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Geotechnical Challenges of Kolkata Metro Construction

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ABSTRACT: The paper gives an account of the Kolkata Metro construction which included the first underground railway for mass rapid transit system of an Indian city. Construction was started in 1975 and the first line of the metro covering a length of 17 km was opened in 1984. Thereafter construction had been taken up in phases. Currently Kolkata metro construction includes an ambitious package of 140 km of underground, at grade and viaduct stretches. Construction has to be done in very difficult condition through congested urban areas which includes a tunnel below the Ganga river. Resource crunch and construction through heavily built-up urban land extended the period of construction but modern design techniques and field instrumentation have helped to ensure high quality work in densely populated urban centre.

KEYWORDS: Urban infrastructure, Cut and cover construction, East west metro, TBM Shield tunneling, Field measurements and instrumentation, Quality control.

1. INTRODUCTION

Urban infrastructure, in recent years, has come in a big way in the developmental effort of most countries. India is no exception. Till very recently the country did not have the resources to build infrastructure to suit the growing needs of a developing society. Since the invasion of computers in our life and living the pace of development has grown manifold. Realization has dawned that we shall not be able to move with the required pace until we give a real thrust to all spheres of infrastructure development.

Infrastructure includes all the different facilities required to be built for good living and growth of national wealth. Without the growth of wealth we shall not be able to afford the kind of living that developed societies are expected to provide. It is not just building houses and keeping them in good shape for people to look at and appreciate. We need to have modern transport facilities, including high quality roads, underground metros, adequate power, health and medical care and an environment that is conducive to healthy living.

2. ROADS AND HIGHWAYS

When we talk of buildings and their present trends we seem to think of high rise structures with beautiful architecture that catches our imagination. If you go out to travel in your car you enjoy your drive on the modern highways that allow you to travel at more than 100 kmph. The boom in construction industry in India has really come in recent years with the National Highway Development Project (NHDP) which is aimed at connecting the major metropolitan centres of India by the golden quadrilateral and North-south & East-west corridors, Figure 1. Side by side the Pradhan Mantri Gram Sadak Yojana (PMGSY) plans to connect the villages through all-weather roads so as to have convenient access to the National highways. The next development in the highway sector would be the expressways which will enable you to drive at a speed of 150 km per hour. Who could have thought even ten years ago that such a scenario would be possible?

3. HIGH RISE BUILDINGS

Today there is a perception that development means high rise buildings which are not only attractive to the eyes, but give a living comfort which only Bollywood cinemas depict in the make believe world of filmy entertainment. Consequently whichever direction you look at you only see multistorey and multiplexes. Even 50 storey complexes are becoming common. How much does a dwelling unit cost in these high rise buildings - anything between half-a-million rupees to one crore or even more. How many people can afford them? Yet, you will see people occupying them – many of whom not having the requirement to live in these dwelling units permanently.

Figure 1 National Highway Projects of India

4. QUALITY OF CONSTRUCTION

The construction industry is perceived as a major industry in the country today. But, how equipped is the industry to ensure quality in all our construction endeavour? There have been lot of concern expressed after major earthquakes about the safety of our buildings in the event of a major earthquake. In the Bhuj earthquake 2001 we found to our dismay that 4-6 storey buildings in Ahmedabad – 200 km away from the epicentre – had collapsed like pack of cards due to seismic design being not incorporated in the construction. True, institutional buildings and multistorey do not fall under this category because they are properly engineered but municipal regulations must ensure complete earthquake resistant design for all buildings.

It is said that wherever you set foot in a country the first thing that attracts your attention is the quality of roads and buildings, how fast the vehicles ply on the roads, how clean is the environment and how disciplined are the people. It is for the government to prepare plans for development and the society at large to build the infrastructure which is befitting to the modern age. Public and private efforts are to go hand in hand to build the required infrastructure. As it is, construction is a much disorganized sector. We have small builders who live from hand to mouth. We also have the big construction houses. The perception of quality is not the same with all. A minimum degree of self-control and quality awareness is essential to establish a sound engineering practice. Failures will occur but it is the effort to learn from these failures that will give us the strength and experience to meet the challenge ahead of us.

5. URBAN INFRASTRUCTURE

Major investment is now being made in the creation of urban infrastructure which is so very essential in the life and living of the urban people. It is not only the urban population which stand to gain by such development but the great number of people who have to commute to the cities every day to earn their living – be it in the service sector or in the industry or in marketing. They have to use these facilities purportedly built for the city dwellers.

Transportation is a key element in such development. Any urban development will have to include in the development process a network of underground and over ground metros which will provide fast and convenient modes of transport to allow people to travel without loss of time. Such construction needs thorough understanding of the subsoil in a given area, the land use pattern and selection of appropriate construction technique to allow the construction to be done with the least hazards and in the most optimum time and using optimal resources. There is no shying away from the fact that metro construction is expensive and time consuming but with appropriate planning and proper deployment of engineering resources metro construction can be made not only cost effective but highly beneficial to the society. The role of geotechnology in urban development cannot, therefore, be overemphasized.

6. KOLKATA METRO IN PERSPECTIVE

The city of Kolkata lies in Gangetic West Bengal – about 200 km north of the Bay of Bengal. Kolkata Metropolitan District (CMD) with an area of 1250 sq. km and a population of more than ten million has grown along the banks of the river Hooghly with the river running along the western boundary and separating it from the neighbouring city of Howrah, Figure 2. Kolkata is a major centre of industrial and commercial activity in Eastern India and the growth of population in recent years has put tremendous pressure on the civic services including transport. The meagre network of road - covering only 6 - 7 per cent of the land area has made the situation chaotic.

7. GENERAL SOIL CHARACTERISTICS

The Calcutta (Kolkata) soil forms part of the Bengal basin which was the site of continuous deposition from the Cretaceous period. Later Tertiary sediments were deposited by the Ajay and Damodar river systems on the west and from the Assam plateau on the east. These were overlain by Pleistocene sediments consisting of succession of gravel, sand and silt which are believed to have been deposited on the Tertiary beds. The soil in the upper strata consist of soft to medium grey silt clay occasionally with organic content.

The terrain of Kolkata is almost flat with a general elevation of about 5 m above MSL. The ground is higher near the river banks on the west but slopes down to the low lying marshy areas in the east. These areas often get flooded by the monsoon rains.Records of soil investigation done by different agencies in the city show that Kolkata lies on the Gangetic alluvial plains of eastern India with subsoil extending to great depth below MSL. No borehole records are, however, available to show the subsoil strata piercing the alluvium and touching the rock below. Records of tube well sinking, more than 300 m deep, have revealed the existence of numerous layers of peat, kankar and silt / clay often interspersed with water bearing sandy strata. Some remains of fossils have been reported in the deposits below 250 m depth.

Figure 2 Cities of Kolkata and Howrah on two banks of Ganga River

From an engineering viewpoint the subsoil in the upper reaches of the Bengal basin which is of immediate relevance to foundation engineers is of recent origin and is believed to have been deposited on the Pleistocene beds by the Ganga river system. Deposition has taken place under typical alluvial environment - in the form of back-swamp deposits, meander belt deposits and channel fill deposits. Opinion differs as to the boundary between the Pleistocene and recent deposits in the area but there seem little doubt that the top 100 m of the sediments, at least, are of recent origin. They consist of successive layers of soft to firm silty clay / clayey silt followed by layers of dense sand/hard clay.

The ground water table in the Kolkata Metropolitan Area is fairly high. There is a perched water table in the upper cohesive strata which undergoes seasonal fluctuation and rises almost to the ground surface in the monsoon. The piezometric head of water, is, however, found 6 m below ground surface in the north to 9 m below G.L. in the central and southern districts. This has been attributed to the large scale pumping of water from deep tube wells for domestic water supply over long periods of time. Such indiscriminate withdrawal of ground water has now been prohibited by municipal regulations In general the low permeability of the silty clay does not require any dewatering even for 10-12 m deep excavations except for areas with local pockets of sand where pumping is resorted to. The river channel deposit, however, require well point dewatering

8. KOLKATA METRO ALIGNMENT

Kolkata Metropolitan area lies in Gangetic West Bengal, 200 km north of the Bay of Bengal and covers an area of 1250 sq. km with a population of more than ten million, Figure 3. The city has grown along the banks of the river Hooghly with the river running along the western boundary and separating it from the neighbouring city of Howrah. The inherent problems of transport in Kolkata arise out of the fact that roads in the KMD account for only 6.2 per cent of the urban land which is much below the national average – not to speak of 30 per cent that is considered ideal for modern cities.

Figure 3 Kolkata metropolitan district showing first line of metro Alignment: Dum Dum – Garia and East West Metro

Figure 4 shows the first line of Kolkata metro network, 16.63 km, built by the Indian Railways during the period 1975 – 1995. The construction was done mostly by the cut and cover method except for a 1.09 km stretch in the northern end which was built by shield tunnelling with compressed air because the alignment had to cross a railway yard near Belgachia station. The alignment was to go through a busy urban area and underground technology was not as advanced as it is today. However, this first metro of Kolkata has been serving very useful purpose since it was opened to traffic partly in 1985. Subsequently the line was extended in the south by 6 km on viaduct along the Tolly's Nalla in 2009. This metro now connects the south suburban railway track of Eastern railway and has been of great benefit to the people of the southern districts of West Bengal in making their communication easier with the city of Kolkata.

9. KOLKATA METRO UNDER CONSTRUCTION

The city of Kolkata is now witnessing a major thrust in metro construction with simultaneous construction of the metro network - covering the city from north to south and east to west - and stretches over a length of more than 100 km. Considering the hazards of such underground construction in a heavily built up urban area present metro construction in Kolkata has been planned to be mostly overground except for the East West Metro which will link the cities of Howrah and Kolkata to provide convenient access from the Eastern Railway and South-eastern Railway network which terminate at Howrah station, Figure 5. This will, however, necessitate construction below the Hooghly River by bored tunnelling, Figures 6-7 The complete Metro network for Kolkata city and the method of construction being adopted for different sections is shown in Table 1.

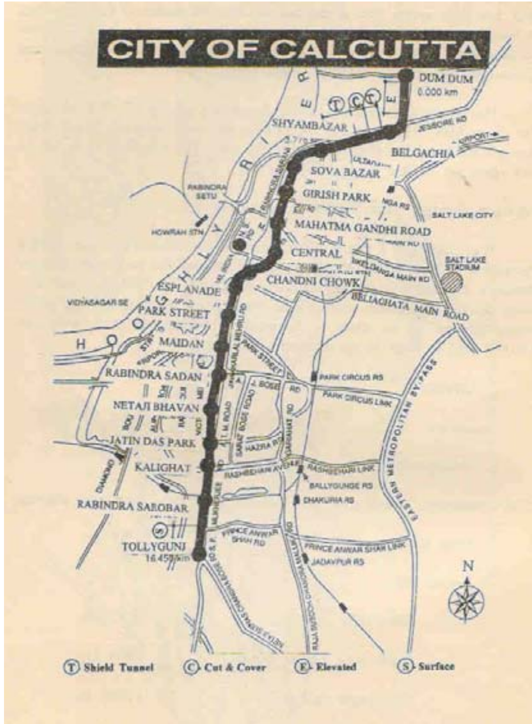

Figure 4 Dum Dum – Tollygunj section of Kolkata Metro (First Metro – now under operation)

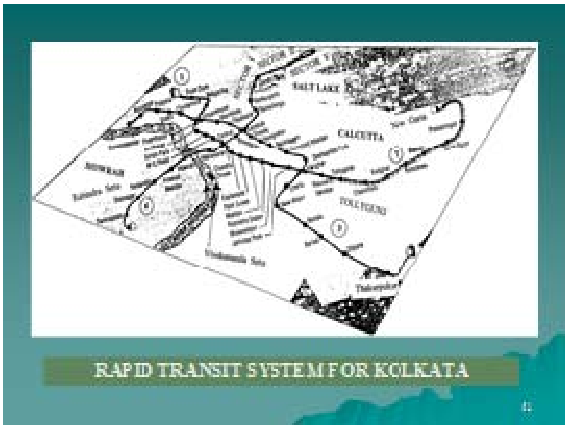

Figure 5 Kolkata Metro Network

Figure 6 East-west Metro – now under construction

Table 1 Metro Network for Kolkata City

Alignment	From / To	Length (km)	Method of Construction	Period of construction
1	Dum Dum - Tollygunj	15	Shield Tunnel/Cut-and cover/ Surface	1975-1995
2	Tollygunj - Garia	5	Overhead / Viaduct	2000-2004
3	East–west Corridor Howrah Maidan – BBD Bag – Central – Sealdah - Swabhumi	14.3	TBM Tunnelling and Cut and cover for stations	2010-2018*
4	Swabhumi–Salt Lake Sector V	6.5	Overhead / Viaduct	2010-2018*
5	Joka-Mominpur– Esplanade	16.7	Overhead/Viaducct	2010-2018*
6	New Garia – Kolkata Airport	32.2	Overhead /Viaduct	2012-2018*
7	Noapara – Barasat via Kolkata Airport	18.3	Overhead / Viaduct	2012-2018*
8	Dakshineswar– Barrackpur	18.0	Overhead / Viaduct	2012-2018* (* Projected)

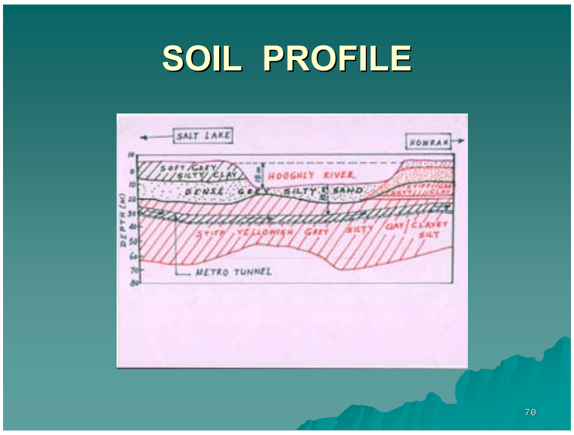

Figure 7 Subsoil below River Hooghly and Metro below river bed

Extensive soil tests have been done for the metro construction in Kolkata. In addition to the investigation in and around the Ganga river soil tests have been done to 60-70 m depth to get the design parameters for the large diameter piles which often have go to 35-40 m depth below G.L. With the substantive design now being made available construction is in progress both for the East West Metro with the underground stations and the TBM and pile foundations for the viaduct stretches.

10. SUBSOIL ALONG METRO ALIGNMENT

In general, the subsoil in the Kolkata area, Table 2, shows weak cohesive strata in the upper layers except for a thin surface crust which appears somewhat firm due to desiccation. The upper strata consist of silty clay/clayey silt, particularly soft in the top 12-15 m, with decayed vegetation. The consistency improves somewhat in the deeper strata and alternate layers of firm to stiff silty clay with laminations are found below 15 m depth. Thereafter dense sand is found below 25 m depth. Below 32 m depth the subsoil consists of stiff to hard mottled brown silty clay/clayey silt followed by dense sand at 40 m depth. This is characterized as Normal Calcutta Deposit. This general pattern is broken somewhat, at some locations by, what is called, the River Channel Deposit with fine sand in the upper strata. This deposit goes down to some depth and ultimately rests on deeper clay beds of the Normal Calcutta Deposit 20-25 m below G.L.

Further below, successive layers of stiff clay and / or dense sand are found to extend to depth of 60-70 m below G.L. In the Ganga river section the same soil pattern continues except that the top 10-12 m is covered by the river water. Thereafter, the soil continues to have sand and gravel down to 25 m depth. Below this depth, the normal Kolkata strata are retained as in the Normal Kolkata deposit elsewhere.

11. SYSTEM DESIGN

In view of the heavily populated urban areas covering the city of Kolkata a combination of different systems has been adopted for building the metro network of Kolkata. Apart from the first metro which was built almost entirely underground by the Indian Railways only the East-west metro is now being built underground. This costs about Rs. 700 million per km on present day prices. The rest of the metro alignment is going to be overhead on viaduct supported on RCC pillars to be founded on piles. While the East west Metro is going to be built by the fully owned public corporation called Kolkata Metro Rail Corporation Ltd with 40 per cent JBIC assistance the remaining metro constructions are in the hands of the Rail Vikas Nigam Limited (RVNL). Foreign funding though welcome makes the system somewhat unwieldy with multiple points of control making the construction more time consuming. This inevitably leads to increased overhead expenses and increased cost. But resources crunch has made this almost a necessity. It is, however, good to see that the dependence on foreign funding is gradually been reduced and internal resources are more and more utilized for infrastructure development.

Another important consideration is there. In order to negotiate the width of Ganga River the only possibility is to have the metro tunnel going below the river bed. From the western end of the river the metro will have to go underneath the heavily built-up central business district of the city. The present design, therefore, envisages the use of tunnel boring machine (TBM) to go about 10 m below the river bed and continue below the CBD to meet the Central station of the existing metro.

12. PRESENT STATE OF CONSTRUCTION

At this point of time the metro construction is going ahead in all fronts. The east-west metro extending from Howrah Maidan to Salt Lake starts with the cut and cover construction for Howrah Maidan on the western side of the river and then on to the Howrah Station on the banks of the river. From here the TBM takes over.

Table 2 Subsoil condition of Kolkata

Stratum	***Depth [m]***	***Description of soil***	***N [blows/30 cm]***	***Soil Parameters***
I	0 - 1.5	Fill of stone, concrete sand, brick pieces etc	-	γ = 18 kN/m3 -
II	3	Brownish grey silty clay with kankar	3	γ = 18 kN/m^3 LL= 40, PL=20, w = 35 Cu = 22 kPa
III	14	Soft grey/dark grey silty clay with decomposed wood	4	γ = 18 kN/m^3 LL= 55, PL=25, w = 40 Cu = 25 kPa
IV	24	Firm to stiff bluish grey silty clay with kankar	10	γ = 19 kN/m^3 LL= 60 PL=25, w = 35 C' = 0, Φ' = 24°
V	32	Dense brown silty sand	30	γ = 19 kN/m^3 w = 35 % C' = 0, Φ' = 32°
VI	40	Stiff to hard mottled brown/brownish grey silty clay with traces of sand	16	γ = 19 kN/m^3 LL= 55, PL=25, w = 35% Cu = 60 kPa C' = 0, Φ' = 26°
VII	50	Medium to dense yellowish grey/brownish grey silty sand	35	γ = 20 kN/m^3 w = 28 % C' = 0, Φ' = 34°

It goes under the river bed till it reaches a ventilation shaft on the eastern side of the Ganga. Thereafter, the TBM will continue below the heavily congested Brabourne Road. A cut and cover station will be built at Mahakaran (Secretariat) opposite the Writers'Buildings (Mahakaran) which has been the seat of Bangla government till very recently. Part of the Secretariat has now been shifted to a new location, Nabanna, on the other side of the Ganga – but away from the Metro alignment. From the Mahakaran station the alignment continues to go south until it reaches the Central Station where it will have an intersection with the first Metro line. Another underground contract, using TBM, starts from Swabhumi, near E.M. Bye Pass and follows the eastern part of the city, viz., Phoolbagan and Sealdah till it meets the East-west tunnel at Central Station. The East-West Metro is built almost entirely with TBM except for the stations.

On the eastern flank of the city the East West Metro takes the overhead route through Salt Lake and terminates at Sector V. There again it intersects with the 32 km long Garia – Airport Metro which follows the eastern periphery on viaduct through New Town (Rajarhat) and Easterm Metropolitan By-pass meet the Central station at Esplanade. The rest of the Metro is all planned to be overhead in the northern fringe of the city. It goes up to Barrackpore and Barasat to meet the suburban railway of Eastern Railway. The entire metro network, when completed, will serve the people of Kolkata in providing convenient transport facilities along the length and breadth of the city. Figures 8 and 9 show typical sections of metro construction for the first line of Kolkata metro through the Central Business District on Central Avenue.

13. EAST WEST METRO

The pride of place in the Kolkata metro network will be the East-West Metro which commences from Howrah Maidan on the western side of the Hooghly river where a station and a cross-over will be built to cross the river by TBM (Figure 10). The cross over will be meant for lowering the TBM which proceeds towards Howrah Metro Station. Thereafter, the alignment goes below the Howrah Station of Indian Railways with the underside of the metro platform placed at 36 m depth. This station will be built by cut and cover method with 55 m deep diaphragm walls and multiple struts/station floors suitably placed to accommodate the station and give access to the Eastern Railway terminus of Indian Railways which is the gateway to the city of Kolkata from the rest of India. From this point the TBM goes below the river with the underside of the metro tunnel remaining 18 m below the river bed , Figure 11.

Figure 8 Cut and cover construction through Chittaranjan Avenue

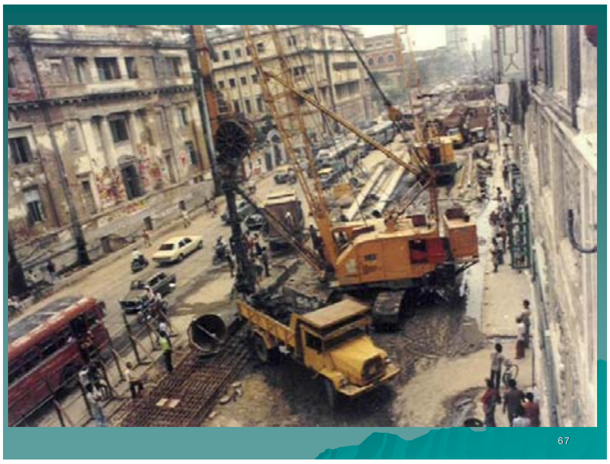

Figure 9 Metro construction through CBD

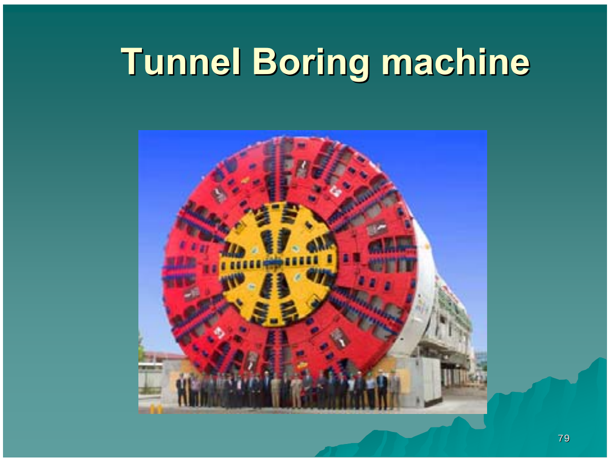

Figure 10 Tunnel Boring Machine for crossing Hooghly River

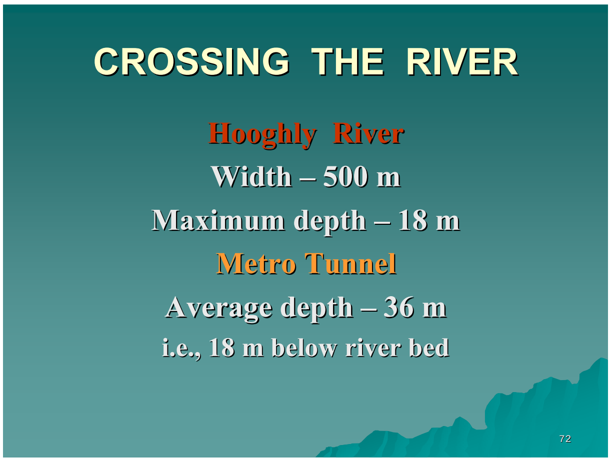

Figure 11 Crossing the Hooghly River

14. ANALYSIS AND DESIGN OF BRACED CUT

Extensive analysis has been done for the Plaxis modelling of the station sections to determine the stability of the excavation and the ground / building settlement profile along the excavation. In the Howrah Maidan area there are buildings in the close proximity of excavation. Even before the present construction near the Howrah station was commenced most of the Metro alignment through Kolkata City had been done by braced excavation with diaphragm wall and multiple struts. Ground settlement evaluation and the condition survey of all buildings along the alignment had been done prior to construction and the buildings had been monitored closely during construction. Figure 12 shows a typical braced excavation for cut and cover construction through Kolkata soil.

Measurement of diaphragm wall movement, strut load and ground settlement had been made at different sections of the metro construction. Figure 13 gives the diaphragm wall deflection at different stages of excavation. These measurements helped to control the the effect of ground movement on nearby buildings on the highly congested Chittaranjan Avenue in Central Kolkata. These buildings were mostly of RCC framed construction or load bearing construction.

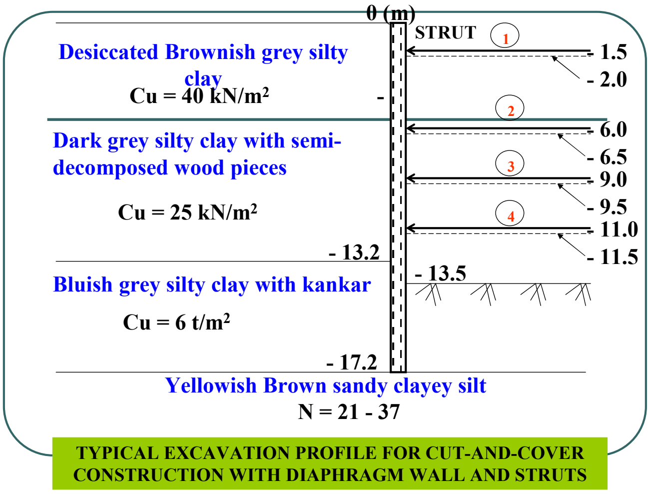

Figure 12 Cut and cover construction with diaphragm wall and struts

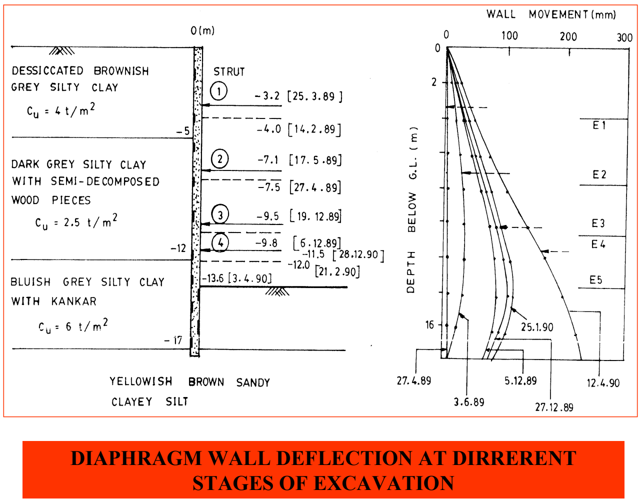

Figure 13 Deflection of diaphragm wall in braced cut

15. SOFT GROUND TUNNELLING

Initially, in the first phase of construction near Belgachia station, shield tunnelling with compressed air had been done to cross a busy railway yard. Although progress was slow and a number of buildings in the vicinity had been distressed due to ground subsidence the tunnelling was done without any major hazards. The observed ground settlement resembled a dish shaped profile with maximum settlement of 200-250 mm, which could be predicted well by error function distribution based on the maximum settlement occurring at the midpoint of two tunnels Figure 14.

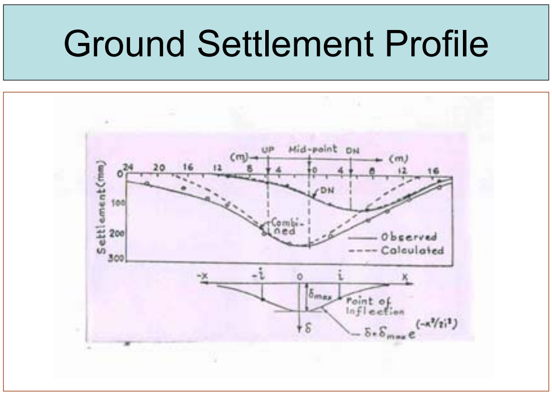

Figure 14 Ground settlement profile for shield tunnelling

Problems were anticipated at Narkeldanga during the present phase of construction when the twin TBM were required to go below two railway bridge abutments, Figure 15. The deformed shape of the ground for the twin tunnel was predicted from the Manual of Design and Construction of Road Tunnels (1965) according to which two parallel tunnels three or more diameters apart (centre to centre) would give surface settlement well predicted by adding the individual settlement of the two tunnels. The centre to centre distance between the two tunnels is 17.344 m apart their combined. ground settlement profile is as shown in Figure 16. No distress was, however, noticed in the railway platform during construction of the TBM tunnel.

16. EXCAVATION NEAR HOWRAH STATION

Figure 17 gives the layout of buildings near Howrah Maidan station/ Howrah Maidan Crossover. The analysis of the excavation by Plaxis modeling gave the deformation pattern around the excavation with diaphragm wall, the concourse and base slabs, wherever required for preventing uplift of the bottom slab, Figure 18. The angular tilt of a typical building near the excavation is shown in Figure. 19. The design objective was to keep the angular distortion within 1/300. The buildings were subjected to close monitoring during construction and contingency measures were taken to ensure the safety of the city. The alignment is planned to proceed to the Central station where there will be an intersection with the existing Dum Dum – Garia Metro.

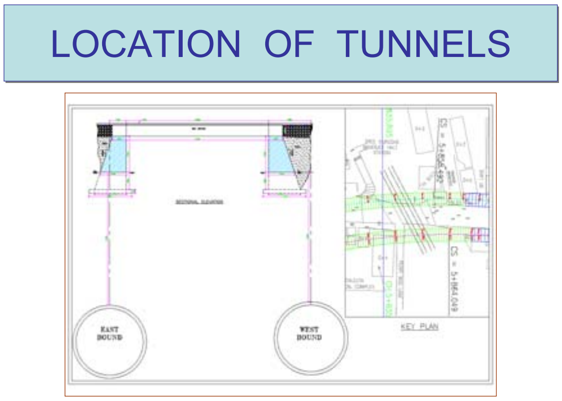

Figure 15 Tunnels below bridge abutments

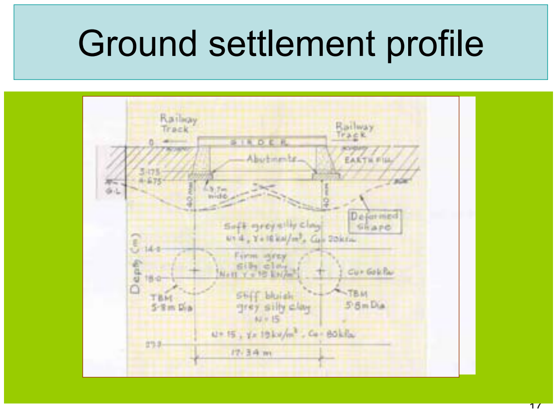

Figure 16 Settlement profile due to twin tunnel

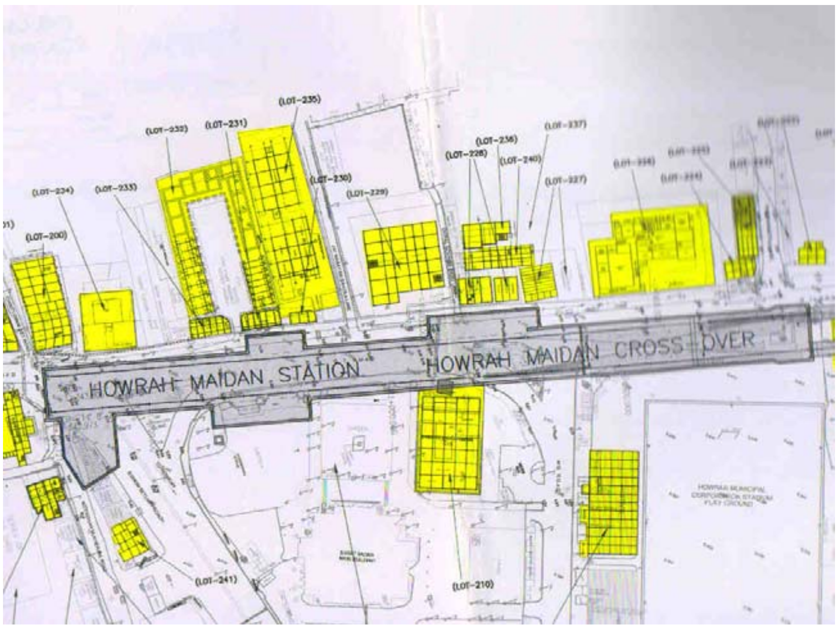

Figure 17 Howrah Maidan Crossover and nearby buildings

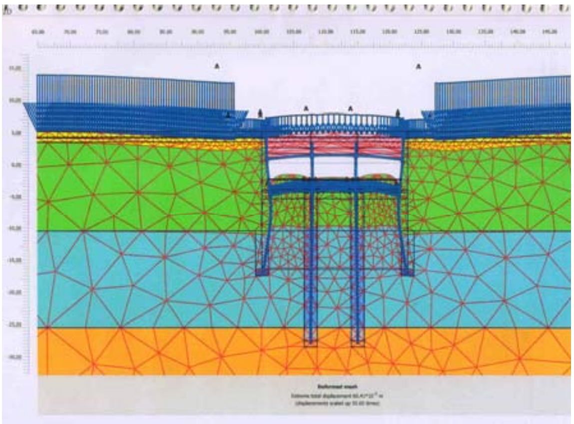

Figure 18 Plaxis modeling of Howrah Maidan excavation

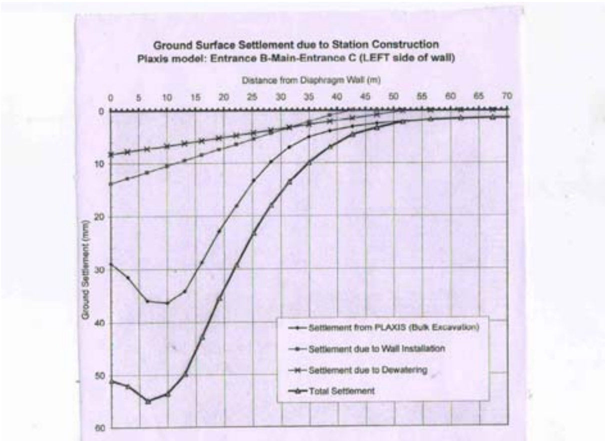

Figure 19 Predicted ground settlement

17. METRO ON VIADUCT

While the existing Dum-Dum Tollygunj Metro and the East - west Metro now under construction – covering a total length of 30 Km in the heart of the city is being built underground the major stretches of the Metro network will be built over ground on viaduct supported on pillars. The subsoil in Kolkata, as already described, consists generally of soft silty clay down to 15 m depth followed by successive layers of firm to stiff silty clay and dense sand below 25-30 m depth. The metro viaduct will be supported on piers, 8 – 12 m high and founded on pile groups at 28-34 m apart. The piles are generally 1200 m dia x 25-30 m deep or even more, depending on subsoil condition - each pile carrying a load of 275-300 t. Extensive soil tests have been done at each pier location. Initial and routine pile tests are being carried out to confirm the pile capacity at each pier location. The railway standards with regard to settlement and angular tilt between pier locations have to be strictly followed to ensure quality control of the pile foundations.

18. SUMMARY AND CONCLUSION

The paper presents a brief account of the Kolkata Metro construction which is now in full swing in the city of Calcutta. An ambitious metro project has been undertaken with a combination of underground and viaduct stretches covering the city of Kolkata with connections to Howrah station. In the process the metro tunnel has to go underneath the river Ganga and a busy railway yard. The underground stretches are being built by Tunnel Boring Machines while the stations are built by cut and cover construction using diaphragm walls and struts. Adequate quality control measure are undertaken to ensure safety of nearby structures by instrumentation and monitoring.

19. ACKNOWLEDGEMENTS

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