A Study on Excavation Induced SurfaceSettlement due to Construction of Underground Station Box

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Abstract. Construction of an underground metro station box is a deep excavation problem. Ground deformations are inevitable in any deep excavation project due to deflection of retaining wall, dewatering and surcharge. Such ground deformations can affect the serviceability of adjoining over ground structures and underground structures or utilities. In cases of severe surface settlement, safety of such adjoining structures may also be at risk. Several researchers have attempted to predict excavation induced surface settlement using empirical, analytical and numerical methods. In this paper, the applicability of empirical methods of surface settlement predictions due to braced excavation has been studied. Surface settlement has been predicted considering in-situ soil stratification, retaining structure, depth and width of excavations and factor of safety against basal heave. During construction of station box, surface settlement adjoining the zone of excavation is measured using surface settlement monitoring points. The empirical predictions have been compared with field data from one of the station boxes of Kolkata East West Metro project. The predicted surface settlement agreed reasonably well with observed instrumentation data.

Keywords: Underground construction, Deep excavation, Surface settlements prediction, Field instrumentation.

1 Introduction

Excavations can range from shallow to deep. The depth of an excavation is dependent on the requirements of the project and specific structure. Typically, shallow excavations are defined as being up to a depth of 1.5 metres and deep excavations as being deeper

than 4.5 metres. Deep excavation involves the construction of retaining walls, excavation, the installation of struts and walers, and the construction of foundations and floor slabs. Braced excavation is a method where a sheeting and bracing system laterally support deep excavations with straight vertical faces until the structure is built. The retaining walls could be either temporary (e.g., sheet pile) or permanent (e.g., diaphragm wall). Some commonly used excavation methods are: the full open cut method, the braced excavation method, the island excavation method, the anchored excavation method, the top-down construction method, and the zoned excavation method. The components of a typical braced excavation have been shown in Fig. 1.
Excavation inevitably induces lateral wall deflection and ground settlements which can have detrimental effects on adjacent structures, such as buildings, pipelines, roads, bridges, and tunnels. The resulting damage can either be architectural or structural, leading to the collapse of superstructures in severe cases. The consequences may be catastrophic in terms of property loss, mortality and also delay in the project. This potential problem is amplified in cases of deep excavations in congested urban areas where existing structures are present adjacent to the excavation. Fig. 1. (c) shows a typical wall deflection and ground movement caused by excavation in soft to medium clays.

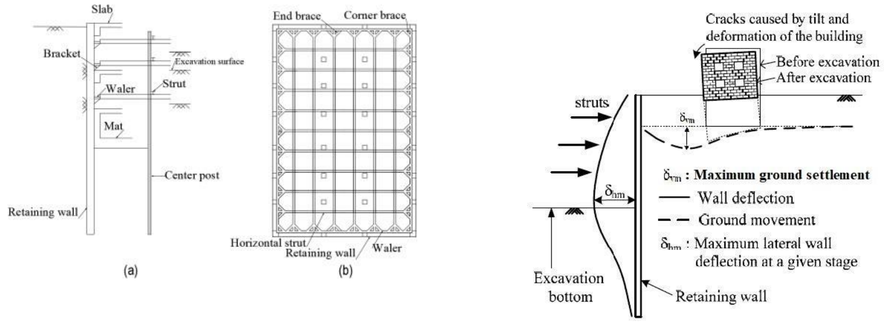

Fig. 1. Braced excavation method: (a) profile and (b) plan (c) Ground surface settlement induced by lateral wall movement.

Chai et al. (2014) described the collapse of a building due to adjacent deep excavation in 2009 (Chai et al. 2014). The authors indicated that the failure was initiated by lateral overloading of the pile foundation due to excavation near one side of the collapsed building and stockpiling of the excavated materials on the opposite side. The unbalanced excavation and fill induced lateral loads on piles.

Instrumentation and monitoring play a critical role in the successful execution of any deep excavation project where-in, various different instruments are installed to monitor retaining wall deflections, movements of adjacent buildings, and geotechnical parameters like pore water pressure and ground deformation. Some of the instruments commonly used are tilt meter, building settlement point, optical prism target, inclinometer and piezometer.

In order to add to the utility of precaution, several researchers have attempted to study the ground settlement profiles caused in previous cases of deep excavation construction projects and have tried to predict the maximum ground surface settlements profile and the maximum settlement (δ_{vm}) due to deep excavation relating with factors like deflection caused in diaphragm wall (δ_h) and depth of excavation to the ground settlement caused via empirical studies. There are several numerical [Bhatkar et al. (2016); Chheng & Likitlersuang (2017); Jasmine Nisha & Muttharam (2017); Likitlersuang et al. (2013); Ou et al. (2013); Xu et al. (2017); Yang et al. (2022)] and empirical studies [(Bowles (1998); Clough & O'Rourke (1990); Hsieh & Ou (1998); Kung et al. (2007); Long (2001); Peck (1969)] dealing with the analysis of short-term excavation-induced displacements. Some of these empirical methods are used till date by practicing engineers for estimating settlements. The objective of this paper is to study the applicability of some of these empirical methods for surface settlement predictions due to braced excavation. The data used for computation has been taken from Howrah metro station box of the Kolkata East West Metro project.

2 Literature review

A number of case histories have been described by researchers to enhance the understanding of deep excavation induced ground settlements. Peck (1969) investigated the surface settlements induced by deep excavation and tunnel construction in soft soils and related ground surface settlement and the distance from wall. The author observed that induced settlements were a function of soil type, lower soil strength and stiffness resulted in larger surface settlements and wall deflections. Similar observation were made by Goldberg et al. (1976) . Clough & O'Rourke (1990) considered different surface settlement envelopes and co-related them with the type of soil. The authors observed that deep excavation in stiff clays and sand resulted in formation of a triangular surface settlement envelope whereas a trapezoidal settlement envelope was formed for soft to medium clays. The magnitude of this settlement decreased with increase in distance from the retaining structure.

Hsieh & Ou (1998) reviewed 10 case histories of surface settlements induced by deep excavation in soft soils and proposed an analytical method to estimate these settlements. A tri-linear settlement profile (also known as spandrel-type settlement) with maxima very close to the retaining wall was also proposed in this study. It was observed that spandrel type ground settlements occurred in initial stages when wall underwent cantilever type deflection with maximum settlement observed at a distance of half the excavation depth from the face of retaining wall. The primary influence zone was up to a distance of twice the excavation depth from wall face concluding approximately at a distance of four times the excavation depth.

Aswathy et al. (2020) established that in the initial stages of retaining wall construction, cantilever type wall deformation resulted in spandrel type ground settlement. Further increase in wall deflection resulted in concave shaped deflection of ground surface. Hsieh & Ou (1998) proposed the following methodology to estimate the ground surface settlement:

I. Prediction of wall movement from FEM or beam on elastic foundation methods.
II. Determination of settlement profile characteristics using area of cantilever and inward wall displacement profile.
III. Maximum surface settlement approximated to be 0.5-1.0 times the lateral deflection of wall.
IV. Plotting concave type or spandrel type settlement profile depending on the stage of retaining wall deflection.

Similar procedure has been proposed by Bowles (1998). The influence range has been calculated initially depending on the excavation depth which is then related directly to the ground surface settlement. Bowles (1998) suggested a parabolic settlement profile rather than spandrel or concave profile. Apart from these, various other analytical methods have been proposed wherein a factor, deformation ratio (ratio of maximum lateral wall deflection and maximum ground surface settlement), has been primarily used to calculate the settlements induced due to deep excavation (Kung et al. 2007).

Whittle & Davies (2006) studied the collapse of Nicoll highway wherein a 20 m wide excavation was carried out up to a depth of 33.3 m. A 0.8 m thick diaphragm wall was used to support the excavation. The primary reason of this failure was under-estimation of settlements during construction of diaphragm wall. Also, embedment depth of diaphragm wall panels was inadequate to ensure toe fixity, resulting in collapse. Endicott (2013) later suggested that faulty connection between waling and struts due to underestimation of stresses during the design led to this incident.

A similar behaviour was observed by Chen & Chen (2007), who studied the collapse of trench in Taiwan caused by construction of a 90 m deep cylindrical diaphragm wall having diameter of 70 m and thickness of 1.2 m. The reclaimed soil layer of 10-12m was underlain by silty sand and low plastic clays. A 10 m long wedge having top width of 2.8 m and estimated mass of more than 100 m^3 collapsed. Large increase in pore water pressures and long durations of stand-by during trench excavations were the major factors that contributed to the failure.

Chen et al. (2015) studied the effect of excessive settlements during deep excavation on surrounding ground. A complete failure of a 15.7 m deep excavation had occurred in a soft organic soil which led to huge economic losses. This led to failure and tilting of retaining walls along with a huge subsidence of a nearby road which in turn lead to damage of existing utilities beneath the road. Similar to the Nicoll highway collapse, under-estimation of soil-structure interaction during the construction of diaphragm wall led to collapse. Basal heave was considered to be another significant factor contributing to this collapse.

Aswathy et al. (2020) studied the behaviour of induced surface settlement due to excavation during construction of a sewage pumping station. 7 m deep screen and inlet chambers were constructed in addition to a collection chamber twice the depth of screen or inlet chamber. The soil strata mainly consisted of low plastic clay underlain by silty sand. Water along with soil particles seeped in to the collection chamber of the dewatering system leading to excessive surface settlement. Several surrounding structures were damaged due to this excessive ground settlement.

3 The site and in-situ soil stratification

The current study pertains to the Kolkata East West Metro project. This project aims to connect Howrah Maidan in the West and Salt Lake in the East through a combination of underground and overground stretches. It covers a total distance of 16.6 kms, of which 5.8 kms is elevated and the rest is underground. The section between Howrah Maidan and Phoolbagan consists of six underground stations, two ventilation shafts and twin bored tunnels. In this study ground deformation due to deep excavation for construction of underground subway station at Howrah has been predicted and compared with field data.

Prior to design of the retaining structure at Howrah station box i.e., the reinforced concrete diaphragm wall, a detailed geotechnical investigation had been conducted. The objective of this exploration program was to identify the in-situ soil stratification and reveal its geotechnical design parameters. Three bore holes were sunk up to a depth of 40 m below EGL. The locations of the bore holes were chosen such that the entire construction site could be covered. From the field bore hole log, field and laboratory test results, the soil stratum as identified are in table 1.

Table 1. Geo stratification data

Layer	Description	From (m EGL)	To (m EGL)	N_{av}	c (kPa)	Ø (°)	γ_{bulk} (kN/m^3)
1	Man-made Ground	0.0	1.5	-	5.0	24.0	16.5
2	Medium stiff clayey silt	1.5	5.5	5.0	32.0	-	19.4
3	Soft to medium stiff organic clayey silt	5.5	14.5	5.0	20.0	5.0	17.5
4	Medium stiff to stiff clayey silt	14.5	20.5	8.0	51.0	-	18.7
5	Stiff sandy silt	20.5	23.5	30.0	10.0	31.0	19.0
6	Stiff to very stiff clayey silt	23.5	31.0	19.0	105.0	-	18.5
7	Very stiff to hard clayey silt	31.0	47.5	37.0	180.0	-	19.5
8	Dense to very dense, fine to medium sand	47.5	50.0	57.0	-	34.0	19.0

c: Cohesion; Ø: Friction angle; $\gamma_{bulk:}$ Bulk unit weight;

4 Prediction of surface settlement

In this study, an attempt has been made to predict the surface settlement due to excavation of various levels of Howrah metro station box. Several empirical methods have been proposed by various researchers [(Bowles (1998); Clough & O'Rourke (1990); Hsieh & Ou (1998); Kung et al. (2007); Peck (1969)] to predict ground surface settlement. Howrah station box is the deepest underground metro station in India where the final depth of excavation ranged from 30 m to 32.5 m below EGL. Deep excavation was achieved by a combination of temporary steel struts and permanent RC slabs. Howrah station box consists of the five different levels: Roof slab, Upper Concourse level, Mechanical, Lower Concourse and Base slab. During excavation for Roof slab, the diaphragm walls were supported by steel struts. Thereafter, during construction of upper concourse, mechanical and lower concourse slabs, each previous storey slab was designed to act as strut for supporting the excavation. For construction of base slab, again steel struts were installed. Surface settlements have been predicted for excavation at all levels using the methodology proposed by [(Bowles (1998); Clough & O'Rourke (1990); Hsieh & Ou (1998); Kung et al. (2007); Peck (1969)].

4.1 Peck's method

Surface settlement profile has been predicted using Peck (1969) by adopting the boundary curve between Zone I and Zone II (the 1 %-curve). It has been observed that magnitude of settlement was maximum near the wall. Vertical ground deformation decreased with increase in distance, in a parabolic manner. The predicted maximum settlement for Roof, Upper Concourse, Mechanical, Lower Concourse and Base slab level excavations are 45, 100, 160, 220 & 300 mm respectively. The settlement profiles are presented in Fig. 2.

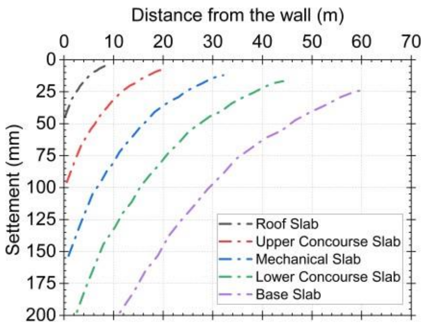

Fig. 2. Settlement predicted using Peck (1969)

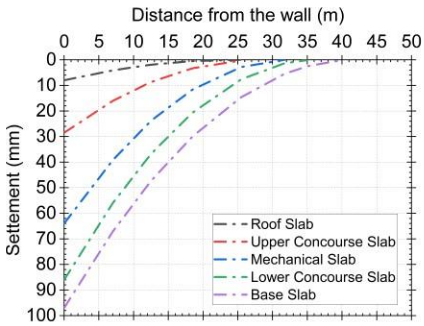

Fig. 3. Settlement predicted using Bowles (1998)

4.2 Bowles method

The method proposed by Bowles (1998) predicts a parabolic settlement profile with the maximum settlement being near the wall itself, similar to Peck (1969). The maximum settlement predicted using Bowles (1998) was observed to be significantly lesser in magnitude than Peck (1969). The methodology proposed by Bowles (1998) has been used to predict the resulting ground deformation. The magnitude of predicted maximum settlement for roof, upper concourse, mechanical, lower concourse and base slab level excavations are 8, 28.5, 64, 86 & 97 mm respectively. The settlement profiles are shown in Fig. 3.

4.3 Hsieh & Ou's method

Hsieh & Ou (1998) proposed a tri-linear curve for concave type surface settlement and divided it into primary and secondary influence zones. The authors proposed that the maximum settlement is likely to be at a distance of 0.5 times the excavation depth. In this method, the maximum settlement is estimated using Long (2001), where-in for a strut spacing less than 0.6 times the depth of excavation, the maximum settlement is estimated to be 0.14% of the depth of excavation. The predicted maximum settlement for Roof, Upper Concourse, Mechanical, Lower Concourse and Base slab level excavations are 7, 15, 24, 33 & 45 mm respectively.

The maximum settlement (δ_{vm}) w.r.t. maximum lateral wall deflection (δ_{hm}) has also been predicted using following equation:

$$\delta_{vm} \approx 0.5 \text{ to } 0.7\ \delta_{hm} \qquad [1]$$

Similar methodology has been proposed by various other researchers [(Goldberg et al., 1976; Hsieh & Ou (1998)] . The predicted maximum settlement for roof, upper concourse, mechanical, lower concourse and base slab level excavations are 1.4, 8.3, 16.5, 29.5 & 42 mm respectively. The settlement profiles are plotted in Fig. 4 & 5 respectively.

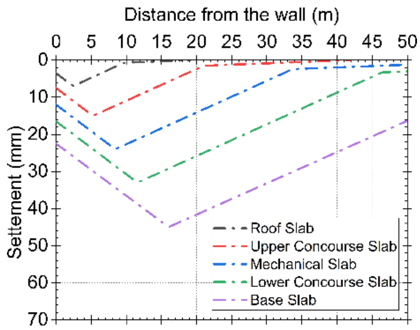

Fig. 4. Settlement predicted using Hsieh & Ou (1998) with Long's study

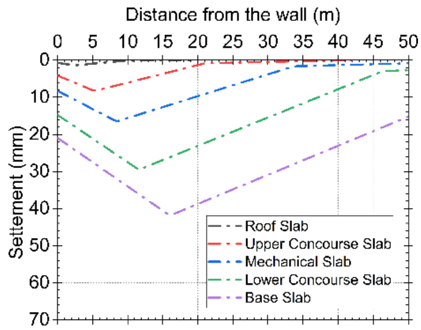

Fig. 5. Settlement predicted using Hsieh & Ou (1998) with 0.5-1 δ_{hm}

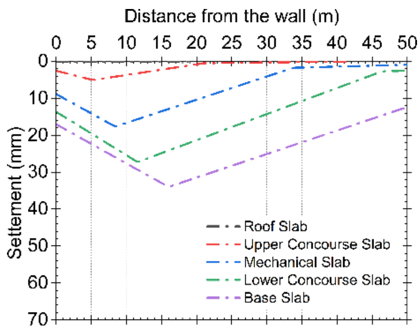

Fig. 6. Settlement predicted using Kung et al. (2007)

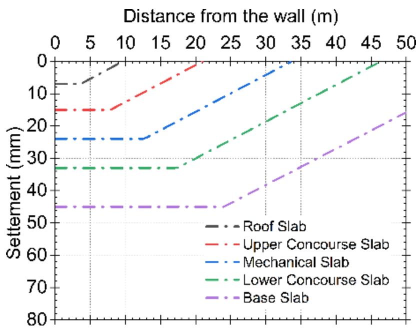

Fig. 7. Settlement predicted using Clough & O'Rourke (1990)

4.4 KJHH method

Kung et al. (2007) proposed an equation based on regression analysis to predict the maximum ground surface settlement. Deformation ratio, ratio of maximum ground surface settlement to maximum wall deflection, has been used in this study. The regression equation is given by:

$$\delta_{vm} = R\delta_{hm} \qquad [2]$$

where δ_{vm} is the maximum settlement and δ_{hm} is the maximum wall deflection. This model uses system stiffness to predict the maximum wall deflection which is then used to predict maximum ground surface settlement. In the present study, we have directly used the maximum wall deflection from the inclinometer data. The predicted maximum settlement for roof, upper concourse, mechanical, lower concourse and base slab level excavations are 0.2, 5, 17.6, 27.2 & 34 mm respectively. The settlement profiles are presented in Fig. 6.

4.5 Clough and O'Rourke's method

Clough & O'Rourke (1990) proposed a bilinear curve to predict the settlement profile. The maximum settlement zone exists between the face of the wall and 0.75 times the depth of excavation. This is followed by a transition zone from 0.75 times the depth of excavation to twice the depth of excavation, wherein settlement linearly decreases to zero. In this method, the maximum settlement has been estimated using Long (2001) study, where-in for a strut spacing of less than 0.6 times the depth of excavation, the maximum settlement is estimated to be 0.14% of the depth of excavation. The predicted maximum settlement for roof, upper concourse, mechanical, lower concourse and base slab level excavations are 7, 15, 24, 33 & 45 mm respectively. The settlement profiles are plotted in Fig. 7.

5 Case study

Prior to commencement of excavation work of the station box, a comprehensive instrumentation and monitoring scheme had been designed and installed. The instrumentation was designed to monitor ground deformation, retaining wall deformation and critical geotechnical parameters that were likely to be affected during excavation work. The benefit of such comprehensive instrumentation and monitoring scheme is that the design assumptions and predictions can be verified and in case of any deviations the engineers can take precautionary measures in advance. The installed instrumentation included surface settlement markers, soil extensometer, inclinometer, vibrating wire piezometer, stand pipe, optical prism target etc. In this section, the predicted surface settlement due to various levels of excavation as described above has been compared with field data.

5.1 Roof slab

Predicted surface settlement and corresponding field data due to excavation for roof slab has been plotted in Fig. 8. The depth of excavation for this case was approximately 4.84 m. Surface settlement predicted using Bowles (1998); Clough & O'Rourke (1990); Hsieh & Ou (1998) have been found to be in good agreement with field data in terms of magnitude where-in, the maximum settlement ranged between 6-8 mm.

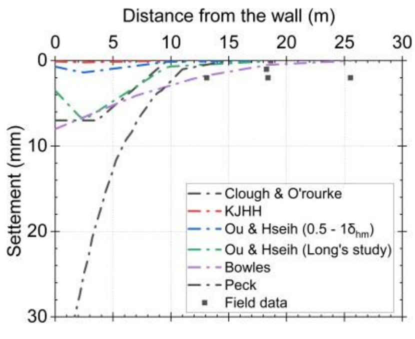

Fig. 8. Predicted vs observed settlements for Roof slab

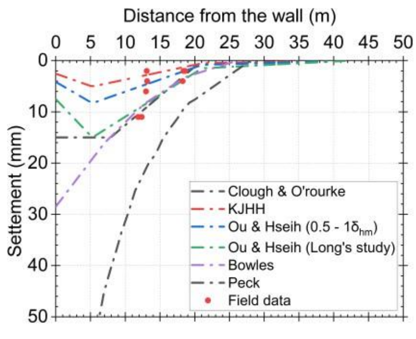

Fig. 9. Predicted vs observed settlements for Upper Concourse slab

From Fig. 8. it is observed that Kung et al. (2007) and Hsieh & Ou (1998) [using 0.5-1 δ_{hm} as max settlement] predicts the least magnitude of surface settlement, which seem unrealistic. Methodology proposed by Peck (1969) significantly overpredicts surface settlements when compared with other methods. Best results were obtained using Bowles (1998) in terms of both magnitude of settlement and the extent of zone of influence when compared with field data.

5.2 Upper Concourse slab

For construction of upper concourse slab, further excavation of 5.7 m was done below the bottom of the roof slab. Predicted ground deformation and that observed in the field during excavation for upper concourse slab has been plotted in Fig. 9. Surface settlements predicted using Clough & O’Rourke (1990) and Hsieh & Ou (1998) using Long's (2001) study compared well with field data where-in the maximum predicted settlement ranged between 14-15 mm. The results obtained using these methods were close to the observed surface settlement in terms of both magnitude and extent of zone of influence. Peck (1969) overpredicts the entire settlement profile significantly whereas Bowles (1998) overpredicts the settlement near the face of the wall when compared with other methods. However, field data was in good agreement with predicted surface settlement using Bowles (1998) beyond perpendicular offset distance of 10 m. Predicted surface settlement using Kung et al. (2007) and Hsieh & Ou (1998) with 0.5-1 δ_{hm} ranged from 2 mm to 4 mm near the face of the wall, which is rather unrealistic for an overall excavation depth of 10.5 m.

5.3 Mechanical slab

For construction of mechanical level slab, further ground excavation of 6.34 m was done, which resulted in overall excavation depth of 16.85 m. The predicted ground deformations and observed surface settlements is plotted in Fig. 10. All the methods overpredicted the settlement profile, compared to the observed values. Best results were obtained using Kung et al. (2007) and Hsieh & Ou (1998) with 0.5-1h_m where-in the maximum settlement ranged from 16 - 18 mm. Observed surface settlement within a perpendicular offset distance of 10 m to 25 m from the excavation zone varied greatly.

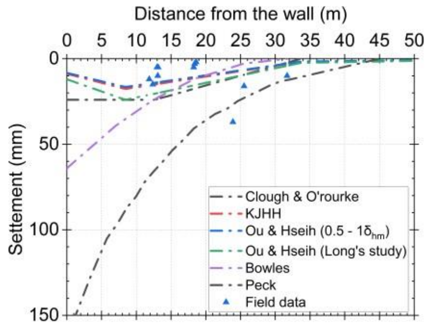

Fig. 10. Predicted vs observed settlements for mechanical slab

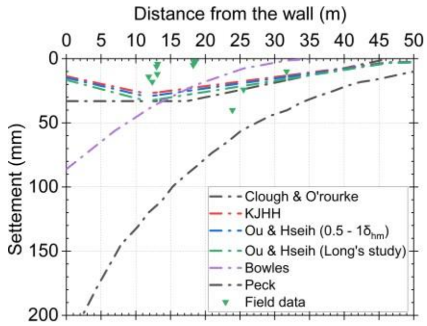

Fig. 11. Predicted vs observed settlements for lower concourse slab

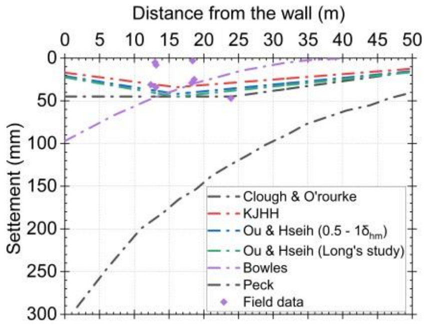

Fig. 12. Predicted vs observed settlements for base slab

This had occurred most likely due to localised variation in soil profile and ground improvement measures implemented as the surface settlement monitoring points were close to active railway tracks. Peck (1969) overpredicted the settlement entirely whereas Bowles (1998) overpredicted the ground deformations near face of the wall.

5.4 Lower Concourse slab

Bottom of the lower concourse slab had to be constructed at an overall depth of 23.19 m below the EGL. A further excavation of 6.34m was done from the base of mechanical slab to reach this level. Predicted vertical ground deformation due to excavation for lower concourse slab and the corresponding data observed in field is plotted in Fig. 11. All the methods seemed to overpredict the settlement profiles in this case. Beyond a perpendicular distance of 10m from the zone of excavation, the maximum ground deformation obtained by using these methods ranged between 27-32 mm, which exceeded the maximum settlement obtained in field by at least 7 mm.

5.5 Base slab

The cross section of the base sab was designed such that its thickness was larger towards the retaining wall and smaller towards the centre. Due to this the depth of excavation was larger towards the retaining wall. For simplicity the overall depth of excavation of base slab has been considered in this analysis as 32.015 m. This essentially means that a further excavation of 8.84 m had to be done below the bottom of the lower concourse slab. Predicted surface settlement and corresponding field data due to excavation for base slab is plotted in Fig. 12. All methodologies overpredicted the surface settlement except Kung et al. (2007), which agreed well with the field data. The maximum settlement obtained using this methodology is 33 mm, which is just 1 mm lesser than the maximum settlement observed in field. Peck (1969) and Bowles (1998) significantly overpredicted the settlement profile.

6 Summary and conclusions

In this study, the empirical methods of predicting excavation induced surface settlement available in literature has been reviewed. Using some of these methods, surface settlement has been predicted for the case of construction of underground subway station at Howrah, West Bengal, India. Further, the predicted surface settlement has been compared with field data. The following conclusions may be drawn:

I. For relatively shallow excavations having D/B ratio greater than 8, where D is the overall depth of excavation and B is the overall width of excavation, Bowles (1998) provided satisfactory results.
II. For excavations having D/B ratio less than 4, Kung et al. (2007) provided satisfactory results throughout the range of excavation depth considered in this study.
III. When surface settlement was predicted using Peck (1969), the magnitude of settlement was significantly greater than field observations as well as other methods considered in this study.
IV. Bowles (1998), Clough & O'Rourke (1990) and Hsieh & Ou (1998) showed good agreement with field data in certain cases and therefore caution and engineering judgement should be exercised while using the available empirical methods to predict excavation induced ground deformations.

In summary, it may be said that for D/B > 8, Bowles (1998) may be used and for D/B < 4, Hsiao et al. (2008) may be used to predict excavation induced surface settlement with reasonable accuracy in similar hydro-geological conditions.

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