunnel. This requires the provision of additional support in the form of rock bolting and shotcreting.

12.2.3 Bored Tunneling by Tunnel Boring Machine (TBM)

TBM is one of the most widely used methods of tunneling for excavating long tunnels. The cutter head mounted on the face of the TBM consists of a number of disk cutters. These cutters while rotated under high pressure chip the rock mass, thus helping to excavate them. In addition to excavation, TBM can also be used to remove the excavated material and install the reinforced concrete lining. The various stages in the tunnel excavation using TBM are shown in Fig. 12.4. While planning the tunnel excavation, the tunnel is divided into various sections. For each section, excavation is done for a launching shaft and retrieval shaft. The TBM is assembled in the launching shaft and the tunnel is excavated. When the excavation reaches its destination, the TBM is dismantled and retrieved through the retrieval shaft. In this case precast lining is provided as permanent tunnel walls immediately after excavation. There are three major types of TBM in use: (a) hard-rock TBM,

Fig. 12.3 Construction sequence of drill and blast technique (Ref: http://www.mtr-kwuntonglineextension.hk/en/construction/construction-methods.html)

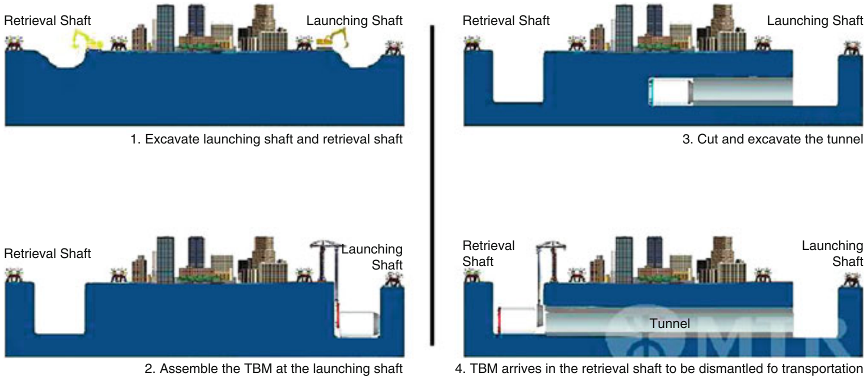


Fig. 12.4 Various stages of excavation using TBM (Ref: http://www.expressraillink.hk/en/construction/construction-methods.html)

(b) soft-ground TBM, and (c) mixed/hybrid TBM. The most important advantage with TBM is that it is suitable for almost all types of soils when the length of the tunnel is high at large depths. However, the handling of this sophisticated equipment requires highly skilled labor, and in case of any corrections required, this method is very expensive.

The above review of various tunneling methods indicates that each has its own advantages and disadvantages. However, the selection of a particular method of tunneling depends on the local geological condition, the length of the tunnel, the depth at which the tunnel is required, the presence of adjoining structures, etc. In the following sections, four different case studies of underground tunneling from different parts of India are presented. The details of each of the metro along with a brief description of the geological conditions of the area and the difficulties associated with the underground metro construction and its impact on the urban infrastructure are reviewed.

12.3 Case Studies

12.3.1 Bangalore Metro

The Bangalore Metro is divided into north-south and east-west corridors. Of the total 42.3 km of Phase 1, 8.8 km consists of twin tunnels with seven underground stations. There are two underground sections in each of these corridors spanning for a length of 4.0 km in north-south and 4.8 km in east-west. This underground section links the city center to the outer elevated sections of the network. The underground section consists of twin tunnels of 5.5 m diameter each with a distance of 5 m in between. The tunnels are at a depth of 12 m from the ground surface. Figure 12.5

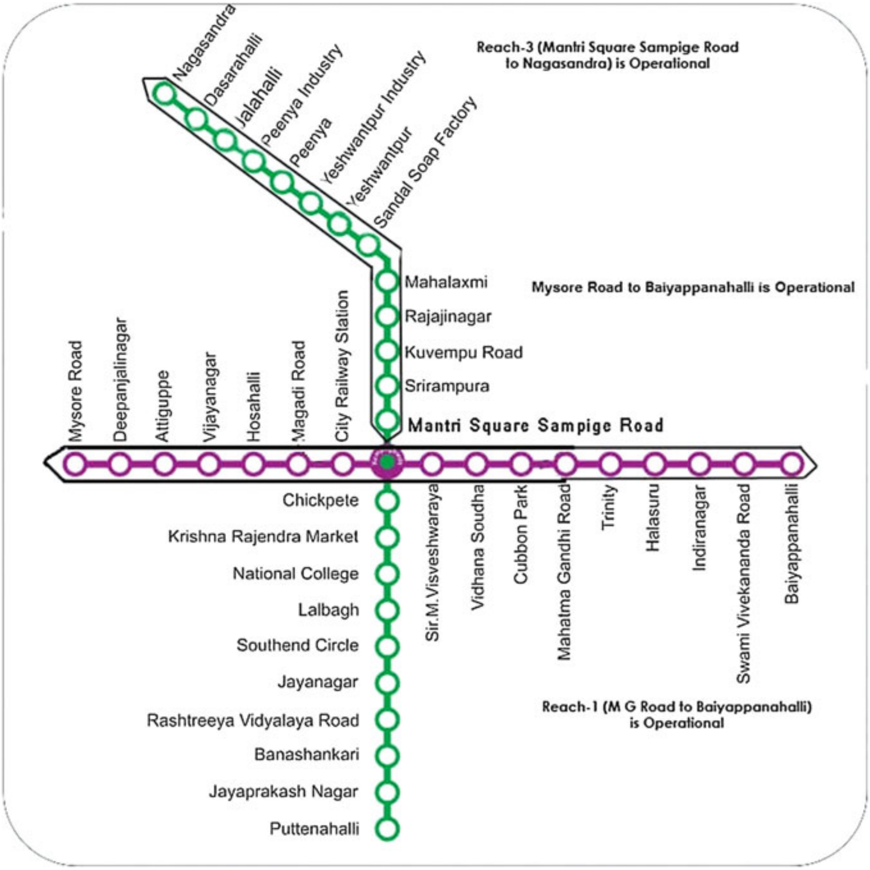


Fig. 12.5 Phase 1 alignment of Bangalore Metro (Ref: http://www.metrotraintimings.com/Bangalore/RouteMap.htm)

shows the Phase 1 alignment of Bangalore Metro. Currently, Reach-1 and Reach 3, 3A, are operational. Figure 12.6 shows the underground twin tunnel construction in Bangalore.

12.3.2 Details About Underground Tunnel/Tunneling Procedure

The geology of the metro project area covering different parts of Bangalore district consists of Precambrian granite and gneiss of which migmatite and gneiss are dominant. However, along the north-west direction across the western part of the district, zones of granite and granodiorite of 20 km width is also present. Small

Fig. 12.6 Underground twin tunnel TBM construction near Kalasipalyam, Bangalore. (**a**) North-south alignment, (**b**) east-west alignment

areas of charnockite are seen in the southwestern part and through the central part of the north-south direction small bodies of amphibolites, and schist is also observed. To know about the groundwater levels, data from exploratory wells through surveying and in situ measurements are done. Figure 12.7a and b illustrates the topography, groundwater level, depth to the bed rock, and the tunnel alignment for the north-south and east-west alignments, respectively. The depth to hard rock varies across the tunnel section in both the alignments which makes it extremely challenging as the tunnel will be passing through both the hard rock as well as fissured zones of saprolite. The north-south alignment in Fig. 12.7a indicates that large stretches of tunnel pass through the fissured zone as the thickness of this saprolite zone is more, thus making the hard bed rock deeper.

As pointed out earlier, the tunneling procedure and the tunnel types depend on the geological conditions of the site. The ground cover in the case of tunnels varies from 60 to 17 m and the underground alignment mostly follows the roads. The geology in the underground section is very challenging with three different layers of soil consisting of a very recently deposited fill as the top layer, which is followed by a layer of silts and sands with varying amounts of clay and gravel. Beneath this, fragmented weak to hard granitic gneiss type of rock is present. In addition to this varying geology, the water table varies from 2 m to 10 m belowground level which is significantly affected by the rainfall. The presence of major structures along the eastern alignment added with shallow depth of tunnels and mixed face conditions

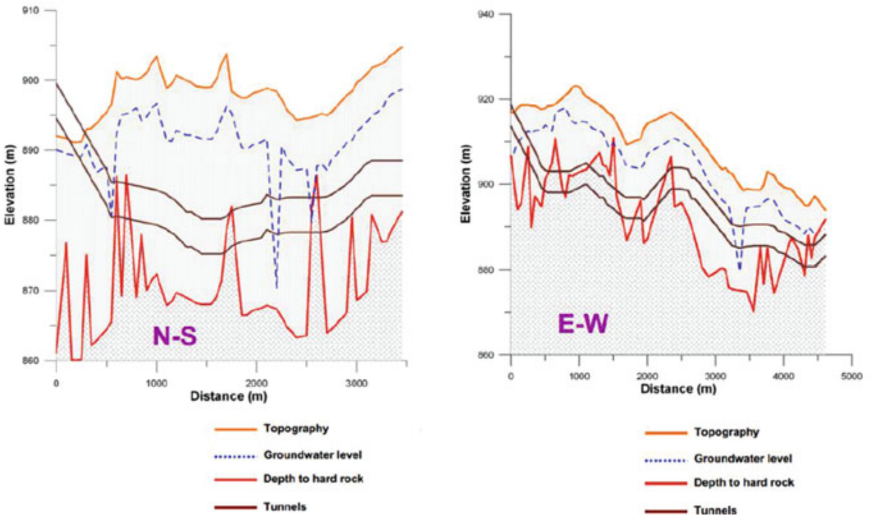


Fig. 12.7 Topography, groundwater level, depth to bed rock, and tunnel position for Bangalore Metro (Ref: http://bmrc.co.in/pdf/news/IISc-Report.pdf)

called for protection measures against subsidence over this section. Based on this, slurry TBMs are selected for tunneling so that the tunnel face will be supported during excavation, thereby minimizing the subsidence during the operation.

12.3.3 Delhi Metro

Delhi Metro is one of the most successfully constructed/operated metro systems in India which consists of four different lines covering a total length of 189.63 kms in Phase 1 and Phase 2 (Fig. 12.8). There are 143 stations, of which 38 underground stations are present in the 48 km of underground metro stretch, five stations are at-grade, and the remaining stations are elevated. Around 45 km of the planned Phase 3 is also underground. In the underground stretch, the stations are constructed by cut and cover method of tunneling. Depending on the geological condition, tunnels are excavated either by cut and cover method, New Austrian Tunneling Method (NATM), earth pressure balance, or slurry-type shield machine. For Phase 2, for the construction of 5.8 m tunnel diameter, DMRC used 14 tunnel boring machines. In this case the excavation diameter was 5.11 m with 14 m to 60 m overburden (http://www.delhimetrorail.com/projectsupdate/delhimasseia.pdf).

The average elevation of the city of Delhi is around 198 to 200 m above MSL. The level of ground water table varies from 20 m to 30 m at different parts of the city. It is observed that the groundwater level is falling at a rate of 3 m per year. Geological study of the subsurface along the Delhi Metro alignment indicates that the soil consists of fine-grained material like clay or silt with different amounts

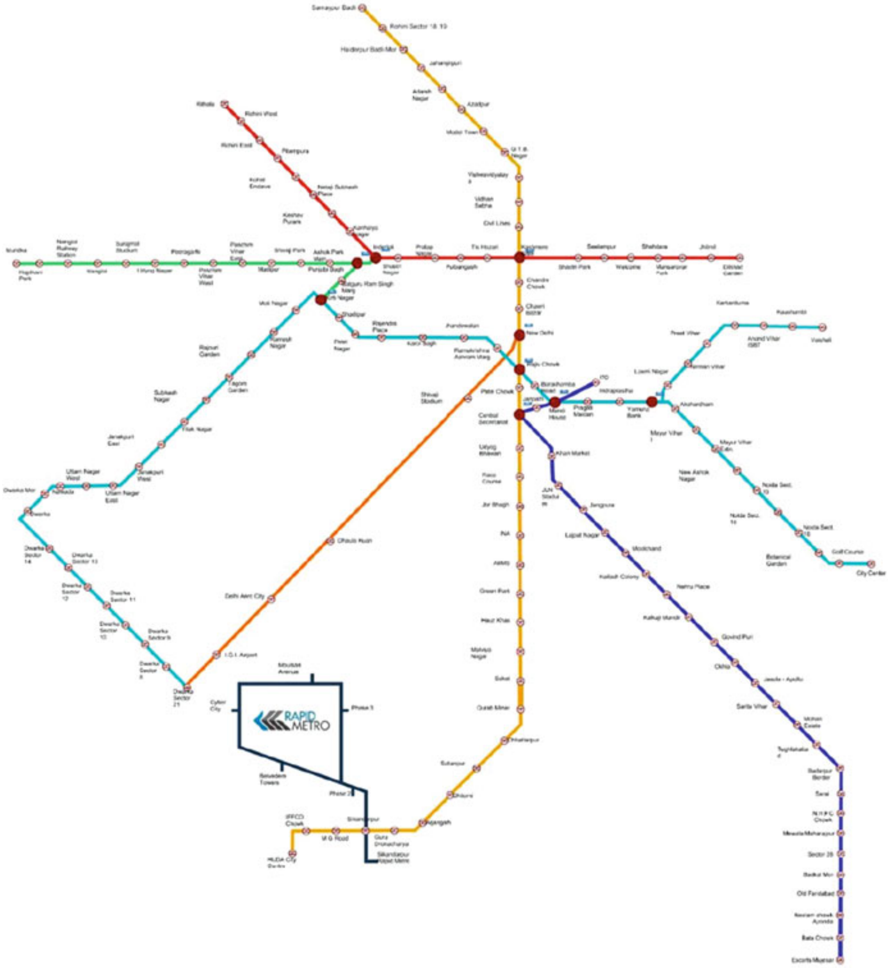


Fig. 12.8 Phase 1 and Phase 2 of the Delhi Metro map (Ref: http://www.delhimetrorail.com/route-map.aspx)

of fine sand content (http://www.delhimetrorail.com/eia%20report/Environment_Impact_Assessment_SECTOR%20_9_TO_IGI-AIRPORT_CORRIDOR.pdf). As there were huge variations in the groundwater level, the overburden was between 3.5 and 22 m. Based on the soil investigation carried out for the underground construction, cut and cover method and tunnel boring machines (TBMs) capable of excavating soft soils are adapted. Here, a minimum soil cover of 6 m is proposed for tunnels.

Phase 1 of Delhi Metro employed 3 TBMs, whereas during Phase 2, 14 TBMs were used to construct around 35 km of underground stretch. However, Phase 3 which is planned to pass under strategic locations including railway tracks,

Fig. 12.9 Tunnel boring machine which is assembled for a length of 96 m begins the tunneling work (Ref: http://www.delhimetrorail.com/whatnew_details.aspx?id=c4kJd1nWTgMlld)

high-rise building, flyovers, ring roads, and below-existing underground metro stretches will be using 34 TBMs to dig these underground strips. The TBM used for the Delhi Metro is specially designed to suit the needs of the project location. This is a 6.61 m diameter earth pressure balancing (EPB) shield. Around 3400 m can be bored by the combined effort of each of the TBM. Figure 12.9 shows an assembled underground TBM which is 96 m long used for tunneling work between Juma Masjid and Delhi Gate Metro stations.

12.3.4 Chennai Metro

Chennai Metro project is planned to create two corridors with a total length of 45.1 kms for the Phase 1 implementation. Corridor 1 is designed to have 23.1 kms of which 14.3 kms is underground and the remaining elevated. The total length of corridor 2 is 22 kms and a length of 9.7 kms is underground in this stretch. Figure 12.10 shows Phase 1 of Chennai Metro. The total length of the underground stations is 24 kms with 19 underground stations. The project involves the construction of 5.5 km of twin tunnels (Fig. 12.11) in one package and 3.1 km of twin tunnels in another package. The tunneling from Nehru Park to Egmore of Chennai Metro Rail which forms a distance of 948 m has been completed using TBM. The speed of operation of TBM depends on the soil conditions and the speed adopted is around 6–10 m/day as the soil is loose. Currently, the TBMs are able to make significant breakthrough for two different sections at Central Metro and Kilpauk Underground station. In the Central Metro underground tunneling, TBM retrieval method was the first of its kind in India. Here, just before the breakthrough, the shaft was filled with bentonite and water till the level of the track slab. The twin tube

Fig. 12.10 Chennai Metro Rail project Phase 1 (Ref: http://chennaimetrorail.gov.in/)

tunneling is performed using five TBMs. The four TBMs in use are EPB shield with 6.6 m diameter. Figure 12.12 shows the tunnel boring machine.

For the project, geotechnical investigations are done using data from 75 boreholes. The data indicates that the project area is composed of granites, gneisses, and sedimentary formations like shale and sandstone with or without fossiliferous beds of various ages. In some places, doleritic dikes are also found which are covered with younger alluvium of thickness varying from 3.0 to 30.0 m. Thus, the ground

Fig. 12.11 Twin tunneling work at Washermanpet, Chennai Metro (Ref: http://www.masterbuilder.co.in/the-tunneling-heroes-of-indian-metros/)

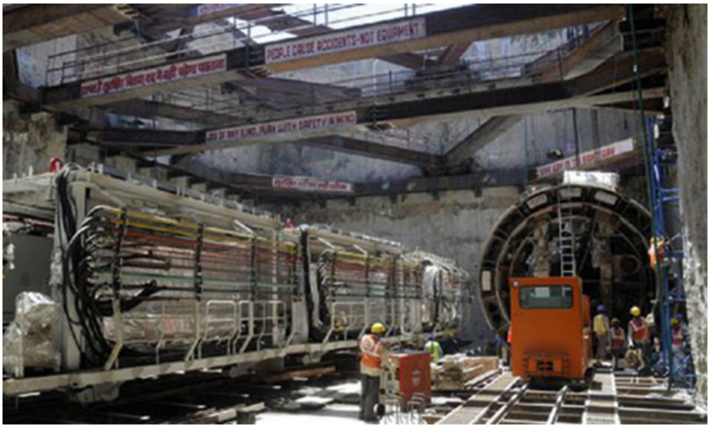


Fig. 12.12 Tunnel boring machine (TBM) (Ref:http://www.thehindu.com/news/cities/chennai/life-of-a-metro-the-first-look-underground/article3502044.ece)

formed by granite, sand, silt, and clay with 300 mm diameter boulders is excavated using EPB. This EPB has a mixed ground cutterhead and specialized small grippers located around the machine's shield. These grippers will hold the cutterhead firmly in harder ground and provide necessary forces to pull the cutterhead back from the tunnel face. In addition to this, for a distance of 3.9 kms stretching from Saidapet ramp area to Gemini station, two Herrenknecht-shielded TBM will be used for boring twin tunnels. The cutterhead diameter of this TBM is 6.63 m and the length is around 80 m.

12.3.5 Kolkata Metro

Kolkata Metro is the first metro system constructed in India. Kolkata is situated on the banks of Hooghly River, and the geology is formed by the Ganga-Brahmaputra river system. Initially, the development of Kolkata city was in the north-south direction for a length of 50 km along the east bank of Hooghly River. This city rests over large thickness of fluvial-marine sediments which forms the pericratonic tertiary basin. This basin has three structural units, viz., westernmost shelf or platform, the Central hinge or shelf/slope break, and deep basinal part in the east and southeast (Diptendra and Chattopadhyay 2009). The water table level in this area is very shallow and may touch the ground level during monsoons. The subsoil exploration done during the construction of north-south line indicated erratic deposition of materials, different thickness of layers, and the presence of bedding planes. Due to this along the metro alignments, soil exploration up to a depth of greater than 30 m from ground level is done.

Three north-south corridors of total length 97.5 km was identified as early as 1971 for Kolkata Metro. This is the first underground railway built in the history of India. Trains first started running in October 1984, and by September 1995, the full stretch that had been initially planned was completed and operational. Currently, the network has one operational line (Line 1) and one under construction (Line 2), with four further lines in various stages of planning. Being the country's first metro, the 17 km stretch of the underground tunnel in the north-south metro took 23 years for the construction. The entire underground part is constructed using cut and cover methodology. Currently the east-west corridor is being built which acts as a second metro for the city. Figure 12.13 shows the route map of the existing metro and the planned east-west corridor of metro. This corridor consists of a total of 14.67 km with 8.9 km underground and 5.77 km elevated. Around 520 m length of this underground tunnel is passing 30 m below Hooghly River as an underwater metro line (Fig. 12.14). Earth pressure balance TBM which is capable of boring up to 35 m per day is used for the construction of the tunnels in this corridor. However, till the first breakthrough, the TBM is used to bore up to 15 m per day. During the initial tunneling process, the presence of stiff clay made the process extremely difficult. All the stations are constructed using cut and cover technology. This TBM consists of a cutterhead which is a rotating cutting wheel, a main bearing, and a thrust system. The diameter of this machine is 6.5 m and it is 120 m long. This TBM can also be used to install the concrete channels which are prefabricated. TBM is the most preferred method of underground tunneling as it causes minimum disturbance to the existing structures and traffic.

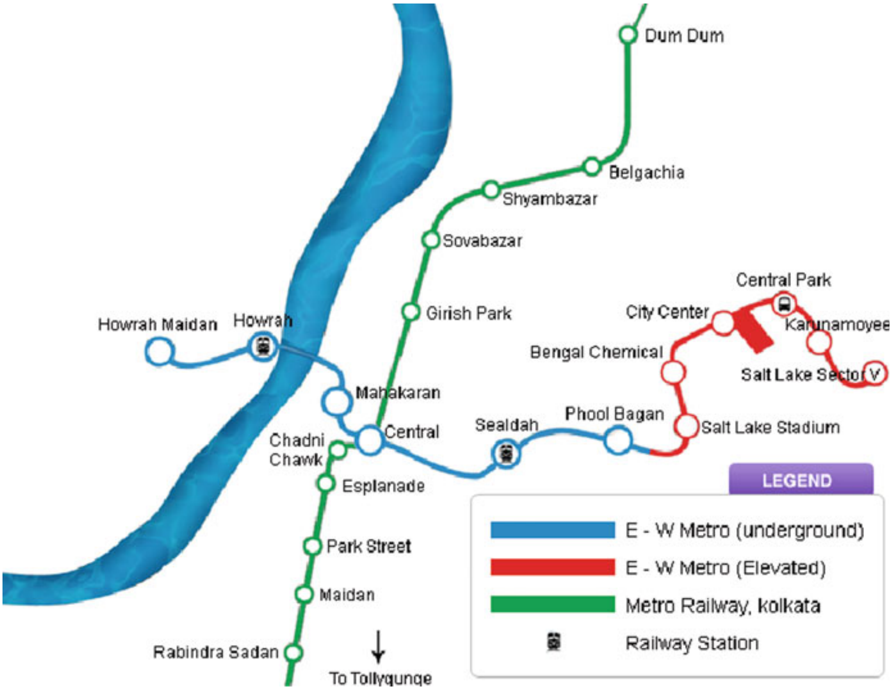


Fig. 12.13 Kolkata Metro

12.4 Numerical Modeling

Having reviewed the history of various metro systems in operation and under construction in India, it is necessary to understand the behavior of the underground soil/rock during and after the construction processes. However, experimental/field monitoring of the processes is time consuming, difficult, and impractical in certain cases which underline the necessity for numerical modeling of the process. Some of works reported on the numerical modeling of underground sections include Coulthard (1999), Ng et al. (2004), Anitha et al. (2012), Anitha and Sitharam (2014), etc. In the following sections, a comprehensive note of the numerical simulations of the tunnel stability using two different numerical methods, viz., discrete element method and finite element method, is presented.

12.4.1 Discrete Element Method

The inherent discrete nature of the soil/rock particles results in transferring of forces through the contacts between the particles. DEM is an explicit finite difference

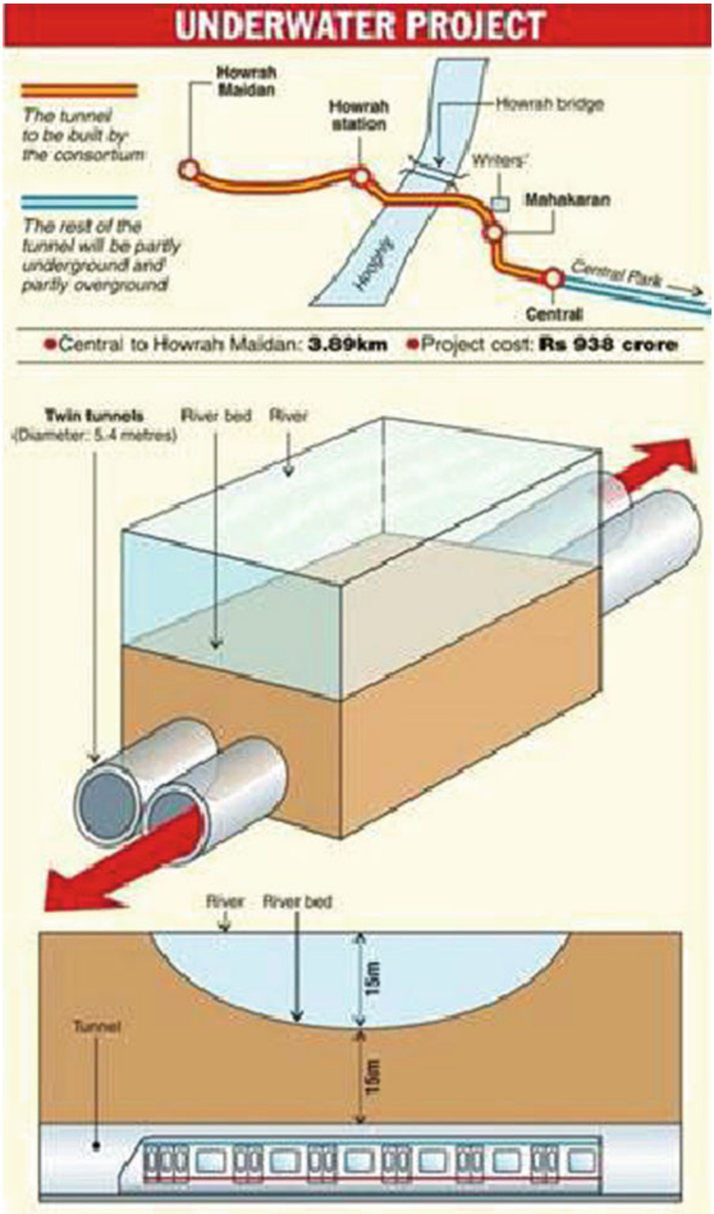


Fig. 12.14 Underwater metro line (Ref: http://www.kmrc.in/route_map.php; http://www.skyscrapercity.com/showthread.php?t=1603028&page=8)

method wherein the interaction of the particles is monitored contact by contact and the motion of the particles modeled particle by particle (Cundall 1971). In discrete element method, the assembly is modeled as a conglomeration of particles which are discrete in nature and interact only through the contacts. In order to model the weak rocks, which are bound by cementing materials, contact bonds are employed. This idea is based on the bonded particle model suggested by Potyondy and Cundall (2004) wherein the rock mass is represented as a dense packing of circular or spherical particles which are bonded together at their contact points. These contact bonds are breakable in nature, and the macro behavior of the rock mass as a whole depends on the strength of these bonds. The excavation of the underground structure in spite of its depth disturbs the soil and rock masses. This results in the settlement of the ground surface which affects the safety of the existing buildings. Due to several practical reasons and site conditions, tunnels are excavated on soft to hard soils/weak rocks at shallow depths. In order to understand the stability of tunnels constructed in a soft ground, simulations are done on an unlined tunnel and tunnel with lining.

12.4.2 Modeling the Assembly Using DEM

A weathered rock assembly having a dimension of 25 m × 10 m × 25 m shown in Fig. 12.15 is modeled for the study. PFC^{3D} (2008) is used for the numerical simulation of the model. The model constitutes 50,000 spherical particles. Table 12.1 shows the properties used for the simulation of the assembly. Once the particles are allowed to settle under gravity, a confining stress of 0.8 MPa which corresponds to the overburden pressure is applied to the sample. To introduce the bonding between the particles forming the rock mass, contact bonds are installed. In this assembly, at a depth of 18 m from the ground surface, a tunnel of radius 3 m is

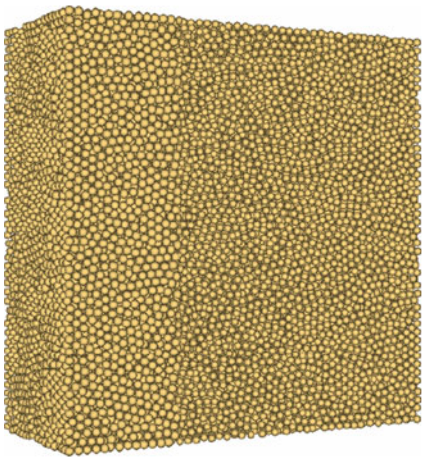


Fig. 12.15 Sample (25 m × 10 m × 25 m)

Table 12.1 Properties of particles used for the simulation of the assembly

Property	Value
Normal stiffness of particles	100 MN/m
Shear stiffness of particles	100 MN/m
Wall stiffness	1000 MN/m
Density of particles	2600 kg/m^3
Normal contact bond strength	20 kN
Shear contact bond strength	20 kN
Porosity	0.4
Number of particles	50,000
Interparticle friction	0.45
Particle size	0.075–0.1 m

excavated. The effect of excavation of the tunnel on the contact force and stress variation is studied for a tunnel unlined/without any support and for a tunnel which is lined.

12.4.3 Finite Element Method

Finite element method is widely used in rock mechanics applications and can be applied to a large spectrum of soil/rock mechanics problems. In finite element method, the assembly is modeled as a continuum consisting of elements which are connected at discrete points called nodes. In two-dimensional analysis, the assembly is discretized into triangle or quadrilateral shapes, and all the forces are transmitted through nodes. The analysis of the problem is basically done in terms of these nodal forces and nodal displacements. The FEM analysis is performed using the commercial software PLAXIS.

12.4.4 Modeling the Assembly Using FEM

A 25 m wide and 32 m deep assembly is modeled. At a depth of 18 m from the ground surface, a 3 m radius tunnel is excavated. After defining the geometry, it is divided into 15 noded triangular elements as shown in Fig. 12.16, and the properties used for the model material and the lining are shown in Table 12.2. Mohr-Coulomb elastoplastic constitutive model is adopted for this study (Plaxis User Manual 2009). Since the ground surface is horizontal, K_0 procedure is followed and gravity loading is applied to the assembly. Following this, loading phase is initiated.

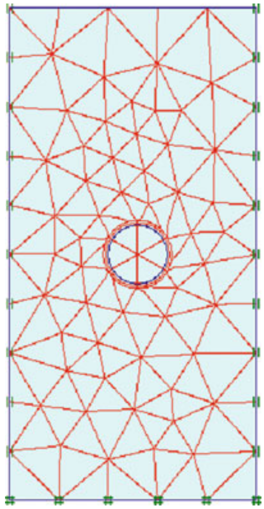


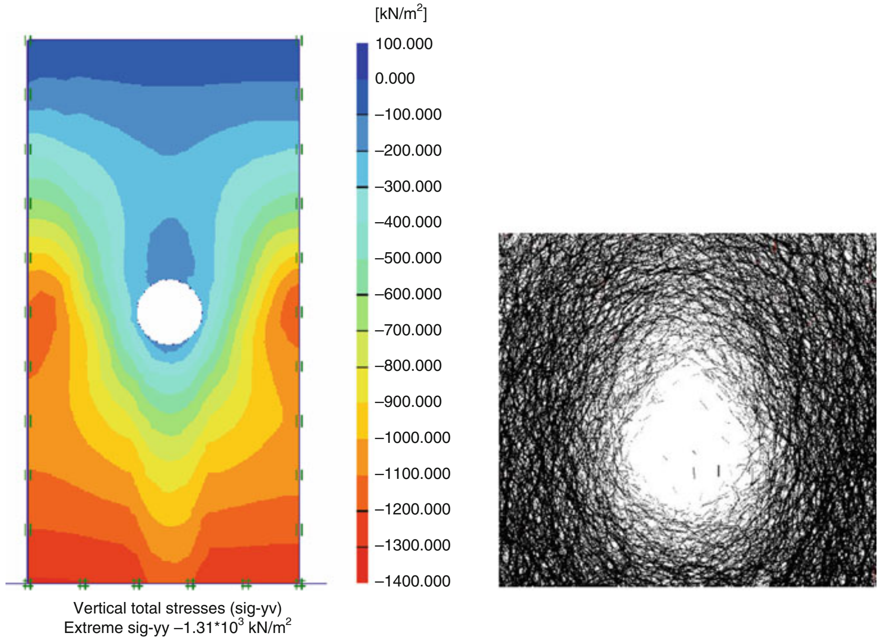
Fig. 12.16 Discretized model

Table 12.2 Properties used for the weak rock material

Model	Mohr-Coulomb
Behavior	Drained
Unit weight	26.5 kN/m^3
Young's modulus	5e6 kN/m^2
Poisson's ratio	0.2
Cohesion	20 kN/m^2
Angle of internal friction	24
Behavior of lining	Elastic
Lining stiffness , EA	1.4e7 kN/m
Lining flexural rigidity, EI	1.43e5 kNm
Lining thickness	0.35 m
Weight/m length	8.4 kN/m/m

12.4.5 Distribution of Contact Forces/Stresses for Unlined and Lined Tunnels

Figure 12.17a and b shows the stress variation and contact force variation around the unlined tunnel modeled using FEM and DEM, respectively. The vertical stress near the crown of the tunnel is very low for the unlined tunnel. However, the tunnel failure is progressing uniformly in all directions around the tunnel as observed from the DEM analysis. The thickness of the lines in Fig. 12.17b indicates the magnitude of the contact force. It is observed that there is significant reduction in the contact force in the area surrounding the tunnel leading to the ultimate failure of the unlined tunnel system. The collapse of the tunnel is progressing from all sides, more being

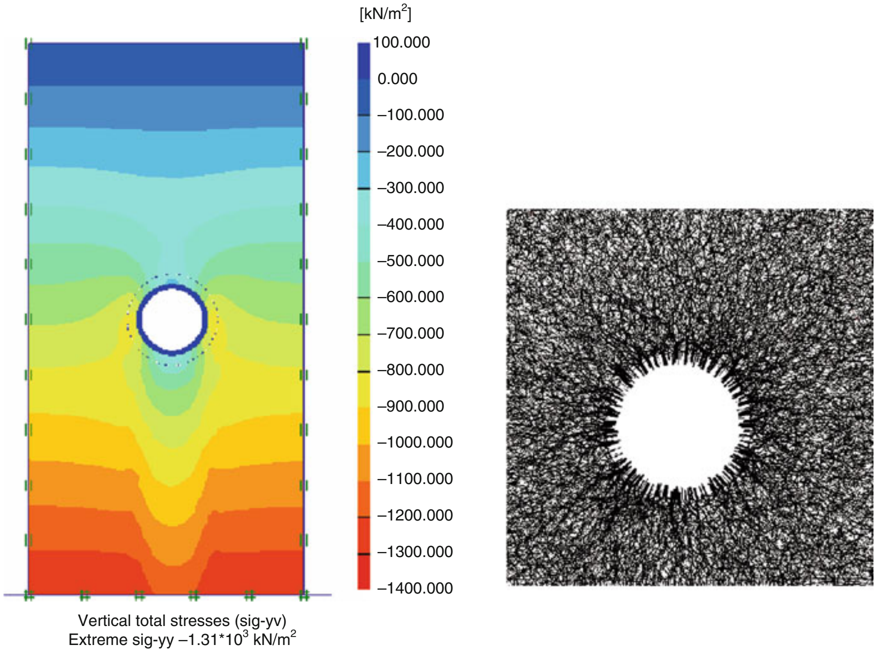


(a) Vertical stress - FEM **(b) Contact forces – DEM**

Fig. 12.17 Stress and force distribution – FEM and DEM analysis, unlined tunnel. (**a**) Vertical stress – FEM. (**b**) Contact forces – DEM

from the top. The analysis results indicate that the unlined tunnel system has completely collapsed immediately. The FEM analysis results also show trends similar to the discrete element simulations; the deformations are very high near the crown of the tunnel indicating a complete collapse of the system. The stress contours along the depth of the considered section points to the stress distribution due to the excavation.

The variation of the stress and contact force for the lined system is shown in Fig. 12.18a and b. For the lined tunnel, the distribution of stresses around the tunnel is uniform which results from the confinement provided by the lining thereby restricting the movement of particles. The stress contours and the contact force distribution around the tunnel opening indicate how the system has stabilized through the introduction of lining even though there is a reduction in the overall contact force and some collapse of the assembly. The arching action provided by the ground due to the confinement introduced by the lining increases the overall stability of the system. Thus the studies helped to identify the requirement of a lining and how the stress or displacement varies over the tunnel crown. Another point worth mentioning is the suitability of both the methods for analyzing the underground structures. However, depending on the surface conditions and the



(a) Vertical stress - FEM **(b) Contact forces – DEM**

Fig. 12.18 Stress and force distribution – FEM and DEM analysis, lined tunnel. (**a**) Vertical stress – FEM. (**b**) Contact forces – DEM

presence of more fissures or discontinuum, suitable method has to be selected for the precise modeling of the stress and displacement around the underground openings.

12.4.6 FEM Simulations of Seismic Response of Twin Tunnels

As seen in various case studies, twin tunnels are being constructed in different underground metros. As these tunnels are passing through heavily crowded and congested urban city centers, it is very important to investigate the seismic response of such structures. Even though it was thought that the underground structures are immune to earthquake structures, recent earthquakes have devastated underground structures thereby emphasizing the requirement of seismic analysis of underground tunnels. Hence in the following section, the behavior of twin tunnels under seismic loading is presented.

Tunnels of 4 m radius which are aligned horizontally are simulated using FEM (Fig. 12.19). The crown of the tunnel is at a depth of 8 m from the ground surface,

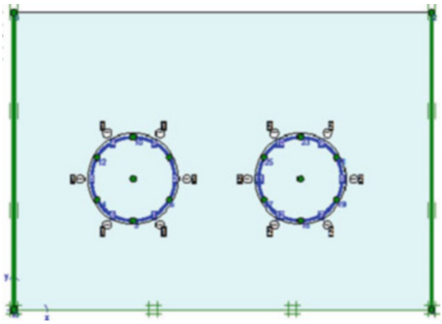


Fig. 12.19 Horizontally aligned circular twin tunnels

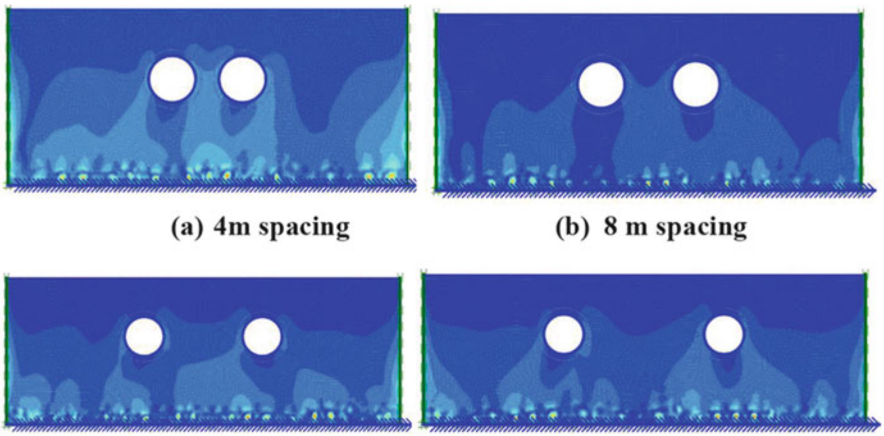


Fig. 12.20 Variation of vertical stresses at different tunnel spacing. (**a**) 4 m spacing. (**b**) 8 m spacing. (**c**) 16 m spacing. (**d**) 24 m spacing

whereas the bottom boundary is at a clear distance of 14 m from the base of the tunnel. A clear distance of 24 m is provided on the sides to avoid the boundary effects. The earthquake effect is studied by applying a loading obtained from the strong motion data of USGS (2011) which is having a peak horizontal acceleration value of 0.2 g. This acceleration is applied to the bottom of the model, and the effect of this loading is studied by varying the spacing between the tunnels. Figure 12.20a–d shows the vertical stress distribution around the tunnels when the tunnel spacing is varied from 4 m to 24 m. When the spacing between the tunnel increases, the stress overlap decreases leading to a more stable configuration. The stress distribution around the tunnels becomes more uniform as the spacing between them increases. However for closely spaced tunnels, nonuniform stress distribution is observed which can be attributed to the stress interference from both the tunnels. It is also observed that when the tunnels are spaced closely, both the tunnels and the rock mass in between them acted as a single body, whereas as spacing increases, they act as independent entities. It was also found that, on an average, the horizontal displacement was around 10 to 15 times that of the vertical displacement.

12.5 Conclusions

The paper consolidates the various details and experiences from the completed and ongoing metro constructions in India with emphasis on the underground engineering for sustainable development. Underground tunnels for the metros are constructed in subsurface whose properties vary from soft clay to hard rocks. The underground part of the Kolkata Metro Rail which is the oldest metro system in India was completely done using cut and cover methodology. The challenges faced during the construction and implementation of this metro paved the way for the successful planning, construction, and implementation of the other metros. Currently the most advanced tunneling technologies including the earth pressure balance tunneling boring machine are being used for the ongoing metro projects. This is evident from the fact that the required 4 years to construct 700 m underground tunnel using cut and cover technology took just less than 2 months using TBM. For the first time in India, underwater metro line is also being constructed across river Hooghly as part of Kolkata Metro system. The detailed investigation of the geology of underground along with subsurface explorations has helped to identify the appropriate tunneling methodology and equipments for the excavation and installation of these structures. These advanced techniques help to build these underground structures with minimum disturbance to the traffic and surface constructions and also minimum environmental impact in a congested urban environment.

Since the behavior of subsurface soil under various loading conditions is not predictable due to the nonhomogeneous strata, the changes occurring during the construction as well as execution of the underground projects are very important. To address this, numerical simulations are done using different methods to understand the variations in stresses and displacements around the tunnels. DEM and FEM were used to study the effect of loading on lined and unlined tunnels. The results indicate that in the case of unlined tunnels, the system collapsed completely due to the low bonding capacity of the soil on which the tunnel is excavated. However in the case of lined tunnels, the lining provided additional support to the structure, and a uniform distribution of the stresses around the tunnel is observed along with the arching action. The formation of the arch action along with the loosening of the ground was captured well by the DEM compared to FEM as it considers the discontinuous nature of the soil strata.

Even though it was considered that underground structures are safe against earthquakes, recent reports show that these are also vulnerable to the impacts of earthquake loading. Hence in this study, the effect of seismic loading on the behavior of underground twin tunnels placed at different spacing is reported. The studies indicate that the spacing between the tunnels affects the stress and displacement distributions. The interference effects due to the adjacent tunnel will be nullified if the distance between the tunnels is more than three times the diameter of the tunnel and the distributions will be uniform.

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