Unforeseen ground conditions met in North Bound Tunnel (TBM - Rudra) in Tunnelling Work and solution found, Remedial measures Implemented – Case study

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Abstract— Carrying out Underground works such as tunneling and stations in difficult geology like Bangalore is challenging task. Designer has to adopt the innovative solution for station design due to limited space. The alignment of an underground metro project is constructed with twin tunnels by Tunnel Boring Machine (TBM) connecting two stations. Any underground excavation has a major influence on the nearby existing structures. Construction of tunnel using TBM needs proper planning in soil investigation, fixing alignment, selection of type of TBM, choosing of right drive sequence considering the logistic and feasibility aspects., deploying appropriate number of TBMs and execution of the work. As the investment over TBMs is huge, any major change effects during project execution leads to cost and time over-run. Also Utility shifting, traffic shifting impact in traffic movement, another challenge is to save the tree, save environment. In case heritage building at the surface, close monitoring is ensured. Bangalore Metro Rail Corporation Ltd (BMRCL) awarded work of underground construction between south ramp to Vellara consisting 3 underground stations and 5.4km of tunnel to M/s AFCONS Infrastructure Ltd. M/s AFCONS deployed 3 TBM's, 2 slurry machines and one EPB machine. Several challenges, unusual hurdles were faced during execution of tunnelling work. This paper covers the challenges faced during tunneling in the ground filled with artificial materials like plastic sheets, animal bones, bottles and solutions found.

Index Terms- Underground metro, Geology, TBM, ground improvement, Face mapping, Excavation, Surface settlement

I. INTRODUCTION

Challenge faced in successfully come out of abandoned stone quarry filled with city waste which was met on the way by TBM named Rudra deployed for north bound tunnel construction from south ramp to Langford by M/s AFCONS for phase-II of Bangalore Metro Project in pink line from Kalena Agrahara to Nagawara. Entire loose fill along the tunnel path was replaced with concrete by piling method and tunneling in the area was successfully completed within 6 months of encountering the loose fill.

Bangalore Metro Rail Corporation Ltd (BMRCL) awarded work of underground construction between south ramp to Vellara consisting 3 underground stations and 5.4km of tunnel to M/s AFCONS Infrastructure Ltd. M/s AFCONS deployed 3 TBM's, 2 slurry machines and one EPB machine. One of the slurry machines named Rudra completed first drive up to Dairy circle station and was deployed from Dairy circle in the second drive. After completing 373.8m (Fig. 1,2) a sink hole was formed ahead of the cutter head. The sink hole was formed in a shed being used as a granite show room. The sink hole was treated and TBM was advanced. But, sink hole was formed again before even one ring was built. Considering repeated formation of sink holes, it was decided to carry out a detailed soil investigation in the area ahead of the TBM.

Fig. 1: Showing location of TBM 1259 of of North bound between Dairy circle to Lakkasandra stretch from CH.9000 to CH.9050

Fig. 2: Showing the google earth view of RT01 Tunnel alignment (Drive 2) North bound between Dairy circle to LAKKASANDRA STRETCH

II. SOIL INVESTIGATION

Bangalore metro has adopted normal twin tunnel system having 5.8m internal diameter. The tunnels are placed 15.2m apart. Therefore, width between external edges of twin tunnel works out to around 21.5m. Considering land availability for stations and minimum gradient & curvature essential for Metro Rail Track, it is difficult to fallow alignment of road. Also, as the road width is seldom lesser than 17m (50 feet road) the tunnel alignment invariably goes beyond ROW of road which generally belongs to private land owners. The tunnel needs to be constructed below private properties. Soil investigation before starting the tunneling work is generally carried out within ROW of road along the alignment and not in private properties situated outside. BMRCL carried out very detailed soil investigation before calling tenders for the work by digging bores at every 30m interval.

Soil investigation carried out beyond location of TBM stopped due to repeated formation of sink holes revealed that soil beneath the ground contained blackish waste (Fig. 3, 4) indicating the presence of deposition of city waste. Such material was not found in any of the soil investigation locations considered while detailed investigation before tendering process. The Geophysical survey was also carried out in the area (from Chainage 8+940 to 9+340m) along Bannerghatta road. Report on such survey is placed as Annexure A. As may be seen from the report, the investigation did not detect artificial materials.

Fig. 3

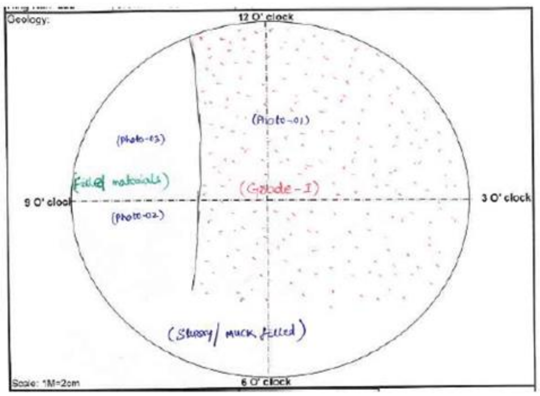
Fig. 4

III. INCIDENT REPORT

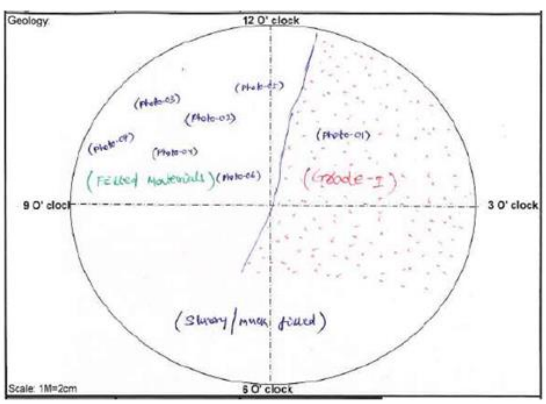
Metro Tunnels are generally placed at a shallow depth. Crown of the tunnel in this location is at a depth of 9.60m below the ground in the area. Multiple cavities were formed during the mining of ring 697, bones, plastic and other man made materials were received in screen of Slurry Treatment Plant while TBM excavation in the area. It was tried to consolidate the area by cement grouting method. The machine was restarted but the ground could not sustain itself and multiple sink holes happened again. TBM face was inspected and a face mapping was prepared (Fig. 5) which revealed again the availability of manmade material in the face. Considering the face condition, it was decided to probe the area beyond cutter head.

Geological mapping of excavated face in this zone indicated the partial exposure of poor geological condition with debris/garbage. Additional drillings dynamic cone penetration tests were also carried out for further investigation.

On west side of properties in which the North bound tunnel alignment is passing, a densely built low cost housing colony is existing. If the TBM is moved further without any precaution, the loosely filled material would likely to flow towards tunnel face from a considerable distance which may cause settlement to the buildings densely built in the area. Refer Annexure B (Incident report photos)



Face Mapping data of Ring No.695



Face Mapping data of Ring No. 697

FIG. 5

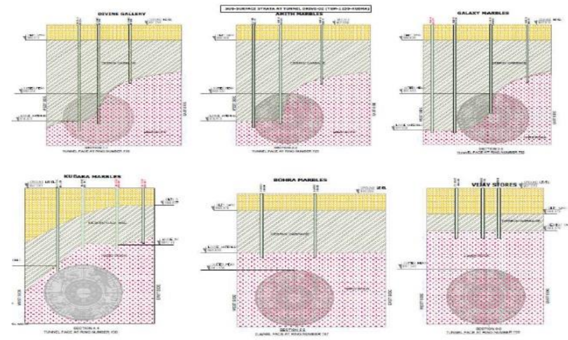
IV. ADDITIONAL INVESTIGATION

Additional investigation was carried out, rock face mapping, dynamic cone penetration test (DCPT) conducted at several locations on the surface to know the rock levels.

Several DCPT probes were drilled along the alignment and different cross sections were plotted with respect to the rock levels found in each probe, the section on each building with rock profile shown below: (Fig. 6,7,8)

Plan showing proposed DCPT locations along with alignment

Fig. 6



Geological Cross Sections ahead of TBM 1259

Fig. 7

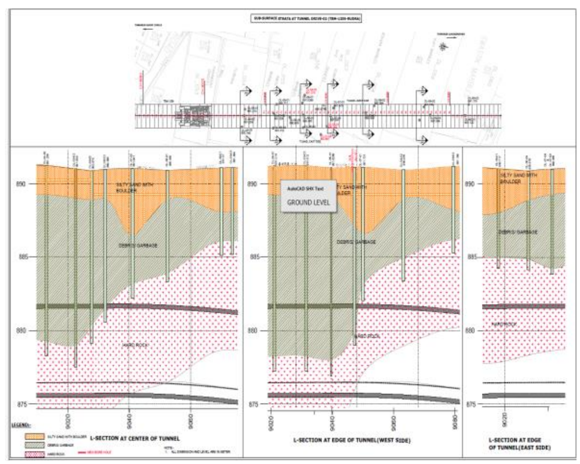


Fig. 8

The investigation revealed that 75% of the tunnel face on East side is in rock and balance 25% on West side is filled with manmade materials. (Fig. 9) All the bore-logs of the DCPT tests are available in Annexure C.

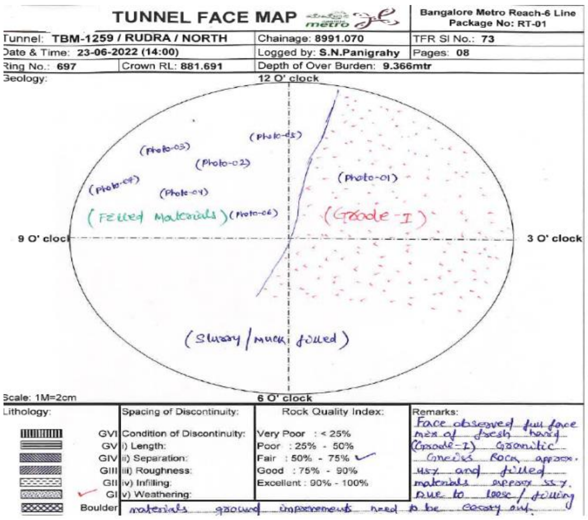


Fig. 9

V. INSTRUMENTATION & MONITORING DATA

Many instruments for example ground settlement marker (GSM), Surface settlement marker (SSM), Building settlement marker (BSM), crack meter, tilt plates, etc were installed during the TBM drive, respective reading of the instruments are attached in Annexure D.

BSM and some of the instruments were damaged due to sink holes. Refer Annexure D for details.

VI. GROUND IMPROVEMENT PROPOSAL

If the TBM is moved further without any precaution, the loosely filled material is likely to flow towards tunnel face from a considerable distance which may cause settlement to the buildings densely built in the area.

Based on the detailed review of the available geological information, incident data and I&M data, to overcome excessive settlement at ground level in the area it was observed that ground improvement is necessary in this area in order to drive the TBM further.

To overcome excessive settlement at ground level in the area, soil replacement method was adopted by providing 1200mm diameter concrete pilling to strengthen the area. To strengthen the area, the work consists of providing one row of RCC piles with liner at a distance of 3.7m on west side of north bound tunnel and 6 rows of consecutive soft piles in the length of around 66.25m. To avoid pressure loss from the space between piles, cement grouting was proposed by driving pipe of suitable diameter. (Refer to Fig. 9)

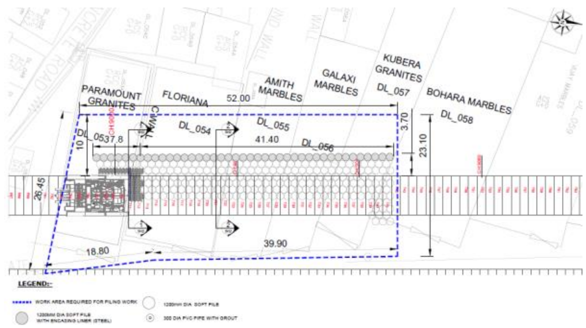
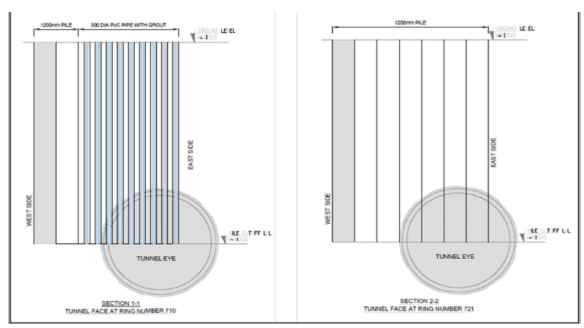


Fig. 9

Piling work was not advised to do very closed to the cutter head of TBM for the reason that the concrete may enter cutting chamber/cutter head and cause damage to TBM. Therefore, pilling was done at a distance of around 2m away from the cutter head. This gap was grouted with suitable material from surface (Fig 9, 10).

The cantilever behavior accordingly the detailed plan of ground improvement shown below (Fig. 10):



Cross Section of the Proposed Ground Improvement

Fig. 10

VII. FEM ANALYSIS

RS2 software has been used for the analyses, as to check the overall stability of the system under different conditions. Material models used to describe the behavior of the ground shall apply suitable constitutive laws to account for the elastic, as well as inelastic ranges of the respective materials. The Mohr-Coulomb model is used for the analysis. All materials (soil and rock) are considered as elastic perfectly plastic.

The side piles are modeled as liner element with elastic material type.

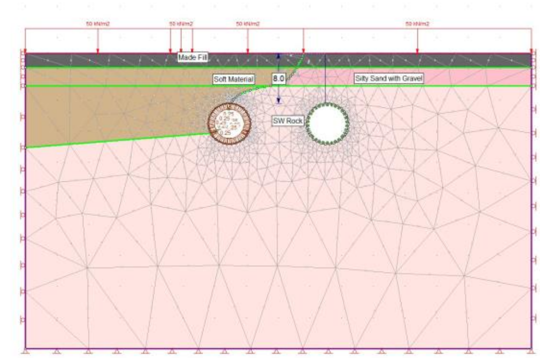
According to two-dimensional stress distributions at tunnel face, the 2D plane strain analyses were used to simulate the TBM drives, the main variables considered in the analyses are the overburden, ground types of parameters.

FEM model consideration:
Earth pressures at rest for normally consolidated soils is considered as per Jaky's equation Ko=1-Sin. The coefficient of earth pressure at rest in rocks of geologically undisturbed regions may be attributed to the vertical gravitational stress and the Poisson's ratio of the rock and estimated using the relation Ko=v/(1-v). For debris material Ko=0.3 has been considered in FEM analysis. Surcharge of 50 Kn/m2 has been considered due to presence of buildings. Water table has been considered at 2.0m below existing ground level.

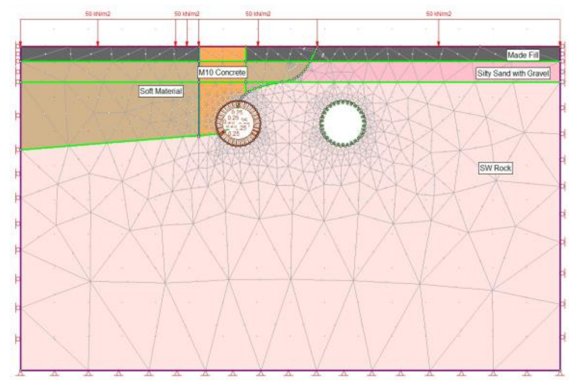
75% of stress relaxation is assumed for North Bound TBM drive due to present of debris material at TBM face. No relaxation is allowed for South Bound TBM tunnel this drive has been already completed successfully.

Following cases are considered for FEM analysis.
Case-1-TBM drives in actual ground condition,
Case-2-TBM drives in improved ground condition with side soft pile only at 2.5m from surrounding edge of North Bound TBM. Refer Annexure E for FEM input parameters.

Refer below given figures for FEM models:



Tunnel excavation in actual ground condition
Fig. 11



Tunnel excavation after ground improvement
Fig. 12

FE analysis sequence:

Table 1: FEM model sequence (Case-1)

Construction stage number	Stage Description
1	In-situ stress field, no surcharge, reset displacement zero
2	Application of surcharge load. Ground water table considered 2.0m below EGL and reset displacement to zero
3	South Bound TBM drive
4	North Bound TBM drive (75% relaxation)

Table 2: FEM model sequence (Case-2)

Construction stage	Stage Description

number	
1	In-situ stress field, no surcharge, reset displacement zero
2	Application of surcharge load. Installation of 13.2m long soft pile wall and M10 concrete material. Ground water table considered 2.0m below EGL and reset displacement to zero
3	South Bound TBM drive
4	North Bound TBM drive (100% relaxation)

- Result comparison and Discussion:

Summary of FE analysis result for different conditions are as below:

Table 3: Summary of ground and TBM settlements

Particulars	Total displacement surrounding TBM-North bound (mm)	Surface settlement (mm)
Case-1: Weak ground	160	55
Case-2 Improved ground	<12	<6.5

For output of FE analyses, refer Annexure E.

CONCLUSION

Face mapping data and DCPT confirmed that the partial exposure of TBM Rudra on the debris zone, as confirmed in the incident report multiple sink holes also reported. The problem was diagnosed based on magnitude of displacements which exceeded the alarm level. The problem was identified as unforeseeable ground conditions (unfavorable debris zone) and consequential construction related issues for the TBM drive.

Immediate measures of grouting along with additional monitoring were proposed.

FEM results showed excessive settlements more than 150mm due to the debris/garbage without ground improvement. Soft pile block of 1200 dia with M10 concrete from CH.9000 TO CH.9050 was proposed, the outer most row of piles were socketed to minimum depth of 300mm in grade I/II rock to obtain the cantilever behavior of pile and casting retained for additional stability.

FEM results after the ground replacement shows negligible surface settlement values of less than 6.5mm and surface settlement values are less than 2mm away from the ground improvement zone.

LESSON LEARNT

Geology plays a very important role, any adverse and unforeseen geological conditions influence the safety of tunnels, construction time and cost. Urban tunneling is always a challenge because of the risk it poses to the structures and public when things go unexpectedly. Action plan for any unforeseen situation shall be kept ready in an event of emergency.

A detailed soil investigation is very essential before taking up any tunnelling project. In urban area, there is acute land scarcity and developmental works are required to be taken up in available land. Before starting Tunnelling, carrying out soil investigation along the alignment of Tunnel can avoid meeting surprises like TBM entering a city fill zone. At the least, if dynamic probing is conducted along the tunnel alignment, strength of the ground can be assessed and remedial measure, if found essential can be taken. Accurate indirect soil investigation methods (geophysical survey, ground penetration radar) are required to be further improved so that soil investigation can be carried out without disturbing the existing ground.

ANNEXURE A

Table 4

The inference of seismic velocities and depths are summarizes as under based on the seismic tomograms:

I. Topmost layer comprises of overburden material as alluvium deposits and debris/rock slumps, sand, boulders, gravel size fragments having seismic velocity of the order of 400 m/sec to 1500 m/sec with thickness varying 3.504m to 4.072m in SR-2. Lower velocities indicate loose nature of overburden.

II. Second layer interpreted as highly compacted, moderately weathered rock strata having moderate seismic velocity of the order >1500m/sec to 2500m/sec with varying thickness of 8.210m to 9.540m, in SR-2 seismic section. This represents highly compacted, moderately weathered rock strata.

III. Third layer interpreted as weathered rock strata having moderately high seismic velocity >2500 m/sec to 3000m/sec indicating weathered rock strata. This layer is considered as base highly compacted & weathered in nature.

Based on the interpretation of Seismic refraction results, interpretative Geological section has been developed along the seismic lines SR-2 presented in the Annexure-II.

Detailed locations of all the Geophones for each Seismic Survey line along with depth of weathered rock are presented as follows.

GEODETIC SURVEY OF SR-2(Along the alignment)

S.No.	Alignment Chainage (m)	Code	Easting (m)	Northing (m)	Elevation (m)	Unconsolidated Overburden (m)	Moderately weathered Rock (m)
1	8+940	SR-2/1	782398.385	1432449.100	890.378	886.468	878.245
2	8+945	SR-2/2	782397.445	1432454.011	890.449	886.516	878.024
3	8+950	SR-2/3	782396.505	1432458.922	890.539	886.641	877.856
4	8+955	SR-2/4	782395.565	1432463.833	890.630	886.792	877.893
5	8+960	SR-2/5	782394.625	1432468.744	890.700	886.891	877.933
6	8+965	SR-2/6	782393.685	1432473.654	890.773	886.981	878.076
7	8+970	SR-2/7	782392.744	1432478.565	890.865	887.135	878.219
8	8+975	SR-2/8	782391.804	1432483.476	890.959	887.240	878.202
9	8+980	SR-2/9	782390.864	1432488.387	891.030	887.284	878.150
10	8+985	SR-2/10	782389.924	1432493.298	891.107	887.302	878.049
11	8+990	SR-2/11	782388.984	1432498.208	891.205	887.351	877.949
12	8+995	SR-2/12	782388.043	1432503.119	891.304	887.422	877.923
13	9+000	SR-2/13	782387.103	1432508.030	891.380	887.415	878.081
14	9+005	SR-2/14	782386.208	1432512.948	891.435	887.405	878.290
15	9+010	SR-2/15	782385.537	1432517.903	891.505	887.433	878.501
21	9+040	SR-2/21	782381.511	1432547.632	892.078	888.100	879.216
22	9+045	SR-2/22	782380.840	1432552.586	892.102	888.190	879.168
23	9+050	SR-2/23	782380.169	1432557.541	892.133	888.218	879.201
24	9+055	SR-2/24	782379.518	1432562.498	892.164	888.239	879.211
25	9+060	SR-2/25	782379.154	1432567.485	892.188	888.256	879.059
26	9+065	SR-2/26	782378.790	1432572.471	892.195	888.255	878.946
27	9+070	SR-2/27	782378.426	1432577.458	892.204	888.255	878.961
28	9+075	SR-2/28	782378.062	1432582.445	892.213	888.274	879.041
29	9+080	SR-2/29	782377.698	1432587.432	892.220	888.309	879.100
30	9+085	SR-2/30	782377.334	1432592.418	892.188	888.308	879.097
31	9+090	SR-2/31	782376.970	1432597.405	892.146	888.272	878.996
32	9+095	SR-2/32	782376.498	1432602.382	892.105	888.200	878.841
33	9+100	SR-2/33	782375.987	1432607.356	892.073	888.126	878.787
34	9+105	SR-2/34	782375.477	1432612.330	891.902	888.041	878.702
35	9+110	SR-2/35	782374.966	1432617.304	891.686	887.880	878.610
36	9+115	SR-2/36	782374.456	1432622.278	891.465	887.643	878.551
37	9+120	SR-2/37	782373.877	1432627.244	891.298	887.394	878.466
38	9+125	SR-2/38	782373.237	1432632.203	891.145	887.199	878.288
39	9+130	SR-2/39	782372.597	1432637.162	890.951	887.047	878.109
40	9+135	SR-2/40	782371.957	1432642.120	890.753	886.923	877.933
41	9+140	SR-2/41	782371.317	1432647.079	890.603	886.843	877.767
42	9+145	SR-2/42	782370.677	1432652.038	890.555	886.741	877.668
43	9+150	SR-2/43	782370.037	1432656.997	890.494	886.632	877.597
44	9+155	SR-2/44	782369.397	1432661.956	890.432	886.520	877.534
45	9+160	SR-2/45	782368.757	1432666.915	890.385	886.458	877.540
46	9+165	SR-2/46	782368.117	1432671.874	890.351	886.447	877.531
47	9+170	SR-2/47	782367.477	1432676.832	890.306	886.459	877.469
48	9+175	SR-2/48	782366.837	1432681.791	890.262	886.544	877.378
49	9+180	SR-2/49	782366.269	1432686.759	890.228	886.535	877.270
50	9+185	SR-2/50	782365.713	1432691.728	890.178	886.421	877.175
51	9+190	SR-2/51	782365.157	1432696.697	890.114	886.261	877.095
52	9+195	SR-2/52	782364.601	1432701.666	890.049	886.124	877.047
53	9+200	SR-2/53	782364.046	1432706.635	890.000	886.005	877.034
54	9+205	SR-2/54	782363.490	1432711.604	889.885	885.856	876.909
55	9+210	SR-2/55	782362.934	1432716.573	889.738	885.708	876.834
56	9+215	SR-2/56	782362.795	1432721.565	889.594	885.616	876.718
57	9+220	SR-2/57	782362.795	1432726.565	889.485	885.526	876.567
58	9+225	SR-2/58	782362.795	1432731.565	889.349	885.472	876.446
59	9+230	SR-2/59	782362.795	1432736.565	889.177	885.383	876.249
60	9+235	SR-2/60	782362.795	1432741.565	889.007	885.226	875.905
61	9+240	SR-2/61	782362.796	1432746.565	888.880	885.021	875.536
62	9+245	SR-2/62	782362.796	1432751.565	888.699	884.800	875.260
63	9+250	SR-2/63	782363.087	1432756.545	888.470	884.522	875.123
64	9+255	SR-2/64	782363.771	1432761.498	888.244	884.258	875.135

ANNEXURE B

- **Sink Hole occurred at "*Paramount Marble Shop*" on 20 July 2022 03:16 am at CH:8992.520m.**

(TBM S1259)

Fig. 13 Showing Sink hole at Paramount Marbel shop

Fig. 14 Showing cracks on Paramount shop

Date: 20 July 2022

- **Grouting (450kg Cement:700Ltr Water) was done on 20th July 2022.**

Fig. 15: Showing grouting is under progress

- Hard Barrication (10 nos.) provided at Sinkhole location for protection.
- Cross bracing column supports also provided at *Paramount Shop*.

Fig. 16: Showing temporary arrangement near sink hole location

Date: 21 August 2022 (Day)

- **Sinkhole occurred at same location at Paramount Marble Shop (Ring 708-710 location)**
- **M20 Concrete: 6 cum, Slurry: 18 cum, Sodium Silicate: 200kg.**

Fig. 17: Showing grouting work at sink hole location

ANNEXURE C

DCPT Points location:

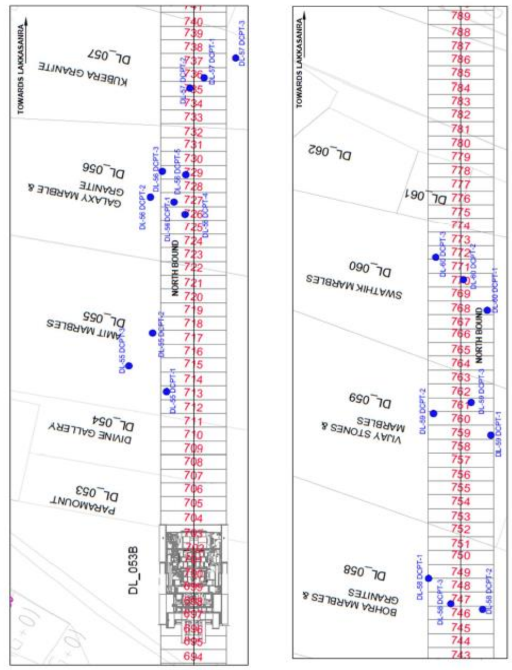


Fig. 18: Showing locations of DCPT points

Table 5: Showing DCPT results

Galaxy Marble & Granites

DCPT-01			DCPT-02			DCPT-03			DCPT-04			DCPT-05		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	56		0 - 1mtr	46		0 - 1mtr	56		0 - 1mtr	93		0 - 1mtr	50	
1 - 2mtr	84		1 - 2mtr	43		1 - 2mtr	53		1 - 2mtr	92		1 - 2mtr	59	
2 - 3mtr	84		2 - 3mtr	41		2 - 3mtr	38		2 - 3mtr	Boulder came		2 - 3mtr	36	
3 - 4mtr	71		3 - 4mtr	35		3 - 4mtr	40		3 - 4mtr			3 - 4mtr	35	
4 - 5mtr	66	24-06-2022	4 - 5mtr	41	24-06-2022	4 - 5mtr	39	24-06-2022	4 - 5mtr		24-06-2022	4 - 5mtr	36	24-06-2022
5 - 6mtr	66		5 - 6mtr	40		5 - 6mtr	53		5 - 6mtr			5 - 6mtr	43	
6 - 7mtr	59		6 - 7mtr	44		6 - 7mtr	54 (7-7.1MTR)		6 - 7mtr			6 - 7mtr	74	
7 - 8mtr	68		7 - 8mtr	53		7 - 8mtr			7 - 8mtr			7 - 8mtr	75	
8 - 9mtr	75		8 - 9mtr	54		8 - 9mtr			8 - 9mtr			8 - 9mtr	76	
9 - 10mtr	74 (9-9.7MTR)		9 - 10mtr	104 (9-9.7MTR)		9 - 10mtr			9 - 10mtr			9 - 10mtr	76	

Kubera Granites

DCPT-01			DCPT-02			DCPT-03		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	69		0 - 1mtr	56		0 - 1mtr	110	
1 - 2mtr	9		1 - 2mtr	89		1 - 2mtr	118 (Stop)	
2 - 3mtr	59		2 - 3mtr	70		2 - 3mtr		
3 - 4mtr	58		3 - 4mtr	63		3 - 4mtr		
4 - 5mtr	66	28-06-2022	4 - 5mtr	54	28-06-2022	4 - 5mtr		28-06-2022
5 - 6mtr	111 (Stop)		5 - 6mtr	58		5 - 6mtr		
6 - 7mtr			6 - 7mtr	71		6 - 7mtr		
7 - 8mtr			7 - 8mtr	82		7 - 8mtr		
8 - 9mtr			8 - 9mtr	108 (Stop)		8 - 9mtr		
9 - 10mtr			9 - 10mtr			9 - 10mtr		

Amit Marbles

DCPT-01			DCPT-02			DCPT-03		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	75		0 - 1mtr	73		0 - 1mtr	108	
1 - 2mtr	96		1 - 2mtr	88		1 - 2mtr	97	
2 - 3mtr	67		2 - 3mtr	61		2 - 3mtr	76	
3 - 4mtr	60		3 - 4mtr	44		3 - 4mtr	67	
4 - 5mtr	60	28-06-2022	4 - 5mtr	44	28-06-2022	4 - 5mtr	78	28-06-2022
5 - 6mtr	62		5 - 6mtr	53		5 - 6mtr	64	
6 - 7mtr	58		6 - 7mtr	75		6 - 7mtr	78	
7 - 8mtr	110 (Stop)		7 - 8mtr	78		7 - 8mtr	91	
8 - 9mtr			8 - 9mtr	72		8 - 9mtr	102 (Stop)	
9 - 10mtr			9 - 10mtr	57		9 - 10mtr		

Bora Marbles & Granites

DCPT-01			DCPT-02			DCPT-03		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	176		0 - 1mtr	219		0 - 1mtr	96	
1 - 2mtr	152		1 - 2mtr	164		1 - 2mtr	128	
2 - 3mtr	64 (2-2.3MTR)		2 - 3mtr	91		2 - 3mtr	76	
3 - 4mtr			3 - 4mtr	92		3 - 4mtr	76	
4 - 5mtr		29-06-2022	4 - 5mtr	89	29-06-2022	4 - 5mtr	71	29-06-2022
5 - 6mtr			5 - 6mtr	86		5 - 6mtr	79	
6 - 7mtr			6 - 7mtr	88		6 - 7mtr	80	
7 - 8mtr			7 - 8mtr	67 blows		7 - 8mtr	80 blows	
8 - 9mtr			8 - 9mtr			8 - 9mtr	36 blows (8-8.2MTR)	
9 - 10mtr			9 - 10mtr			9 - 10mtr		

Vijaya Stone & Marble

DCPT-01			DCPT-02			DCPT-03		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	45		0 - 1mtr	43		0 - 1mtr	78	
1 - 2mtr	38		1 - 2mtr	100		1 - 2mtr	130	
2 - 3mtr	18		2 - 3mtr	73		2 - 3mtr	99	
3 - 4mtr	14		3 - 4mtr	63		3 - 4mtr	93	
4 - 5mtr	35	30-06-2022	4 - 5mtr	65	30-06-2022	4 - 5mtr	96	30-06-2022
5 - 6mtr	40 (5-5.4MTR)		5 - 6mtr	85 (5-5.8MTR)		5 - 6mtr	105	
6 - 7mtr			6 - 7mtr			6 - 7mtr		
7 - 8mtr			7 - 8mtr			7 - 8mtr		
8 - 9mtr			8 - 9mtr			8 - 9mtr		
9 - 10mtr			9 - 10mtr			9 - 10mtr		

Swastick Marbles

DCPT-01			DCPT-02			DCPT-03		
Mtr	No of blows	Date	Mtr	No of blows	Date	Mtr	No of blows	Date
0 - 1mtr	87		0 - 1mtr	75		0 - 1mtr	123	
1 - 2mtr	96		1 - 2mtr	86		1 - 2mtr	111	
2 - 3mtr	76		2 - 3mtr	82		2 - 3mtr	72	
3 - 4mtr	77		3 - 4mtr	68		3 - 4mtr	72	
4 - 5mtr	71	01-07-2022	4 - 5mtr	56	01-07-2022	4 - 5mtr	69	01-07-2022

ANNEXURE D

INSTRUMENTATION AND MONITORING DATA RECORDING AT SITE

Fig. 19: Showing Instrumentation and monitoring array at the location

Table 6: Showing BSM instrument and monitoring data at site and few instrument damaged due to sink hole

Location	TUNNEL DRIVE-02 (BSM DATA)																					
Building Name	NAGARAJ AND RAGU KRISHNA BUILDING				GRANITE PALACE		OMPRAKASH LADHA BUILDING				DIVINE GALLERY		AMITH MARBLES		GALAXY MARBLES AND GRANITE		KUBERA GRANITES		MAHESH BUILDING			
Instrument ID	DL-27-1-1		DL-27-1-2		DL-39-1-1		DL-41-1-1		DL-41-1-2		DL-54-1-1		DL-55-1-1		DL-56-1-1		DL-57-1-1		DL-124-1-1		DL-124-1-2	
Base Reading	890.0766		890.0928		890.1822		890.342		890.3961		891.4602		891.9608		891.8767		891.8453		890.4915		890.6714	
Date	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm
20-12-22	890.0753	-1.3	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3923	-3.8	DAMAGE	#VALUE!	891.9565	-4.3	891.8758	-0.9	891.845	-0.3	890.4956	4.1	890.6763	4.9
21-12-22	890.0753	-1.3	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3923	-3.8	DAMAGE	#VALUE!	891.9565	-4.3	891.8755	-1.2	891.845	-0.3	890.4955	4.0	890.6763	4.9
22-12-22	890.0753	-1.3	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3923	-3.8	DAMAGE	#VALUE!	891.9565	-4.3	891.8754	-1.3	891.845	-0.3	890.4957	4.2	890.6763	4.9
23-12-22	890.0753	-1.3	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3923	-3.8	DAMAGE	#VALUE!	891.9565	-4.3	891.8754	-1.3	891.845	-0.3	890.4957	4.2	890.6763	4.9
24-12-22	890.0753	-1.3	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3923	-3.8	DAMAGE	#VALUE!	891.9565	-4.3	891.8752	-1.5	891.845	-0.3	890.4957	4.2	890.6763	4.9
26-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8752	-1.5	891.845	-0.3	890.4954	3.9	890.6763	4.9
27-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8752	-1.5	891.845	-0.3	890.4954	3.9	890.6763	4.9
28-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8742	-2.5	891.845	-0.3	890.4955	4.0	890.6763	4.9
29-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8742	-2.5	891.845	-0.3	890.4957	4.2	890.6763	4.9
30-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8742	-2.5	891.845	-0.3	890.4955	4.0	890.6763	4.9
31-12-22	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8746	-2.1	891.8435	-1.8	890.4956	4.1	890.6763	4.9
02-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8744	-2.3	891.8434	-1.9	890.4954	3.9	890.6763	4.9
03-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8745	-2.2	891.8436	-1.7	890.4956	4.1	890.6763	4.9
04-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8745	-2.2	891.8441	-1.2	890.4956	4.1	890.6763	4.9
05-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8745	-2.2	891.8439	-1.4	890.4955	4.0	890.6763	4.9
06-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8746	-2.1	891.8442	-1.1	890.4956	4.1	890.6763	4.9
07-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8741	-2.6	891.844	-1.3	890.4954	3.9	890.6763	4.9
09-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8744	-2.3	891.844	-1.3	890.4955	4.0	890.6763	4.9
10-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8739	-2.8	891.8436	-1.7	890.4955	4.0	890.6763	4.9
11-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8739	-2.8	891.8436	-1.7	890.4954	3.9	890.6763	4.9
12-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8735	-3.2	891.8432	-2.1	890.4954	3.9	890.6763	4.9
13-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8732	-3.5	891.8435	-1.8	890.4954	3.9	890.6763	4.9
14-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8735	-3.2	891.8432	-2.1	890.4954	3.9	890.6763	4.9
16-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8732	-3.5	891.8431	-2.2	890.4954	3.9	890.6763	4.9
17-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8732	-3.5	891.8431	-2.2	890.4954	3.9	890.6763	4.9
18-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8732	-3.5	891.8431	-2.2	890.4954	3.9	890.6763	4.9
19-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8732	-3.5	891.8431	-2.2	890.4954	3.9	890.6763	4.9
20-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8731	-3.6	891.8431	-2.2	890.4954	3.9	890.6763	4.9
21-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.8731	-3.6	891.8431	-2.2	890.4954	3.9	890.6763	4.9
23-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9
24-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9
25-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9
27-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4953	3.8	890.6763	4.9
28-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9
30-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9
31-01-23	890.0752	-1.4	890.0915	-1.3	890.1785	-3.7	890.3405	-1.5	890.3922	-3.9	DAMAGE	#VALUE!	891.9565	-4.3	891.873	-3.7	891.8432	-2.1	890.4954	3.9	890.6763	4.9

Location				TUNNEL DRIVE-02 (BSM DATA)							
Building Name	MEER MARBLES		MAHALAKSHMI ROCKS		PARAMOUNT						
Insrument ID	DL-05-1-1		DL-06-1-1		DL-53-1-1		DL-53-1-2		DL-53-1-3		DL-53-1-1A
Base Reading	890.791		890.208		891.4011		891.3711		891.8958		891.3744
Date	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm	Current Reading	Diff in mm
20-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
21-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
22-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
23-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
24-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
26-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
27-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
28-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
29-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
30-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
31-12-22	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
02-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
03-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
04-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
05-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
06-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
07-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
09-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
10-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
11-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
12-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
13-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
14-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
16-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
17-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
18-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
19-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
20-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
21-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
23-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
24-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
25-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
27-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
28-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
30-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6
31-01-23	890.7905	-0.5	890.2076	-0.4	DAMGED		891.3706	-0.5	891.8935	-2.3	891.3738	-0.6

Table 7: Showing crack meter data at site

Instrument Name	Crack Meter					
Buliding name	DL-53 Paramount				DL-82 Masjid Aala	
Instalation date	11-07-22			20.08.22	15-11-22	
Date	CM-01 (mm)	CM-02(mm)	CM-03(mm)	CM-04(mm)	DL-82 CM-01 (mm)	DL-82 CM-02 (mm)
20-12-22	7	10	12	0	0	0
21-12-22	7	10	12	0	0	0
22-12-22	7	10	12	0	0	0
23-12-22	7	10	12	0	0	0
24-12-22	7	10	12	0	0	0
26-12-22	7	10	12	0	0	0
27-12-22	7	10	12	0	0	0
28-12-22	7	10	12	0	0	0
29-12-22	7	10	12	0	0	0
30-12-22	7	10	12	0	0	0
31-12-22	7	10	12	0	0	0
02-01-23	7	10	12	0	0	0
03-01-23	7	10	12	0	0	0
04-01-23	7	10	12	0	0	0
05-01-23	7	10	12	0	0	0
06-01-23	7	10	12	0	0	0
07-01-23	7	10	12	0	0	0
09-01-23	7	10	12	0	0	0
10-01-23	7	10	12	0	0	0
11-01-23	7	10	12	0	0	0
12-01-23	7	10	12	0	0	0
13-01-23	7	10	12	0	0	0
14-01-23	7	10	12	0	0	0
16-01-23	7	10	12	0	0	0
17-01-23	7	10	12	0	0	0
18-01-23	7	10	12	0	0	0
19-01-23	7	10	12	0	0	0
20-01-23	7	10	12	0	0	0
21-01-23	7	10	12	0	0	0
23-01-23	7	10	12	0	0	0
24-01-23	7	10	12	0	0	0
25-01-23	7	10	12	0	0	0
27-01-23	7	10	12	0	0	0
28-01-23	7	10	12	0	0	0
30-01-23	7	10	12	0	0	0
31-01-23	7	10	12	0	0	0

Table 8: Showing Vibration Monitoring data

VIBRATION MONITORING DATA (SDC to LKS / TD-2)					TBM-1259/RUDRA/N
SL.NO	Date	ABOVE CUTTER HEAD			BL ID / Chainage
		Time	PPV(mm/s)	ZC Frequency(HZ)	
1	02-01-23	09.55 AM	3.302	47	CH:9020 - 9040
2	03-01-23	09.20 AM	1.884	57	CH:9020 - 9040
3	04-01-23	09.10 AM	2.696	100	CH:9020 - 9040
4	05-01-23	10.00 AM	2.964	51	CH:9020 - 9040
5	07-01-23	10.20 AM	2.317	47	CH:9040 - 9060
6	09-01-23	10.10 AM	0.977	51	CH:9040 - 9060
7	10-01-23	10.30 AM	0.985	51	CH:9040 - 9060
8	11-01-23	09.00 AM	1.167	47	CH:9040 - 9060
9	12-01-23	09.20 AM	0.977	47	CH:9060 - 9080
10	13-01-23	09.10 AM	0.575	43	CH:9060 - 9080
11	14-01-23	09.20 AM	0.977	57	CH:9060 - 9080
12	16-01-23	10.30 AM	0.567	51	CH:9060 - 9080
13	18-01-23	09.00 AM	0.504	43	CH:9060 - 9080
14	20-01-23	09.30 AM	0.504	51	CH:9080 - 9100
15	23-01-23	09.20 AM	0.796	47	CH:9080 - 9100
16	24-01-23	09.10 AM	0.646	43	CH:9080 - 9100
17	25-01-23	10.10 AM	0.576	51	CH:9100 - 9120
18	27-01-23	10.20 AM	0.785	47	CH:9100 - 9121
19	28-01-23	10.10 AM	0.747	47	CH:9100 - 9122
20	30-01-23	09.00 AM	0.504	51	CH:9100 - 9123
21	31-01-23	09.20 AM	0.567	43	CH:9100 - 9124

ANNEXURE E

Input & Output of FEM Analyses-Snapshots

Material Properties

Silty Sand with Gravel

Material Color	
Initial Element Loading	Field Stress and Body Force
Unit Weight	18 kN/m3
Initial Water Condition	Dry
Elastic Type	Isotropic
Poisson's Ratio	0.3
Young's Modulus	5000 kPa
Use Residual Young's Modulus	No
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Peak Tensile Strength	0 kPa
Peak Friction Angle	27 degrees
Peak Cohesion	5 kPa
Residual Tensile Strength	0 kPa
Residual Friction Angle	27 degrees
Residual Cohesion	5 kPa
Dilation Angle	0 degrees
Use Unsaturated Parameters	No
Material Behaviour	Drained
Porosity Value	0.5
Ks	1e-05 m/s
K2 / K1	1
K1 Definition	Angle
K1 Angle	0 degrees
Soil Type	General
Field Stress	Gravity
Using actual ground surface	Yes
Effective stress ratio (horizontal/vertical in-plane)	0.52
Effective stress ratio (horizontal/vertical out-of-plane)	0.52
Locked-in horizontal stress (in-plane)	0
Locked-in horizontal stress (out-of-plane)	0

SW Rock

Material Color	
Initial Element Loading	Field Stress and Body Force
Unit Weight	26 kN/m3
Initial Water Condition	Dry
Elastic Type	Isotropic
Poisson's Ratio	0.2
Young's Modulus	3.9e+07 kPa
Use Residual Young's Modulus	No
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Peak Tensile Strength	850 kPa
Peak Friction Angle	50 degrees
Peak Cohesion	8500 kPa
Residual Tensile Strength	850 kPa
Residual Friction Angle	50 degrees
Residual Cohesion	8500 kPa
Dilation Angle	0 degrees
Use Unsaturated Parameters	No
Material Behaviour	Drained
Porosity Value	0.5
Ks	1e-08 m/s
K2 / K1	1
K1 Definition	Angle
K1 Angle	0 degrees
Soil Type	General
Field Stress	Gravity
Using actual ground surface	Yes
Effective stress ratio (horizontal/vertical in-plane)	0.25
Effective stress ratio (horizontal/vertical out-of-plane)	0.25
Locked-in horizontal stress (in-plane)	0
Locked-in horizontal stress (out-of-plane)	0

Made Filling

Material Color	
Initial Element Loading	Field Stress and Body Force
Unit Weight	16 kN/m3
Initial Water Condition	Dry
Elastic Type	Isotropic
Poisson's Ratio	0.3
Young's Modulus	5000 kPa
Use Residual Young's Modulus	No
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Peak Tensile Strength	0 kPa
Peak Friction Angle	25 degrees
Peak Cohesion	0 kPa
Residual Tensile Strength	0 kPa
Residual Friction Angle	25 degrees
Residual Cohesion	0 kPa
Dilation Angle	0 degrees
Use Unsaturated Parameters	No
Material Behaviour	Drained
Porosity Value	0.5
Ks	5e-05 m/s
K2 / K1	1
K1 Definition	Angle
K1 Angle	0 degrees
Soil Type	General
Field Stress	Gravity
Using actual ground surface	Yes
Effective stress ratio (horizontal/vertical in-plane)	0.58
Effective stress ratio (horizontal/vertical out-of-plane)	0.58
Locked-in horizontal stress (in-plane)	0
Locked-in horizontal stress (out-of-plane)	0

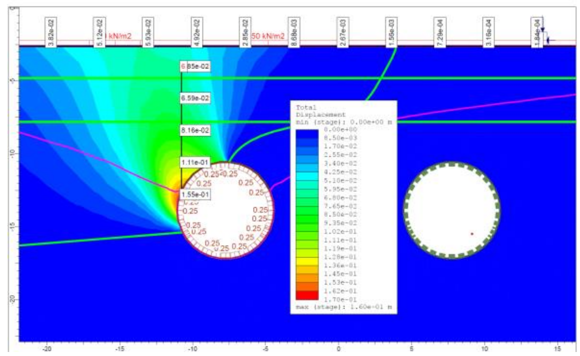
Soft Materil

Material Color	
Initial Element Loading	Field Stress and Body Force
Unit Weight	16 kN/m3
Initial Water Condition	Dry
Elastic Type	Isotropic
Poisson's Ratio	0.3
Young's Modulus	5000 kPa
Use Residual Young's Modulus	No
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Peak Tensile Strength	0 kPa
Peak Friction Angle	24 degrees
Peak Cohesion	8 kPa
Residual Tensile Strength	0 kPa
Residual Friction Angle	24 degrees
Residual Cohesion	8 kPa
Dilation Angle	0 degrees
Use Unsaturated Parameters	No
Material Behaviour	Drained
Porosity Value	0.5
Ks	5e-05 m/s
K2 / K1	1
K1 Definition	Angle
K1 Angle	0 degrees
Soil Type	General
Field Stress	Gravity
Using actual ground surface	Yes
Effective stress ratio (horizontal/vertical in-plane)	0.3
Effective stress ratio (horizontal/vertical out-of-plane)	0.3
Locked-in horizontal stress (in-plane)	0
Locked-in horizontal stress (out-of-plane)	0

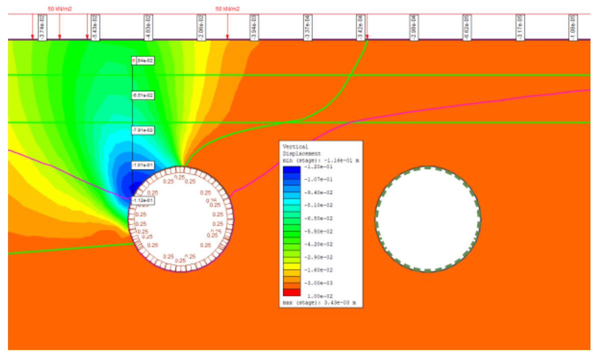
M5

Material Color	
Initial Element Loading	Body Force Only
Unit Weight	24 kN/m3
Initial Water Condition	Dry
Elastic Type	Isotropic
Poisson's Ratio	0.2
Young's Modulus	1.118e+07 kPa
Use Residual Young's Modulus	No
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Peak Tensile Strength	10 kPa
Peak Friction Angle	0 degrees
Peak Cohesion	500 kPa
Residual Tensile Strength	1 kPa
Residual Friction Angle	0 degrees
Residual Cohesion	50 kPa
Dilation Angle	0 degrees
Use Unsaturated Parameters	No
Material Behaviour	Drained
Porosity Value	0.05
Ks	1e-07 m/s
K2 / K1	1
K1 Definition	Angle
K1 Angle	0 degrees
Soil Type	General

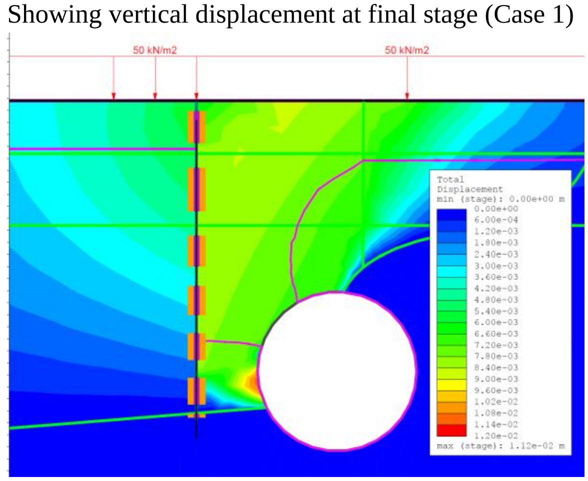
OUTPUT



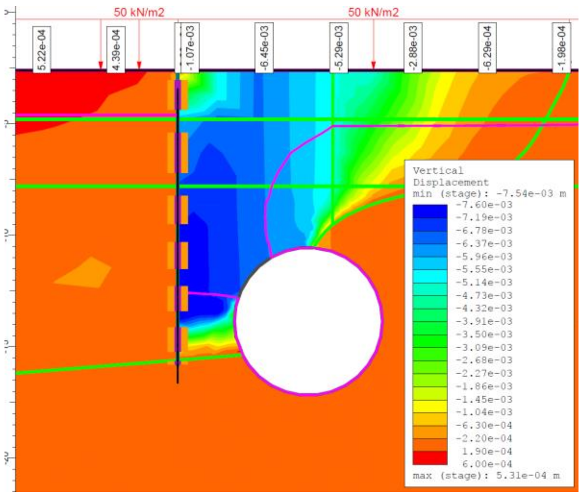
Showing total Displacement at final stage (Case 1)



Showing vertical displacement at final stage (Case 1)



Showing Total Displacement at final stage (Case 2)



Showing Vertical Displacement at final stage (Case 2)

REFERENCES

[1] Geological Interpretative Report – From South Ramp to Vellara Station (Chainage 7521.162m to Chainage 11176.615m), Document No: BMRC3023-REP-045

[2] Bangalore Metro Rail Corporation (Tender Document) : Design & Construction of Underground structures (Tunnels & Stations) of length 3.655 Km (approx.) from South ramp (including) to Vellara junction station (excluding) (Chainage 7521.162m to 11176.615m) including allied works and 3 Nos. of UG Metro Stations viz, Dairy Circle, MICO Industries and Langford Town in Reach-6 line of Bangalore Metro Rail Project, Phase-2, Section: 2 (Outline Design Specification), Section: 8 (Outline construction Specification)

[3] Urban tunnelling in mixed soil conditions: A study of tunnelling works in Bangalore metro rail project, India, Subrahmanya Gudge, Bangalore Metro Rail Corporation Ltd, Bengaluru, India

[4] Responses of a circular tunnel in an elastic ground with an improvement of the subgrade modulus, Chenrong Zhang [a,b], Hao Zhang [a,b], Maosong Huang [a,b], Jian Yu [a,b],*

[5] Discussion on the mechanism of ground improvement method at the excavation of shallow overburden tunnel in difficult ground, Kiyoshi Kishida [a,*] Ying Cui [b], Masaichi Nonomura [c], Tomomi Iura [d], Makoto Kimura [e]

[6] Bieniawski, Z.T. (1979). The geomechanics classification rock engineering applications. Proc. 4th Int. Congr. Rock Mech., ISRM, Montreux, 1979, vol.2, 41-48.

[7] Bieniawski, Z.T. (1989). Engineering rock mass classification: Jhon Wiley & Sons. New York, 272 Hoek-Brown Failure Criterion – 2002 Edition.

[8] A case study on TBM tunnelling in fault zones and lessons learned from ground improvement, Massoud Bayati [a,*] Jafar Khademi Hamidi [b]