1. INTRODUCTION

Delhi Metro Phase II started in 2006 and is targeted for completion by the common wealth games in October 2010, in Delhi. Phase II comprises an extension of the operating Phase I lines completed between 2002 & 2006, plus the addition of new lines, and consists of the construction of 125km of track, 81 stations and 4 depots. The works comprise 94km of viaduct section and 30 km underground works. This US$ 4 billion scheme has been jointly funded by the Japan International Cooperation Agency (JICA), the Government of India and the Delhi Government.

The bored tunnelling works were divided into 3 contracts, with the contractors employing launch/retrieval shafts either within the station box footprint or external to the station box. Various proposals for the method of tunnel eye breaking were made by the contractors for the passage of the TBM into or out of shafts. Because of the tight construction schedule, 7.2km of the Qutab Minar Line (Line-2) had been allocated 6(six) TBMs, and 4.2km of the Badarpur Line(Line-6) had been allocated 4(four) TBMs. The first tunnel TBM started in the Qutab Minar Line (Line-2) on 31st December 2007 and the last tunnel TBM completed the Badapur Line(Line-6) on 11th October 2009.

In this paper, the various construction methods for tunnel eye breaking and related design issues are discussed.
2. GEOLOGICAL CONDITIONS
The recent alluvial deposits are separated into “older” and ‘younger’ alluvium. The older alluvium is typically found on the higher topography and consists of fine grained deposits with ‘Kankar’. This is locally known as Delhi silt. The younger alluvium is found in association with the Yamuna River and is sandier in nature and without Kankar. Younger alluvial deposits were not expected to occur along the Contract alignment. Kankar is a term for irregularly shaped calcareous nodules that are formed by leaching of minerals from the soil by fluctuating ground water levels.

They are typically of gravel size but can be up to cobble size. The alluvium has infilled previous channels along the route and a variable rock head was expected along the alignment. A summary of the geological sequence is shown in Table 1.

**Figure 2. Geology of Delhi and TBM section**

![Geology of Delhi and TBM section](image)

**Table 1. Summary of Geological sequence**

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger Alluvium</td>
<td>Present</td>
<td>Typically found as sand in close proximity with the Yamuna River</td>
</tr>
<tr>
<td>Older Alluvium</td>
<td>Pleistocene</td>
<td>Fine grained soil with kankar and ferruginous concretions typically found at elevations above immediate river bank level on river terraces</td>
</tr>
<tr>
<td>Aeolian</td>
<td>Pleistocene</td>
<td>Possible occurrence of Aeolian silts</td>
</tr>
<tr>
<td>Intrusives</td>
<td>Pleistocene</td>
<td>Quartz and pegmatite</td>
</tr>
<tr>
<td>Alwar Series</td>
<td>Proterozoic</td>
<td>Metasedimentary sequence consisting primarily of quartzite with schist and calcareous rocks</td>
</tr>
</tbody>
</table>

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**Central Secretariat to Qutab Minar section (Line-2)**
The tunnel alignment in this section passes through mainly alluvium ie clayey silt with Kankar. Quartzite was encountered at Central Secretariat and the depth of rock from ground level increases along the proposed alignment towards Qutab Minar. The rock head level is above the base level of Udyog Bhawan station which is very near to Central Secretariat. The rocky stratum again appears at shallow depth at Jorbagh station south end (the TBM cutter head was replaced at this location as rock in approximately 240 metres length was encountered). The same rocky stratum is again encountered at Malviya Nagar station.

The strata through which tunneling has been done is mainly Delhi silt, consisting of 3% to 12% of clay, 60% to 86% of silt with 3% to 15% of sand & gravels. The laboratory test results reveal that the soil has been over consolidated though consolidation test results suggested a normally consolidated soil; this may be attributed to disturbances occurring during sampling and testing. The natural moisture content which is less than plastic limit also indicates that the soil is over consolidated and OCR is more than 1. Cohesion has been assumed negligible whereas the angle of internal friction was observed as 30°- 32°. The site condition shows some cohesion present in the strata. The water table gradually decreases from Central Secretariat to Saket and dewatering was required during station and cross passage construction from Udyog Bhawan to Jorbagh.

**Central Secretariat to Lajpat Nagar (Line-6)**
Geotechnical investigations revealed that the stratum from Central Secretariat to Lajpat Nagar was generally Delhi silt other than the area immediately south of Central Secretariat station, which consisted of rocky strata followed by alluvial deposits. The rocky stratum is quartzite with schist. The laboratory tests revealed mainly Delhi silt consisting of a clay fraction less than 10%, silt from 40% to 89% with 4% to 14% sand & gravels. The water table is high near Khan Market station, about 5m below ground level. Extensive dewatering at the time of construction of the station and cross passages was required.
3. TUNNEL EYE BREAKING METHOD
The underground stations were planned with island type platforms, and shafts at both ends of the stations were planned for tunnelling operations.
A plan of a typical underground station is shown in Figure 3. The tunnel eye breaking method for each shaft is introduced below, and a summary is shown in Figure 4.

3.1 Contract BC16 (Continental Engineering Corporation-Soma JV)
(a) Geotechnical conditions:
The soil condition is generally Delhi silt, and the ground water level from Udyog Bhawan to Jorbagh station is 8 to 16 meters below ground level. Dewatering was carried out during station excavation and tunnel eye breaking. The ground water level from I.N.A to Green Park station is 25 to 37 meters below ground level. Installation of entrance packing at the tunnel eyes was carried out.
(b) Structural form of launching and retrieval shaft:
The launching shaft end walls were constructed as diaphragm walls (t=800mm) with GFRP (Glass Fiber Reinforced Plastic) reinforcement generally at the tunnel eyes for easy break through. All TBM retrieval shafts in stations were constructed by diaphragm wall (t=800mm).
(c) Tunnel eye breaking method at launching shaft:
BC16 proposed the following tunnel eye breaking methods.
Method 1: Diaphragm wall was cut by TBM directly. (Jor Bagh station north shaft)
Due to difficulties encountered with TBM’s cutting through the diaphragm wall, Method 2 was also adopted.
Method 2: Steel pipe piles (φ273mm×9.5mm) were installed on the earth side of the diaphragm wall. The tunnel eye of the diaphragm wall was then demolished by coring and breaker and then the TBM was moved forward to support the soil face after which the steel pipe piles were removed. Due to the good soil condition, the tunnel eye soil face was able to stand up with a nominal layer of shotcrete sealing the exposed surface. Steel pipe pile construction is shown in Figure 5 and tunnel eye is shown in Figure 6. The execution precision of the steel pipe piles was not very good, but it did support the soil pressure safely.
Figure 4. Summary of tunnel eye breaking method
(d) Tunnel eye breaking method at retrieval shaft:
Before the TBM was about to touch the diaphragm wall, a hole in centre was made by coring so that fish tail of the TBM could move inside retrieval shaft and the cutter could almost touch the diaphragm wall. The tunnel eye was then demolished by breaker and the TBM pushed into the shaft. Soil improvement on the earth side of the diaphragm wall was not planned, due to good ground conditions.

3.2 Contract BC18: (Metro Tunneling Group, Dywidag-L&T-Samsung-Ircon-Shimizu JV)
In this site, JV had proposed various tunnel eye breaking method from the monitoring result of shaft excavation. This monitoring result is explained briefly below.

**Example of monitoring result of Retaining wall for Cut and Cover [2]**
The section drawing of the shaft at BC18 Malviya Nagar station is shown in Figure 8. The size of a Shaft (L×B×D) was 61.2m×23.6m×19.2m. For the retaining wall, concrete bored piles, 900mm in diameter at 1.6m centre to centre were used. Soil parameters i.e., γ=19.5kN/m³, ϕ=30°, C=0 kN/m² and E=350Cu kN/m²(Cu=10+6z) were selected for design of the retaining wall. The ground water level was 30 meters below ground level. The actual axial force of the struts and the horizontal displacement of the retaining wall were obtained by monitoring. The axial force is shown in Table 2 and the horizontal displacement is shown in Figure 9. From the monitoring results, the actual active soil pressure was less than the design value. This indicated that the Delhi silt without ground water had good cohesion properties.

![Figure 8. Section of shaft (BC18 Malviya Nagar station)](image)

**Table 2. Axial force of strut (measured by strain gage)**

<table>
<thead>
<tr>
<th>Strut position</th>
<th>(1) Design value (kN)</th>
<th>(2) Monitoring result (kN)</th>
<th>Ratio (2)/(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>1,940</td>
<td>540~640</td>
<td>0.28~0.33</td>
</tr>
<tr>
<td>2nd layer</td>
<td>9,900</td>
<td>1,800~1,980</td>
<td>0.18~0.20</td>
</tr>
</tbody>
</table>

(a) Geotechnical conditions:
The soil condition is generally Delhi silt, and ground water level is 30 meters below ground level. Dewatering was not necessary during station excavation and tunnel eye breaking.

(b) Structural form of launching and retrieval shaft:
- The TBM north shaft in Malviya Nagar station was constructed by bored piles (φ=900mm, ctc 1.6m) with GFRP reinforcement at the tunnel eyes for ease of break through.
- The TBM south shaft in Malviya Nagar station was constructed by steel soldier piles.
- The TBM shaft in Hauz Khas station was constructed by diaphragm wall with GFRP reinforcement at the tunnel eyes for ease of break through.
(c) Tunnel eye breaking method at launching shaft; 
BC18 proposed the following three tunnel eye breaking methods for launching. 
Method 1: (North shaft in Malviya Nagar station): (Figure 10)  
Half of the bored piles were demolished before the TBM entry, and the remaining cut by TBM. 
Method 2: (North shaft in Hauz Khauz station): (Figure 11)  
Diaphragm wall was demolished up to the soil face reinforcement (GFRP) and a 50mm thickness shotcrete layer applied, and the TBM later cut through this outer rebar layer. Soil improvement on the earth side of the diaphragm wall was not required. 
Method 3: (South shaft in Malviya Nagar station): (Figure 12,13)  
The permanent end wall of the shaft was constructed with a vertical circular opening by bottom up construction using soldier piles and the gap between the permanent end wall and soldier piles was filled with plain concrete (M5). The TBM cut through the plain concrete wall. Soldier piles were removed before the TBM entry.

(d) Tunnel eye breaking method at retrieval shaft; (Figure 14)  
The diaphragm wall was demolished by breaker up to the soil face reinforcement before the TBM arrived. This soil face reinforcement was cut after the TBM touched the face of the diaphragm wall. Rebar was cut and removed and the remaining concrete cover cut by TBM. Soil improvement on the earth side of the diaphragm wall was not required.
3.3 Contract BC24 (ITD-ITD Cem JV)

(a) Geotechnical conditions:
The soil condition is generally Delhi silt, and ground water level is 4 to 15 meters below ground level. Dewatering and installation of entrance packing at tunnel eyes was carried out.

(b) Structural form of launching and retrieval shaft:
All TBM launching and retrieval shafts were constructed by diaphragm wall (t=800mm) with GFRP reinforcement at the tunnel eyes for ease of break through.

(c) Tunnel eye breaking method at launching shaft: (Figure 15, 17)
Although the contractor planned to cut the diaphragm wall (with GFRP reinforcement) directly by TBM, the procedure was too slow therefore the following alternative method was considered. A plain concrete wall (M10) was constructed on the earth side by similar method to that of the diaphragm wall. The tunnel eye was demolished by coring and breaker and the TBM cut through the plain concrete wall. Due to good soil conditions with reasonable stand up time, soil improvement planned with Jet Grouting was not required.

(d) Tunnel eye breaking method at retrieval shaft: (Figure 16)
Two plain concrete walls (M10) (2x t = 800mm) were constructed on the earth side of the diaphragm wall by similar method to that of the diaphragm wall. The TBM cut through both plain concrete walls and the TBM touched the face of the diaphragm wall, the diaphragm wall was demolished by breaker and the TBM pushed into the shaft.
JLN Station, the diaphragm wall was demolished by breaker up to the soil face reinforcement before the TBM arrived, the TBM cut through both the plain concrete wall and the remaining diaphragm wall layer. The ground water level was monitored before construction started. The diaphragm wall was cut by TBM directly at the Lajpat Nagar shaft.

Figure 15. JLN launching shaft  
Figure 16. Khan Market retrieval shaft  
Figure 17. Tunnel eye reinforcement method by M10 concrete for the TBM launching
(e) Design of the plain concrete wall at launching shaft:
The JV applied circular plate theory for design of the plain concrete wall. The basic formula is shown below;

\[ Mr = \frac{wh^2}{64} (3 + \nu)(1 - \xi^2) \]

\[ Mr = \text{moment in radial direction} (kN \cdot m), \ w = \text{soil pressure} (kN/m^2) \]
\[ h = \text{diameter} = 2r(m), \ \nu = \text{Poisson’s ratio} \]
\[ \xi = \text{distance of point considered from slab centre} \]
\[ r = \text{radius of slab} \]

4. CONCLUSION
The execution of all Tunnel eye breaking progressed satisfactorily. Each JV adopted different construction methods, with a total of eleven techniques adopted (6 for launching shafts, 5 for retrieval shafts). Safe cutting of the diaphragm walls was achieved due to the favourable ground conditions prevailing in Delhi which allowed a number of design options to be considered. The following conclusions were noted;

1) The ground conditions were relatively good with a reasonable stand up time, most of the tunnel eye breaking was performed in advance of the TBM launch or arrival with the arrangement of a temporary wall by lean concrete or steel pipe behind the diaphragm wall, together with localized dewatering.

2) At some locations, cutting the diaphragm wall (with GFRP reinforcement) directly by TBM proved difficult because of the cutting bit arrangement of the TBM face, the bit material strength and limitations in the adjustment of the TBM face rotation speed.

3) It is common to apply soil improvement behind the diaphragm wall at the retrieval shaft to prevent soil and water leakage at the gap between the diaphragm wall and TBM, however, it was not found necessary in Delhi Silt with good dry soil conditions.

4) With a high ground water level, dewatering was adopted for safe tunnel eye breaking, although 10~15mm ground surface settlement resulted.

5. ACKNOWLEDGEMENTS
We would like to thank the civil contractors, namely Continental Engineering Corporation-Soma JV (BC16), Dywidag-L&T-Samsung-Iron-Shimizu JV (BC18), ITD-ITD Cem JV (BC24), for providing the data for the tunnel eye breaking methods. We also thank Mr. Ravindra Dutta (Tunnel expert of the general consultants) for his assistance.

REFERENCE