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Geotechnical Assessment of Building Damaged by Tunnelling Works and Suitable Remedial Measures – A Case Study

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Abstract. In New Delhi, the rapid development of urban infrastructure in the recent past led to a high demand for utilizing underground space. In the expedition to utilize the underground space effectively numerous underground tunnels are being constructed to facilitate transportation through metros. During the construction of Delhi metro (magenta line), two buildings developed cracks during and after tunneling activities. Both the damaged buildings were load-bearing masonry structures and lie exactly above the tunnel alignment. At these locations, metro line runs at a depth of 24m below Existing Ground Level (EGL). Field settlement monitoring was carried out in 12 different locations to monitor building settlement. The settlement analysis was also carried out using the analytical method developed by Loganathan and Poulos and numerical approach using PLAXIS 3D. From the analysis, it was found that after considering the settlement from foundation pressure and due to tunneling activities, the total settlement of the buildings was within the permissible limit as prescribed in the IS code 1904-1986. Therefore, considering all the settlement data it was identified that these cracks and settlement might be due to the presence of some loose soil pockets below the building. In-order to mitigate settlement, a suitable remedial measure is also suggested.

Keywords: Tunneling, Settlement, PLAXIS 3D, Grouting

1 Introduction

In metropolitan cities like Delhi, where the main problem of daily commuters is traffic congestion, underground metros eases the situation by providing a faster and an eco-friendly transportation alternate. Overall, Delhi Metro system features a combination of underground, at-grade, and elevated sections. The construction of underground infrastructure in densely populated cities like Delhi is a challenging task. The unpredictable soil conditions and presence of water table could increase the risk to the overlying buildings or other infrastructure facilities. Hence it is necessary to assess the safety of the superstructures which are in the influence zone of tunneling works.

The paper describes the effect of tunneling on particularly two buildings in the Defence colony location of Delhi Metro project site. The buildings lie above the tunnel alignment where it runs at a depth of 24m below the Existing Ground Level. Since the building developed cracks after the tunneling works, settlement analysis is carried out and remedial measures for the enhancement of soil profile below these buildings and mitigation of further settlements is also provided.

2 Subsurface Profile and Design Parameters

The sub-soil profile in the region consists mainly of medium dense to dense sandy silt of low plasticity. The soil profile with average SPT N values is given in Table 1. Ground water table was not encountered up to the depth of investigation of 28m.

Table 1. Soil Profile

Soil Type	Thickness (m)	SPT N
Fine Sand	2	13
Sandy Silt	2	20
Sandy Silt	2	30
Sandy Silt	5	42
Sandy Silt	17	>50

The strength parameters of the soil are obtained based on the laboratory test results and general correlations with SPT N values as per CIRIA report 143. Table 2 summarises the properties of soil considered in the numerical simulation.

Table 2. Soil Parameters Considered in the Analysis

Layer	Angle of internal friction(°)	Modulus of Elasticity (kPa)
Fine Sand	31	33,800
Sandy Silt	33	47500
Sandy Silt	36	62,000
Sandy Silt	36	75,000
Sandy Silt	38	80,000

3 Distress in Buildings

Two buildings developed thin to wide cracks in the ground floor and thin to medium cracks in the first floor. The buildings were 34 years old, load bearing type and with G+1 and G+2 storeys.

One of the buildings had an old non-operational bore-well which was left unplugged and foam like substance came through it when tunneling activities was carried out right below the building. Only after this, major crack developed in the building and visible settlement of wall in the courtyard has been observed (refer Figure 1) and the bore-well was plugged immediately. In another building, such incidents were not observed but minor to major cracks are seen in many locations. In-order to address these issues settlement analysis due to building load and tunneling activities has been carried out using the nearby borehole data. Based on analysis suitable remedial measures have been suggested in the following sections.

Fig .1. Settlement of Wall in the Courtyard of Building

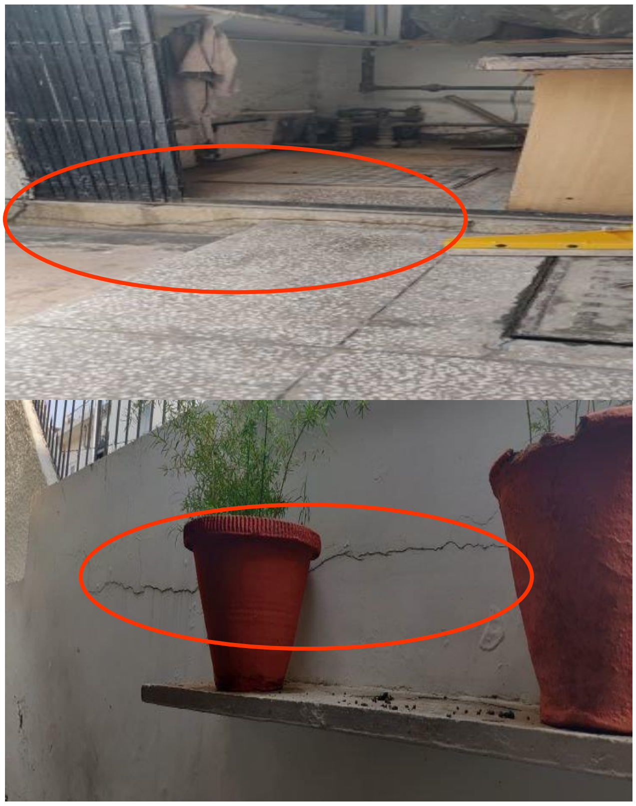

Fig.2. Photographs of cracks in the building

4 Settlement of Soil

(a) Due to Foundation Pressure

Considering the foundation of the buildings to be strip footing at a depth of 1.5m from EGL, the safe bearing capacity of the soil is 120kPa (IS 6403:1981). As the buildings were G+1/G+2 storey structures which would induce a maximum pressure of 60kPa (assuming 20kPa pressure for each floor) on the soil. Therefore, for settlement analysis only 60kPa pressure was taken. The settlement due to the building load is calculated from IS 8009 (Part1) -1976.

(b) Due to Tunneling

The surface settlement due to tunnelling was determined analytically by the equation given by Loganathan and Poulos (1998) as:

Settlement due to tunnelling,

$$U=\varepsilon_o R^2[4H(1-\nu)/(H^2 + x^2)].\exp\{-1.38x^2/(H \cot \beta + R)^2\} \quad -(1)$$

where,

ε_o = Average Ground Loss Ratio

R = Radius of Tunnel

H = Depth to tunnel axis level, H = 27m

ν = Poison's Ratio of Soil

x = Lateral distance from tunnel center line

β = Limit Angle ($45° + \phi/2$)

The effect of tunnelling on the surface settlement of soil was also determined numerically analysed by using PLAXIS 3D finite element software.
The model is 30mx 80m extending to a depth of 50m. The typical Geometry model in PLAXIS is shown in Figure 3.

Finite element mesh is generated in the next stage during which the entire geometry model is divided into a number of volume elements and compatible structural elements. For geometry entities, the fineness factor is considered as 1 while for stuctural elements and loads it is 0.5. During meshing 6518 elements and 9889 nodes were generated. A typical view of model after generating mesh in PLAXIS has been shown in Figure 4.

When the tunnel lining is being erected, the tunnel boring machine remains stationary. After the complete erection of tunnel lining ring, excavation is recommenced, until sufficient soil has been removed to erect the next lining ring. Construction process is divided into a number of stages and same number of stages has been captured in the present PLAXIS 3D analysis in staged construction phase. There are totally 8 plastic phases in the calculation, each phase simulating the excavation process consisting of: the face support pressure at the tunnel face to avert face failure, the removal of the soil inside the TBM, installation of tunnel lining and grouting of the gap between the soil and the newly installed lining. This process continues until tunnelling has been completed till the desired length.

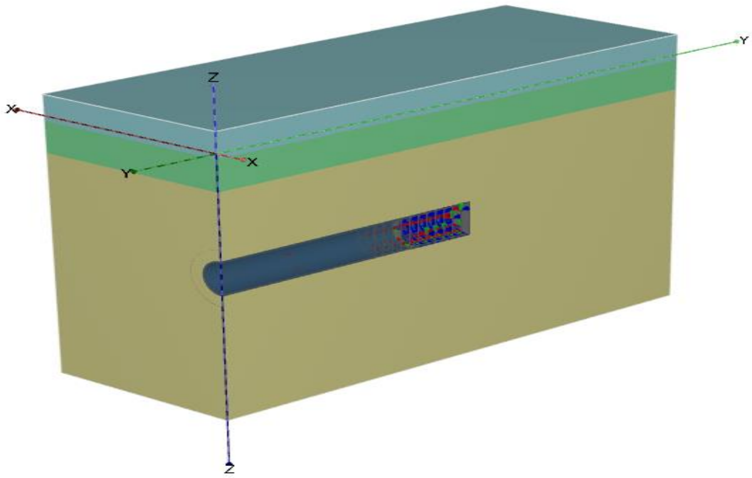

Fig. 3. Typical Geometry Model in PLAXIS 3D

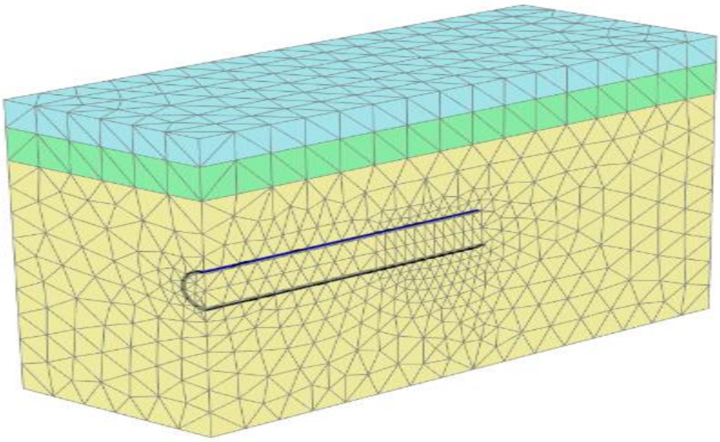

Fig. 4. Mesh Connectivity Plot

5 Settlement Monitoring

Settlement monitoring has been carried out in 12 different locations, 3 in the front side and 3 at the back side of both the houses respectively. The photographs showing settlement markers in buildings are shown in Figure 5.

Fig. 5. Building Settlement Marker Locations

6 Results and Discussion

6.1 Surface settlement

The output showing the cross-section of surface settlement profile is shown in Figure 4. The profile shows a maximum settlement of 10.21mm at a depth of 1.5m from the ground level (approximate foundation level of buildings). Overall settlement undergone by the buildings (B1& B2) due to building foundation pressure and tunneling along with permissible settlement are given in Table 3.

Table 3. Settlement of Buildings due to Foundation Pressure & Tunnelling

Building	Settlement due to Foundation Pressure (mm)	Settlement due to Tunnelling (mm)		Total Settlement due to Foundation Pressure & Tunnelling (mm)*	Permissible Settlement as per IS 1904-1986 (mm)
		Analytical	Numerical		
B1	18	12.52	10.21	28.21	60
B2	12	12.52	10.21	22.21	60

* Calculated considering maximum settlement out of analytical & numerical values

From Table 3 it can be seen that after considering the settlement from foundation pressure and due to tunnelling activities, the total settlement of the building is within the permissible limit as prescribed in the IS code 1904-1986. Moreover, from the settlement readings, it was observed that for the last one month period no progressive settlement was noticed in the buildings.Therefore, these cracks and settlement might be due to the presence of some loose soil pockets below the building. These loose soil pockets might have been triggered when foam came through the old unplugged non-operational bore-well during tunneling process.

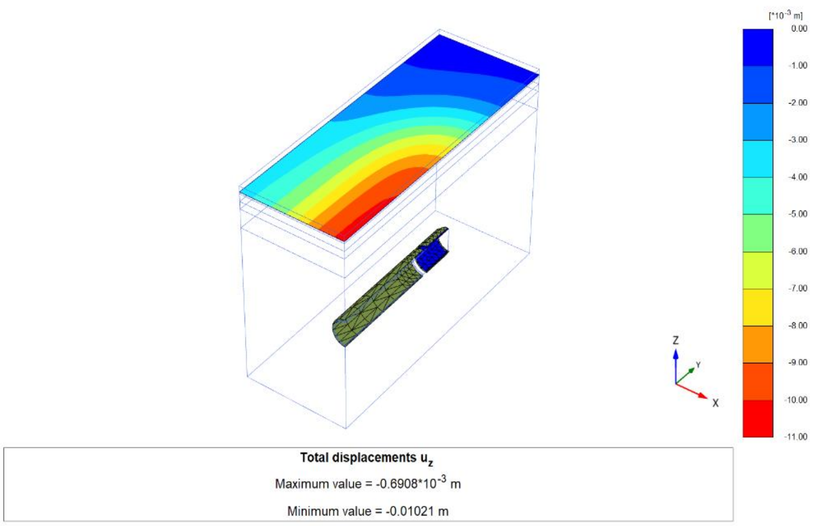

Fig.4. Settlement profile due to Tunneling

6.2 Grouting

In-order to fill the voids below the buildings B1 and B2 and to strengthen the ground, compensation grouting was proposed below and adjacent to the buildings. Compensation grouting was suggested in critical locations where excessive settlements has occured. The criteria considered for grouting are based on the in-situ soil conditions like void ratio and the overburden pressure at each layer. Since the site predominantly consists of fine sand/ sandy silt, the permeability ranges from 10-4 to 10-7 m/s (CIRIA Report - Groundwater control - design and practice C515). A Cement - Bentonite grout with water cement ratio in the range of 1 to 2 was suggested. Grout spacing adopted was typically on the order of 1.5m to 3m to reasonably assure overlap and coverage. Based on the subsoil profile provided in the soil investigation report, loose pockets are likely to be present up to a depth of maximum 5m to 6m beyond which soil is dense to very dense. Hence grouting needs to be carried out up to this depth. However, the detailed design and execution of grouting is beyond the scope of this paper.

7 Conclusions

Based on the numerical analysis and analytical method, it was found that the cracks in the building were not the result of tunneling activities. The settlement could be due to the presence of some loose pockets below the building. Grouting was proposed below and adjacent to the building in order to fill the loose pockets and to strengthen the ground.

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