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Research Article

STUDY OF UNDERGROUND STRUCTURES OF HERITAGE LINE OF DELHI METRO

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A B S T R A C T

Delhi Metro is one of the modern public transport system in the country. Delhi metro is developed Phase wise. Expansion of Metro is still continued. The entire network was planned to be completed in 20 years. A number of tunnels are designed on the lines. Blue Line, Red Line, Yellow Line, Magenta Line, etc. are some examples of metro route developed so for. It was a big challenge to our engineers to make it operational in highly populated and dense area of Delhi.

INTRODUCTION

Delhi Metro, the second metro system constructed in India after Kolkata Metro, is a modern public transport system. It consists of a network of 190 kilometers, servicing 141 stations of which 35 stations are underground, 5 are on ground and remaining are elevated. Delhi Metro Rail Corporation (DMRC), a state-owned company under administrative control of the Ministry of Urban Development is involved in the planning, implementation and operations of the Delhi metro system. The Construction started on October 1, 1998 and the first section the Red Line was opened in 2002 followed by the Yellow Line in 2004, the Blue Line in 2005, its branch line in 2009, the Green Line and Violet Lines in 2010, and the Delhi Airport Metro Express in 2011. The entire network was planned to be built in phases spread over approximately 20 years. Phase I (65km) and Phase II (125 km) were completed in 2006 and 2011, respectively, and Phase III and Phase IV are scheduled for completion in 2016 and 2021, respectively. Work on Phase III started in 2011 while planning for Phase IV has begun. Phase III will have 28 underground stations covering 41 km. After completion of Phase III the passenger traffic is expected to go up to 4 million. Till Phase II, Delhi Metro focused on expanding the reach of the metro and thus built long radial lines. However, in Phase III, Delhi Metro is aiming to interconnect existing lines by ring lines to improve connectivity.

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This will not only help in reducing distances but will also relieve radial lines of some congestion. The total length of the underground corridors in Delhi Metro's proposed Phase III will be almost equivalent to the total underground sections built so far by DMRC in both Phase I and Phase II, making it one of the most challenging construction phases. The 59-km long Majlis Park-Shiv Vihar corridor of Phase III consists of about 14kms of underground lines. Presently, five other TBMs are working in different parts of the corridor across the city. In total, 19 TBMs are operational for the tunneling works of Phase III. In addition to this, DMRC is slated to construct 53 km of underground Metro lines as part of its Phase III construction work for which about 34 TBMs are expected to be used. A total of 74 tunnels will be constructed in this phase.

Contribution in Delhi Metro

HCC is involved in five packages of the undergroundsection of the Delhi Metro. The first package MC1Awas awarded to construct a 4.142 km long tunnel.

HCC completes up-line tunnel for DMRC CC30

The 2.2 km twin-tunnel of DMRC's CC30 package, part of the 59km long Majlis Park to Shiv Vihar Metro Corridor of Phase III. Vishwavidyalaya Station to ISBT station on the Yellow Line. The project was completed eightmonths ahead of schedule in December 2004. The next two packages were part of the Airport Express Line which include C1: a 2.2 km longtwin bored tunnel and a 1.3km cut and covertunnel From New Delhi station to Rajiv Chowkand C6: a 2.6km long NATM tunnel from Talkatora area to Buddha Jayanti Park. The route alignment for this Metro line passed belowvarious heritage structures and buildings of national importance. The tunnelling depth below the Rajiv Chowk Metro station at 44m was the deepest ever for the Delhi Metropolitan Region, going below two existing lines. C1 was awarded in September 2007 and completedin July 2010 whereas C6 was awarded in Dec.2007 and completed in Feb. 2011. The CC30 package of the 2.2km twin tunnel between Shalimar Bagh and Subhash Placestations (Pink Line) on the Mukundpur- YamunaVihar corridor was awarded in October 2012. The most recent package awarded to HCC is CC34 package involving designand construction of a 4.4 km long tunnel on Janakpuri West–KalindiKunj Corridor (BrownLine) under Phase III of the metro development.

CC30 Package

The CC30 package of DMRC is part of the59km long Majlis Park to Shiv Vihar MetroCorridor (Pink Line) of Phase III. The scope ofwork includes design & construction of the twin tunnel between Shalimar Bagh and Subhash Place stations by Shield TBM, twin box tunnelsby cut & cover method, underground ramp, architectural finishing of Shalimar Bagh station (underground) and NetajiSubhash Place station (semi-underground). The notice to proceed with the work wasissued on October 29, 2012 and HCC immediately undertook the detailed geotechnical investigation of the project along the alignment of the project. The soil was tested bydrilling boreholes at nine locations and samplesextracted were tested in the laboratory. The detailed investigation revealed that the soilalong the project alignment was sandy silt andsilty fine sand primarily. It was medium denseto highly dense at the depth of 30 meters. The ground water was encountered at about11 to 15 meters depth. The geology along the alignment of the tunnel was of mixed type.

Based on the geo-technical study done byDMRC during the tender stage, Earth PressureBalance Tunnel Boring Machine was finalized for the tunnelling. Earth Pressure Balance (EPB) TBMs are used in excavation of soft groundor soil condition. The EPB method consists ofcutting chamber located behind the cutter headof the TBM. This chamber is used to mix thesoil with water foam. It is maintained underpressure by the mucking system. The ground at the cutting face is supported by earth pressure by balancing the advancement of the tunnel with the discharge rate of the excavated soil.

The underlying principle of the EPB methodis that the excavated soil itself is used toprovide continuous support to the tunnelface by balancing earth pressure against theforward pressure of the machine. The thrust force generated from the rear section of TBMis transferred to the earth in the cutter headchamber so as to prevent uncontrolled intrusionof excavated materials into the chamber. Whenthe shield advances at the face of excavation, the excavated soil is then mixed together witha special foam material which changes its viscosity or thickness and transforms it intoa flowing material. This muck is then stored and is used to provide support and to balance the pressure at the tunnel face during the excavation process.

The CC30 package orientation is north-southwith Shalimar Station located on the northern end and an underground ramp on the southern end of the project. The northern boundary ofthe project is shared with CEC who is working on DMRC's CC04 package and on the southern boundary where L&T is working on the elevated corridor package of CC28.

Construction Sequence

The Shalimar Station location was the first areahanded over to HCC for work. It is a complete underground station and goes up to 30 meters deep. After barricading the area, underground utilities shifting was the first task undertaken before commencing the excavation work. First the 1500 mm diameter PSC pipe lineand MTNL Lines were shifted, after which the electrical lines of 11 KV and 33 KV were shifted. Prior to shifting, the permissions from TATAPower Delhi Distribution Ltd. were taken.

Shaft location next to the NetajiSubhash Place station on the southern part of the CC30 package, was the second area handed overto HCC for construction. The shaft is of 20 min length, 17 mtr in width and is 12 mtr deep.Soldier piles are drawn at the periphery of theshaft to stabilize the ground. Between the shaftand Subhash Place station area is a 75 mtr long tunnel done by the Cut and Cover method. The entire length of shaft plus the cut andcover tunnel area was utilized for installation ofTBM. After lowering the TBM part by part and assembling it in the Shaft and Cut and Coverarea, it started its drive towards Shalimar Bagh Station. The Cut and Cover area was an added advantage to assemble the TBM in one-gobefore the start of the Initial Drive. The Subhash Place station was the next area handed overto HCC to begin work. This station is semiunderground as only 12 mtr of this stationis below the ground level and the balance isabove.In the Cut and Cover area there were three PSCpipe lines of 800mm, 900mm and 1100mm diameters which were to be diverted beforethe start of the excavation for which the approval from the owner agency was to beobtained. HCC initiated the documentation to seek approval. However, the permission formalities for shifting these utilities was taking considerable time. Hence, in consultation with DMRC, it was decided to hang these pipelines with the help of a temporary bridge to proceedwith the work on the station and the excavation was completed. The station was built withthe bottom-up approach where soldier pilesare built first to stabilise the ground, then theexcavation starts followed by the intermediate operations of Earth Pressure Balance Tunnel Boring Machine construction sequence.

Challenges Encountered

While tunnelling in an urban environment, utmost care is taken so that the underground construction activities do not disturb the buildings on the ground. Along the alignment of the CC30 tunnel, there are various new and old buildings. A detailed study was undertaken to find out the status of various structures, their building foundations and adequate stepswere taken including stabilisation of ground and continuous monitoring during the TBM drive so that these structures were not disturbed. For instance, adjacent to the Shalimar Baghstation there is a shopping centre where the distance between the two is bare minimum. A rigorous scheme of instrumentation was set-up on this structure to measure deflections if any. Instruments like 3D tilt meters, Ground Settlement Markers (GSM), inclinometer...etc were set-up to measure the slightest variationsas minute as few millimetres. These were monitored continuously during the construction phase.

The first major challenge encountered after commencing the TBM operations was crossing the via-duct. Around 138 meters from the TBM entry point the tunnel was crossing between the piers of the via-duct of an existing metroline. The depth of tunnel below the ground level under the viaduct was only 10 meters. While planning the project, DMRC had taken care todraw the tunnel alignment between the two pillars. The challenge was tunnelling between these pillars without disturbing the pillars in any way. HCC did a three dimensional analysis of the area using "Plaxis" software suggested by its Drawing Design Consultant (DDC). The instrumentation was in place to measure thevolume loss during tunnelling and it was notallowed to cross 0.3 per cent. The soil condition was clayey with significant water presence.

Hence the ground between the pillars was strengthened by TAM Grouting. TAM grouting is done by drilling boreholes in the soil and injecting cement slurry under pressure so thatall cracks or fissures gets filled with the slurry. This process consolidates the ground so that there is no lateral deflection on the piles during tunnelling. Around 90 bore holes were drilled between these two pillars to make the muddy ground hard for tunnelling. After consolidation of the ground a sample piece was tested for the required strength and then tunneling process began under the viaduct. While tunnelling the vibrations caused by the TBM drive were measured. The vibrations during tunnel driving was less than the one caused bythe movement of the train on the viaduct.

The next challenge was tunnelling under an existing canal. The tunnel was passing under the canal at a depth of 14 meters. Though the canal had very less amount of water in that season, the lining of the canal was weathered. Due to seepage of water, the ground underthe canal was muddy. A similar exercisewas carried our while tunnelling under thecanal by putting various instrumentation andregular monitoring of the soil conditions duringtunnelling. Thus the TBM could successfully beused without disturbing the canal.Rajesh Kumar, HCC's Project Manager for CC30 project explains, "All along the tunnel alignment we installed intensive ground instrumentation and monitoring schemes such as ground settlement monitor and settlement markers in order to study the impact of TBM on above ground structures.

The tunnel passed under some of the landmark structures such as Kasturba Polytechnic building, KendriyaVidyalaya and even theslum area where the building conditions arevery poor. In addition, while carrying out the tunnelling work, proper care was taken while finalising the alignment of the tunnel that itdid not infringe the Pile area of the 'Azadpur.

HCC team celebrating the break-through of up-line tunnel achieved on March 13, 2014 at DMRC's CC 30 project The TBM is lowered in the shaft piece by piece and assembled for the drive towards Shalimar Bagh Station Tunnelling below two pillars of the viaductto Prem Bari fly over'. TBM steering was difficult in the last 500 mtr excavation as thestrata encountered in this stretch was clayey where in driving of TBM was difficult. Despite these challenges we managed to complete construction of Tunnel 1 without causing any damage to the structures on ground and also without affecting the movement of the Trafficwhich runs over Ring road."The tunnel boring began in October 2013 and completed the 1,247 meter long tunnel from NetajiSubhash Place to Shalimar Bagh consisting of 1,037 rings with a finished diameter of 5.7 meter in 111 days. The average monthly boring progress achieved during the construction was 337 meters with installation of over 9 rings per day.

Equipment Used

Grouting Plant -18 cum	01 No
Tower Crane 10 Ton @30 mtr	01 No
Locomotives – Schoma / Atlas Copco 25 MT	03 No
Gantry Crane – Demag 25 MT	01 No
Compressor GA 45	01 No
MAI Pump	01 No

RESEARCH METHODOLOGY

Most of the time urban tunneling is carried out at a very shallow depth where the magnitude of in-situ stresses is very less. In urban tunneling the basic concern is mainly to control the ground around the work sites to be minimize implications of the adjacent structures and utilities. The analysis carried out by several researchers for such type of problems with different methods is as under:

Closed Form Solutions

The closed form solutions are based on simplified assumptions, e.g, shape of the opening is regular (mostly circular, elliptical or rectangular), the media is homogenous and isotropic. However, they provide an easy solution to get a preliminary idea of really complex situation and about the accuracy of results obtained by various numerical solution procedures.

Elastic Solutions

The closed form solutions for regular tunnels (circular, elliptical, rectangular and rectangular with rounded corners) in an infinite mass are well discussed by Savin (1961), Obert and Duvall (1967), Poulos and Davis (1973) and Jaegar and Cooke (1976). Pender (1980) has given the solution for stress distribution and displacements around a circular tunnel for a plain strain case.

Elasto-Plastic Solution

Closed form elasto-plastic solution are difficult to obtain. However, some solutions have been obtained for isotropic insitu stress conditions considering openings as circular in shape. One of the first calculations of an elasto-plastic stress distribution around a cylindrical underground opening was performed by Terzaghi (1925). However, Terzaghi did not apply his calculations to be design of tunnel support system. The next contributions were made by Kastner (1949) and by Labasse (1949), who presented solutions for the case in which the pre-tunneling stress filed was not hydrostatic and discussed the question of rock support interaction assuming Mohr-Coulomb yield criterion.

Finite Element Method (FEM)

Different numerical methods are being used for analysis of the underground structures as the problems of stress and displacements around the openings cannot be analysed by closed form solutions due to variability of ground conditions, non-homogenous media and irregular geometric shapes of the openings

Use of Finite Element Method is most common now-a-days for simulation of very complex situations, viz., non-homogenous media, non-linear material behavior, in-situ stress conditions, spatial variation in material properties, irregular geometries and discontinuities.

Boundary Element Method (BEM)

The boundary element method (BEM) offers advantages over finite element method (FEM). Only the boundary of the domain is required to be discretised. Therefore, smaller system of equations and letter data are required for the problem. The numerical accuracy of BEM is generally greater than the FEM.

Finite Element Method Coupled with Boundary Element Method (FE-BEM)

Many practical problems in geotechnical engineering e.g. underground openings deal with regions containing non-homogeneities and non-linearities within a semi-infinite body. In order to minimize the computational efforts without sacrificing the accuracy of results beyond a certain limit, the are analysed by coupling finite element with boundary element methods.

Finite Element Method Coupled with Infinite Element Method

In finite element method, boundary is truncated at a sufficient distance in order of minimize computational efforts otherwise this may lead to a costly analysis. In order to minimize the cost of computation without sacrificing accuracy of results analysis is done by combining finite and infinite elements.

Finite Difference Method

Finite Difference Method is perhaps the oldest numerical technique used for solution of sets of differential equations for given initial values and/or boundary values (Desai and Christian, 1977). In finite difference method every derivative in the set of governing equations is replaced directly by an algebraic expression written in terms of field variables (e.g., stress or displacement) at discrete points in space. These variables are undefined within elements. In contract finite element method has a central requirement that the field variables (stress, displacement) vary throughout each element in a prescribed fashion using specific functions controlled by parameters. The formulation involves adjustment of these parameters to minimize errors terms or energy terms. Both methods produce a set of algebraic equations to solve. Eventhough these equations are identical for the two methods. Wilkins (1964) presented a method of deriving difference equations for elements of any shape. The finite difference code developed by ITASCA (2000) on the basis of Lagrangian Analysis of Continua (commonly known as Fast Langrangian Analysis of Continua, FLAC) has used this approach. Many researchers used this code for the analysis of two-dimensional (ITASCA-2000) and three-dimensional (ITASCA, 2002) geomechanics problems.

Evaluation of Rock Mass & Future Scope

The analysis of tunnels in rocky strata is generally carried out by Distinct Element Methods by simulating joint geometry. In some cases the analysis is done by treating medium as continuum incorporating the effect of joints in the form of reduction factors for strength parameters. Detailed field study of rock mass encountered during excavations at Delhi Gate and Jama Masjid indicated that the rock mass is highly weathered and extensively jointed. The modeling of the tunnels in such media by Distinct element method was not found to be reasonable as simulation of joint geometry and its condition is very complex and difficult to simulate reasonably. Therefore, the only option left is to evaluate the media for engineering parameters of the continuum (rock mass) with the help of several test procedures developed by different researchers in the past to characterize the rock materials. Rock Mass Rating (RMR) by Bieniawski (1984), Joint Factor (Jf) by Ramamurty and Arora (1994), Geological Strength Index (GSI) by Hoek and Brown (1997) and Weathering System (Rw) by Rao and Gupta (2001) are some of the useful methods for predicting the strength and deformation response of jointed and weathered rock mass.

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