

Comparison of Ground Movement Near Buildings Due to Underground Station Excavation With Analytical and Numerical Methods



A. Srinivas and C. Anburaj

Abstract In urban areas, construction of underground stations and basements is always a challenging task due to the presence of dense sensitive buildings in the vicinity. The main objective of this paper is to predict the ground movements associated with construction phase of launching shaft excavation in Bangalore Metro project analytically. Also, the comparison of these predicted values with numerical values, and subsequently with actual measurements is presented. These values will help to assess the potential damage, both architecturally and structurally, to the existing building in the influence zone due to ground movements. The principles given by (Bowles JE (1990) Foundation analysis and design, 4th Edn. McGraw-Hill book company, New York, USA. Foundation Analysis and design. 4th Ed., McGraw-Hill book company, New York, USA.) and (Clough and O'Rourke, Specialty conference on Design and Performance of Earth Retaining structures, ASCE Special publication, No. 25:439–470, Clough GW, O'Rourke TD (1990) Construction induced movements of in-situ walls. In: Specialty conference on Design and Performance of Earth Retaining structures, vol. 25. ASCE Special publication, pp. 439-470) depending on the type of soil shall be used to compute ground movements of buildings present in the influence zone. Based on several case histories, (Clough and O'Rourke, Specialty conference on Design and Performance of Earth Retaining structures, ASCE Special publication, No. 25:439–470, Clough GW, O'Rourke TD (1990) Construction induced movements of in-situ walls. In: Specialty conference on Design and Performance of Earth Retaining structures, vol. 25. ASCE Special publication, pp. 439-470) suggested that the settlement profile is triangular for an excavation in sandy soil or stiff clay. The maximum ground surface settlement will occur just behind the wall. The influence zone of the corresponding settlement will extend about twice to thrice of the influence depth (H_e) for sandy soil and stiff to very hard clays, respectively. This paper compares ground movement of building predicted by above analytical method and numerical analysis carried out using PLAXIS 2D

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finite element software. The buildings that are in the influence zone of excavation are considered. On comparing the results obtained from numerical, analytical and actual settlement values, it is observed that wall deflection from numerical values is about 33% higher than actual value. In addition, the maximum ground settlement obtained from numerical analysis is comparable with the settlement obtained from analytical approach. However, the observed settlements at the building locations are significantly smaller than predicted. This might be due to support provided by the secant pile walls in the opposite side as the stress around the retaining wall will be in a three-dimensional direction. Also, the deep ground water table during the excavation could have helped in reducing the wall movement and the ground settlement.

Keywords Ground movement · Influence zone · Instrumentation · PLAXIS 2D

1 Introduction

For the construction of underground metro stations, there is a major concern about the influence of the resulting ground movements on the adjacent buildings, structures, pavements or paved roads, utilities etc. In general, during excavation, there is a change in state of stress and the orientation of principal planes. This change in state of stress often leads to induce vertical and lateral movements on the ground. As a result, the structures which are close to the excavation tends to rotate, distort, deform and even lead to damage also. Therefore, for the urban constructional works, the magnitude of the ground movements and the building movements should be within the tolerance limits. Many studies have been made about the building response due to excavation and tunneling. The vertical and horizontal ground movements on the adjacent buildings and structures can be estimated based on Boscardin and Cording (1989) and the limiting tensile strain induced on the adjacent buildings is calculated as suggested by Burland and Wroth (1974). Secant piles are used as the temporary retaining structure with internal horizontal struts for the construction of a shaft to lower or launch the tunnel boring machine (TBM). This paper presents the comparison of ground movement due to construction of Launching shaft in Bangalore Metro project from available analytical methods with numerical results using PLAXIS 2D. For the evaluation of ground movements near excavation, the buildings in the proximity of influence zone are only considered. The analytical and numerical results are further compared with the values recorded at site with the help of instrumentation installed in the adjacent buildings close to the excavation and in the retention systems of the launching shaft.

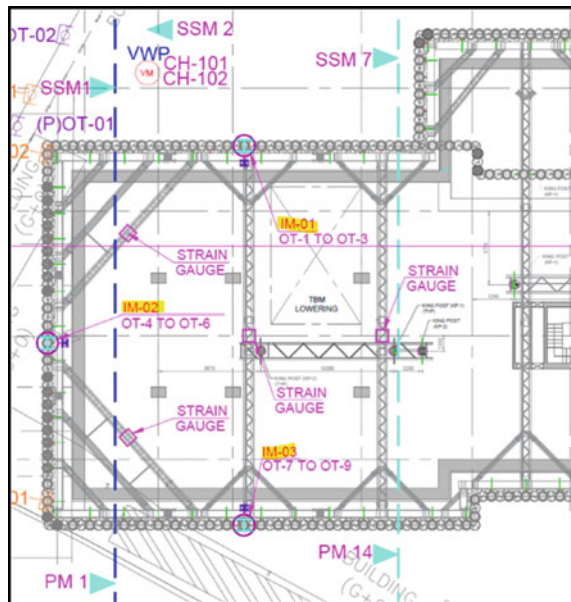
2 Description of Site

The launching shaft is located in the South of the Shivajinagar Station, which is one of the underground stations in Reach 6 of Bangalore Metro Phase II. The launching shaft is aligned to the south of Gottigere–Nagawara line. Secant piles are proposed and used as temporary earth retaining structures for the construction of the launching shaft. The construction of launching shaft is done by bottom-up method of construction. Struts are used as a support system to hold the secant pile walls. The depth of excavation is about 20 meters and that of water table is about 5 m below the existing ground level. Two buildings are very close to the excavation of launching shaft, which are named as B1 and B2. The strut layout plan of the launching shaft with the adjacent buildings is shown in Fig. 1.

2.1 Details of the Buildings

The buildings B1 and B2, which are close to the launching shaft is located at 3m and 13m respectively from the edge of the secant piles. As seen from Fig. 2, both the buildings B1 and B2 are skewed to the edge of the excavation boundary. The general details of the building such as dimensions, height, number of floors, and foundation type are mentioned in Table 1. The details of the building are obtained from the building condition survey (BCS) reports.

Fig. 1 Plan of launching shaft with instruments



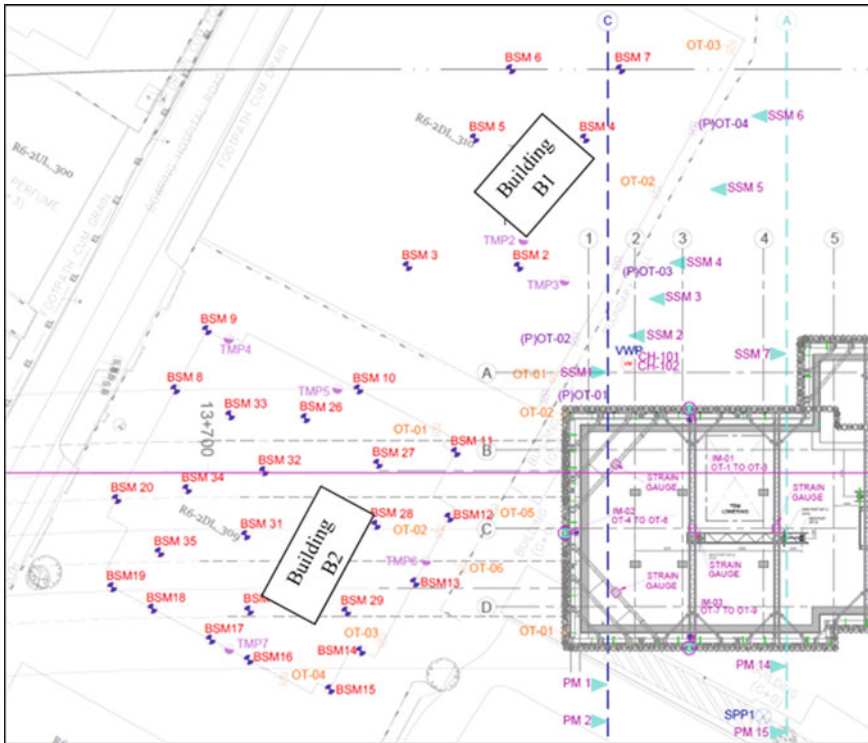


Fig. 2 Plan and orientation of adjacent buildings and the instrumentation

Table 1 Building details near to launching shaft

Building ID	Dimension	Number of stories	Type of building	Distance from excavation boundary	Foundation system
B1	38 m × 58 m	3B+G+3	RCC Framed structure	3 m	Isolated shallow foundation
B2	32 m × 34 m	B+G+5	RCC Framed structure	13 m	Isolated shallow foundation

3 Ground Settlement Based on Analytical Approach

Ground movements can be computed by the principles given by Bowles (1990) and Clough & O’Rourke (1990) depending on the type of soil. Based on several case histories, Clough and O’Rourke (1990) suggested that the settlement profile is triangular for an excavation in sandy soil or stiff clay. The maximum ground surface

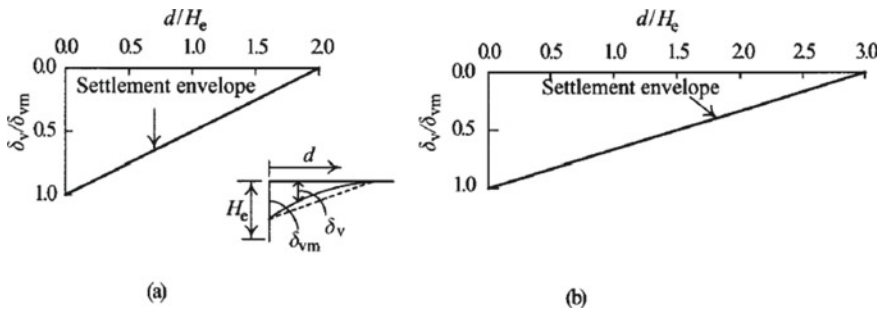


Fig. 3 Dimensionless settlement envelope adjacent to excavation **a** sandy soil **b** stiff clays (Clough and O'Rourke, 1990)

settlement will occur just behind the wall. The non-dimensional profiles given in Fig. 3 shows that the corresponding settlement extends to about 2 and 3H_e for sandy soil and stiff to very hard clays, respectively where the influence depth for clayey soil is the depth of excavation plus the width of excavation. However, it shall be limited to 4 times the depth of excavation in the case of very soft soil for a large depth.

As the excavation progresses, the lateral pressure imposed by the ground behind the wall would induce wall deflections into the excavation. This would result in vertical and lateral displacements of the ground adjacent to the retaining wall. In principle, the magnitude and extent of this ground movement is a function of the retention system type, the adopted construction methodology and the properties of the soil and/or rock materials. The depth of influence (H_e) is considered depending on the depth of the secant pile wall and depth of the excavation. The geology of Bangalore is predominantly mixed soil condition and mainly comprises mixtures of silty sand and clays with low to high plasticity and compressibility. The maximum deflection on the ground adjacent to secant pile due to excavation at launching shaft can be estimated with the deflection profile of secant pile. As the strata is generally mixed, the typical settlement profile just behind the secant pile wall is shown in Fig. 4.

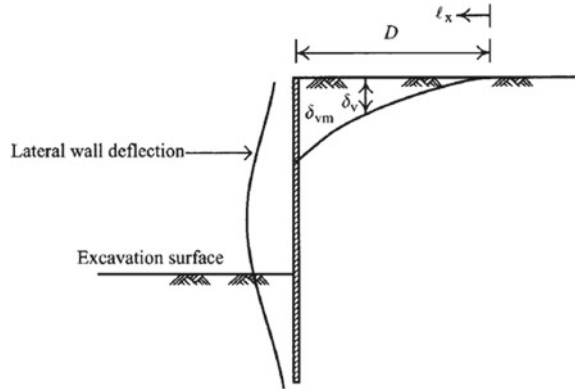
The ground settlement curve is taken as “second degree exponential curve” as suggested by Bowles (1986) where the maximum ground settlement occurs just behind the wall. Bowles (1986) suggested a procedure to estimate the excavation induced ground surface settlements using the following relations,

$$\delta_v = \delta_{vm} \left(\frac{l_x}{D} \right)^2 \tag{1}$$

where δ_v = settlement at a distance of $D - l_x$; δ_{vm} = maximum ground surface settlement; l_x = Distance from a point at a distance D from the wall and D is the influence range of ground surface settlement.

The maximum ground surface settlement δ_{vm} , is estimated from the following equation,

Fig. 4 Estimation of ground settlement (Bowles, 1986)



$$\delta_{vm} = \frac{2A}{D} \quad (2)$$

where A is the area of the lateral wall deflection. The lateral deflection of the secant pile wall is obtained using finite element software, PLAXIS 2D. For excavations which are close to the existing building and structures, differential settlement and angular distortion are the main factors causing damage to structures when the ground settles. The results of the differential settlement and angular distortion for buildings B1 and B2 based on analytical approach are presented in the subsequent section.

4 Numerical Modelling

Numerical analysis constantly proves to be an efficient tool in analyzing complex problems. Analyses are performed considering all the aspects such as construction methodology, foundations of the adjacent buildings and secant pile walls of the launching shaft. The general assumptions involved in any deep excavation problems holds good in this case also. The entire analysis is carried out using PLAXIS 2D with the available data. Soil layers are modelled as linearly elastic perfectly plastic model i.e., Mohr-Coulomb constitutive model to simulate the behavior. The secant piles and the adjacent buildings B1 and B2 are modelled as plate elements. The properties used for the soil layers are mentioned in Table 2. The material properties used for plate elements are mentioned in Table 3.

4.1 Analysis using PLAXIS 2D

As observed from Fig. 1, it is clearly evident that buildings B1 and B2 are skewed to the excavation of launching shaft. Therefore, to simulate behaviour of foundation of

Table 2 Soil parameters used in the PLAXIS 2D

Depth (m)	Strata Type	γ (kN/m ³)	E' (MPa)	c' (kPa)	ϕ'
0–2.5	Filled up	18	10	–	28°
2.5–7.5	Clay & silt of low plasticity	18.5	11+3.8z	26	24°
7.5–16.5		18.5	30+3.8z	46	25°
16.5–21	SM	18.5	64.2+3.8z	–	38°
21–26	SC	18.5	81.3+3.8z	15	23°
>26	Soft rock	18.5	136	–	40°

Table 3 Material properties for secant pile wall and buildings used in PLAXIS 2D

Material type	Young modulus (kPa)	Cross sectional area A (m ²)	Spacing (m)	Moment of inertia I (m ⁴)	EA (kN/m)	EI (kNm ² /m)
Secant pile	2.74E6	0.5026	1.35	0.0201	10.2E6	407.9E3
B1	2.74E6	0.6	–	0.018	16.4E6	493.0E3
B2	2.74E6	0.6	–	0.018	16.4E6	493.0E3

the buildings due to response of secant pile is a three-dimensional problem. However, in order to reduce the complexity, it is assumed that the building B1 is aligned perpendicular to the direction of the TBM launching. By doing so, it is easier to model both the building and secant piles in 2D itself. As the excavation is symmetrical, only half of the excavation is modelled in PLAXIS 2D to estimate the ground movements behind the secant pile wall. The cross sections considered for the PLAXIS 2D analysis is shown in Fig. 5.

The entire excavation at Launching shaft location is simulated in the PLAXIS 2D based on stage wise construction sequence. The surcharge of the building and construction surcharge are also modelled before the commencement of excavation at launching shaft. Typical PLAXIS 2D model with soil, secant piles and building foundation with loads are shown in Figs. 6, 7.

In PLAXIS 2D, analysis is carried out up to final excavation of the launching shaft only. The backfilling sequence which is usually being done for any underground metro construction is not considered. This is due to the fact that the maximum deflection in the secant pile is encountered during excavation activity itself. The results of ground settlement behind the secant pile wall from PLAXIS 2D are presented in the next section.

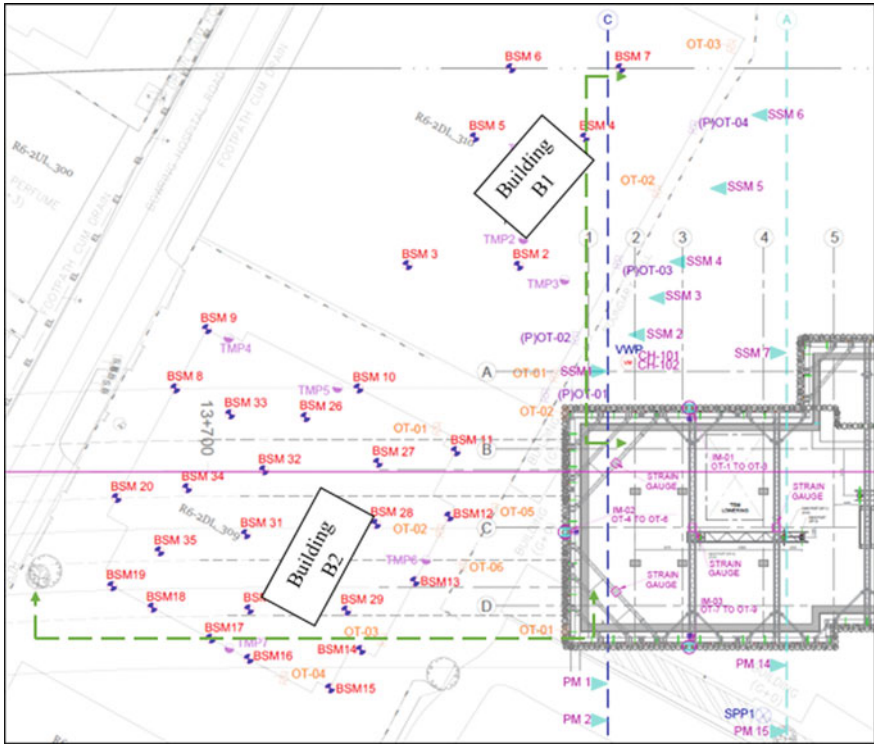


Fig. 5 Foundation layout for the buildings B1 & B2 Plan indicating cross-section considered for analysis

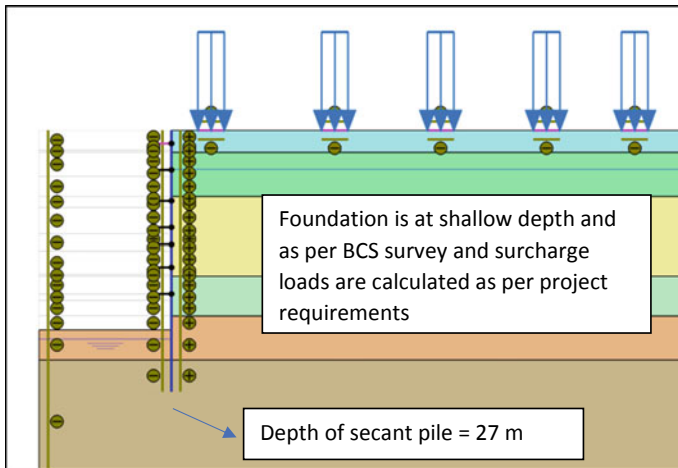


Fig. 6 Typical Excavation at Launching shafts near building B1

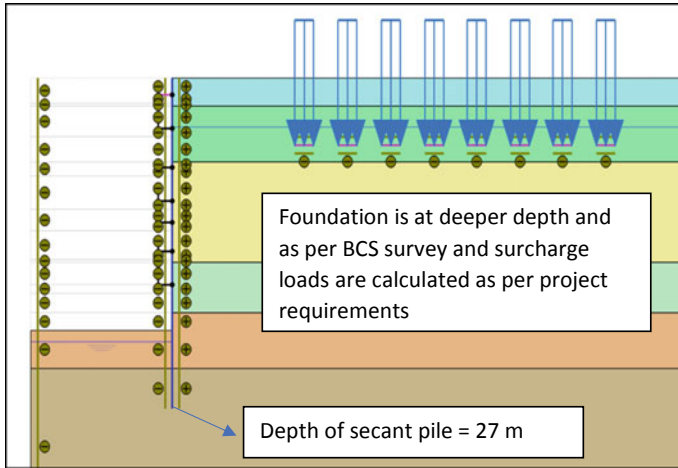


Fig. 7 Typical Excavation at Launching shafts near building B2

5 Field Instrumentation Measurements

For any underground metro construction activity, instrumentation plays a major role in confirming the assumptions made in the design and also the predicted behaviour of the support system during excavation. Therefore, instruments like inclinometers (IM) and optical targets (OT) are installed on the secant piles at the launching shaft location which is already shown in Fig. 5. In a similar manner, certain instruments are installed on the ground and adjacent buildings and structures to monitor and verify the predicted behaviour. The instruments installed in site are provided with trigger levels to check the actual measured values. Mostly building settlement markers (BSM), tilt meter plate (TMP) and optical targets for buildings are used in monitoring the adjacent buildings whereas soil settlement markers (SSM) are placed on the ground and pavement markers (PM) are kept directly on the pavements. The detailed instrumentation plan near the launching shaft location is presented in Fig. 5.

Only limited number of instruments are considered for comparing the results with analytical and numerical methods as mentioned in Table 4.

The comparison between numerical, analytical results and site-measured data explained in detail in the next section.

Table 4 Data observed from Instruments located at site used for interpretation

Instruments type	Instruments considered
Building settlement markers (BSM)	BSM 2, BSM 4, BSM 7, BSM 11, BSM 12, BSM 13, BSM 14, BSM 15
Inclinometers (IM)	IM-02
Tilt meter plate (TMP)	TMP 3, TMP 6

6 Results and Discussion

The movements of secant pile wall deflection installed at site is recorded with the help of two inclinometers IM-01 and IM-02. The construction adopted in site is exactly simulated in PLAXIS 2D and the behaviour of the secant piles is obtained. The results of the instrumented data and numerical analysis is compared and shown in Fig. 8.

From Fig. 8, it is clear that the predicted maximum deflection of secant pile is higher than the observed data which is actually recorded at site up to the final excavation level. The deflection recorded at site shows a similar trend to numerical results below 15 meters. But from the ground level to a depth of 15 m, the deflection observed in the site is higher than numerical results. The maximum deflection predicted from numerical analysis is 66 mm. However, the maximum deflection observed at site is 44 mm i.e., the maximum deflection predicted from numerical analysis is 33% higher than the actual observed value. This could be due to the support provided by the adjacent and opposite secant pile walls as the stress will be acting in three-dimensional directions. And also might be due to the water pressure on the retaining side of the secant pile wall. Hence, the deflection on the wall is comparatively higher in numerical analysis than observed instrumented data. The comparison of ground movement behind the wall obtained from numerical and analytical methods is shown in Fig. 9.

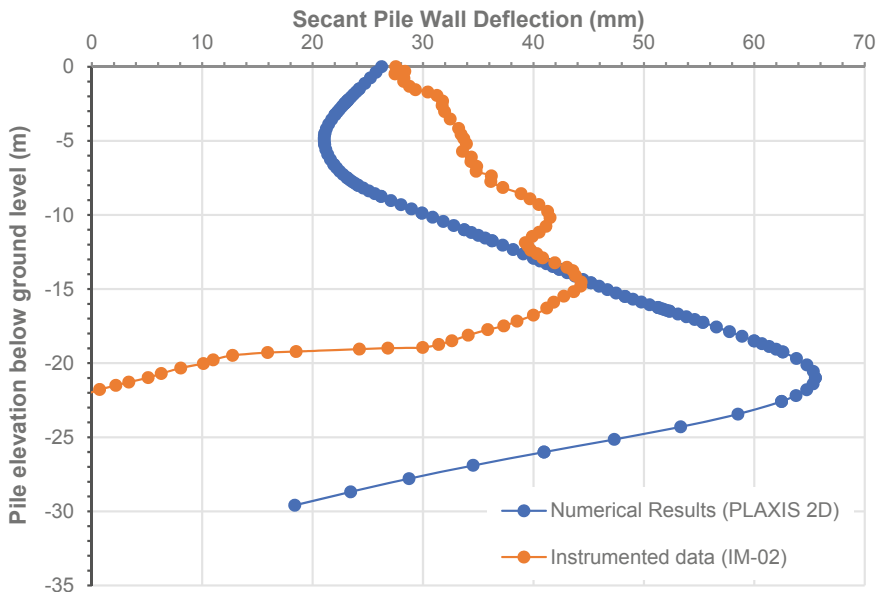


Fig. 8 Comparison of Deflection Profile of Secant pile wall

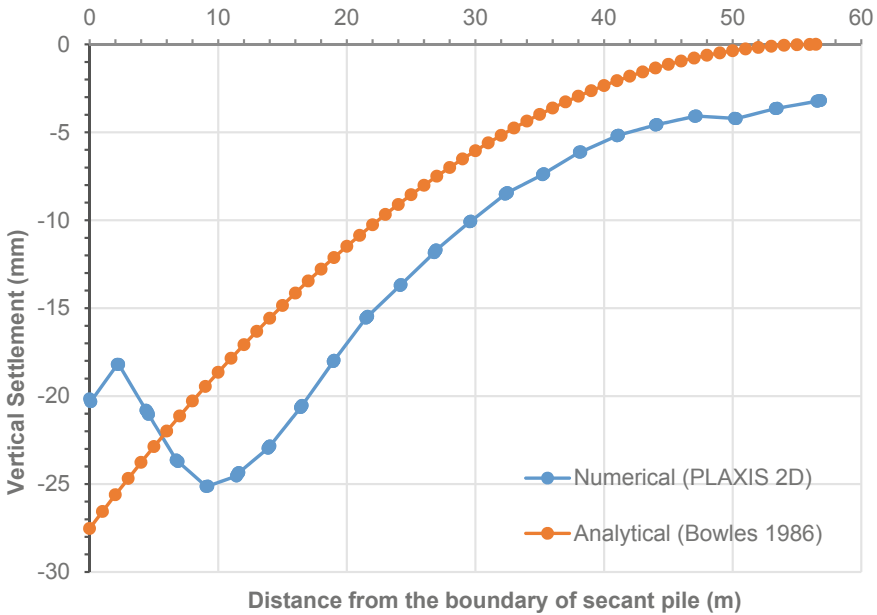


Fig. 9 Comparison of ground movement behind the secant pile wall

The results show that the maximum ground settlement predicted from analytical approach is 1% higher than the numerical results. However, the ground settlement profile remains identical beyond the distance of 10m from the wall. The ground settlement predicted from numerical results is higher than analytical approach from 6m beyond the wall. The initial variation in ground settlement obtained from the numerical analysis is due to the interaction between soil and the secant pile wall and might be due to the strut installation during excavation. Similarly, the building settlement markers, installed at site observed the settlements of the building during excavation is shown in Tables 5, 6.

From Tables 5 and 6, it is clear that settlements observed at site is much lesser than settlements predicted from numerical and analytical analysis. This might be due to conservative use of soil parameters in the design. The negative values indicate that instead of settlement, heaving has occurred at some locations of the buildings. This indicates that the building is trying to rotate but the results of tilt meter plates installed at those buildings shows no rotation at all during the excavation. From this,

Table 5 Comparison of ground movements for building B1

Building	Distance from the secant pile wall	Numerical analysis	Analytical approach	Settlement markers		
				BSM 2	BSM 4	BSM 7
B1	3 m	19 mm	25 mm	1.1 mm	-1.7 mm	-2.7 mm

Table 6 Comparison of ground movements for building B2

Building	Distance from the secant pile wall	Numerical analysis	Analytical approach	Settlement markers				
				BSM 11	BSM 12	BSM 13	BSM 14	BSM 15
B1	13 m	23.5 mm	16.5 mm	3.0 mm	3.3 mm	3.3 mm	-6.9 mm	-3.3 mm

Table 7 Results of Building rotation for Building B1 and B2

Building	Numerical analysis	Analytical method	Tilt meter plate	
			TMP 3	TMP 6
B1	0.056°	0.036°	0°	—
B2	0.027°	0.025°	—	0°

a conclusion can be drawn that either tilt meter plate is insensitive to capture the movement or the people who are living there might have disturbed the settlement markers 4, 7, 14 and BSM 15. The results of the building rotation from the numerical, analytical and tilt meter are shown in Table 7.

From Table 7, it is understood that numerical analysis gives higher values than analytical method. It is due to the fact that ground settlement is predicted higher in numerical analysis hence consequently the rotation predicted will be higher in case of numerical analysis than analytical method. However, the instruments TMP 3 and TMP 6 show that there is no rotation for the building B1 and for building B2. The safety of the building is ensured in a way that excavation being done in a controlled manner and at every stage.

7 Summary

Results of the numerical analysis and instrumented data shows that the deflection of the secant pile predicted from PLAXIS 2D is 33% higher than the deflection observed during excavation. The probable reason might be the support provided by the secant piles in opposite sides as the stress around the secant piles will be acting in three-dimensional directions. This might be due to water level at site during excavation is lesser than what was considered during design stage. The higher the water pressure, the higher the active force on the wall, which in turn increases the wall deflection from numerical analysis. Similarly, when the wall deflection is high, the ground settlements will also be high. The ground settlement predicted from analytical approach is approximately 1% higher than numerical analysis. In addition, the ground settlement from PLAXIS 2D is higher than analytical approach beyond 6 m from the wall boundary. However, the actual settlement markers installed on the

buildings shows minimal amount of settlement observed during excavation. This is due to the fact that construction carried is out in a controlled manner and observations are monitored throughout the excavation phase. However, some settlement markers indicate heaving which shows that buildings try to rotate. Even the results from PLAXIS 2D and analytical approach indicates rotation may happen. However, the tilt meters installed on the buildings shows no rotation. This confirms that the excavation is carried out in a safe and progressive manner. The assumptions considered during design stage are conservative and the results predicted from numerical and analytical results are much higher than the instruments recorded at site.

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