

Prediction of Ground Settlements Due to Deep Excavations

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ABSTRACTS: Effects of ground settlements on adjacent structures have been a critical issue in deep excavations in urban areas. Empirical methods commonly adopted in the past cannot always give reasonable predictions on maximum settlements or settlement troughs. As computers and computer software become more and more popular, engineers nowadays tend to rely more and more on advanced numerical analyses together with comprehensive soil models for predicting the performance of deep excavations.

This study uses a simplified method developed by Jen(1998) for predicting ground settlements due to deep excavations in Taipei. The method is founded on a sound analytical framework and has been validated by many projects in Boston area. Since cohesive deposits in Taipei are lean sensitive clay with properties similar to those of the Boston Blue Clay, the method has been used in two excavations in Taipei to see whether it is equally applicable to the Taipei deposits. Reasonable results were obtained leading to the conclusion that the method is not only good for the Boston area but may also be suitable for other areas. However, it is noted that certain parameters used have to be adjusted to suit local ground conditions.

1. INTRODUCTION

Prediction of ground settlements on adjacent structures is a critical, and always very difficult, task for deep excavations in urban areas. Many empirical methods were derived based on settlement observations (Peck, 1969 and Clough & O'Rourke, 1990) of past constructions. These empirical methods cannot always give reasonable predictions on either the maximum settlements or the shapes of the settlement troughs. Especially settlement profiles described by straight lines proposed in many empirical methods are unsuitable for evaluating the effects of "sagging" or "hogging" of existing structures. Another major drawback associated with the use of empirical methods is that they fail to account for some of the major factors affecting ground settlements.

More reliable site specific predictions can be achieved by using advanced numerical techniques together with comprehensive soil models. However, this not only requires a sophisticated knowledge of computer coding, but also requires a good understanding of soil modeling which is by no means an easy job.

Since the late 1980s Massachusetts Institute of Technology (MIT) has been actively carrying out a series of studies on the prediction of ground settlements due to deep excavations in soft ground. Jen (1998) evaluated the performance of deep excavations in Boston Blue Clay using non-linear finite element analysis (program ABAQUS) equipped with an effective stress soil model, MIT-E3 (Whittle, 1987) and reasonable results were obtained. She has also conducted an extensive parametric study to investigate

how excavation-induced ground movements are related to key parameters including depth of excavation, length of wall, soil properties, stiffness of support system, etc. From the parametric study, she derived a generalized equation to describe settlement troughs in terms of dimensionless parameters to account for the effects of fore-mentioned factors. Jen's simplified method provides a new tool to enable geotechnical engineers to make preliminary evaluations on ground settlements caused by deep excavations.

However, Jen's study focused only on the deposits in the Boston area. Studies indicate that cohesive deposits in Taipei (also know as Taipei Silt) have the characteristics of lean sensitive clay and are similar to Boston Blue Clay in all aspects, it is therefore interesting to see if Jen's method is also applicable to Taipei Silt. Attempts were thus made to compare the settlements so estimated with the observations in two cases and results are encouraging.

2. JEN'S STUDIES

Jen continued Hashash's (1992) research on deep excavations with a more powerful finite element computational tool, i.e., the new version of ABAQUS. Based on her extensive studies, she developed a generalized equation for obtaining ground settlements and charts for obtaining most of the coefficients in the equation. This equation does account for the effects of depth to bedrock, overconsolidation ratio, overlying cohesionless soil, and stiffness of support system on ground settlements, etc. The procedures are presented as follows.

2.1 Normalized settlement trough

Based on the results of numerical analyses and regression analyses, for excavations with depths greater than 7.5 m, settlement troughs can be normalized to the maximum settlements as follows:

$$\frac{\delta_v}{\delta_{v(\max)}} = \frac{\left[e^{(ax^2+bx)} \right] (1+x^2)^c}{\beta} \quad (1)$$

where

δ_v = settlement in cm,

$\delta_{v(\max)}$ = maximum settlement in cm,

x = distance from excavation in meters

$$\beta = \left(e^{ax_{(\max)}^2 + bx_{(\max)}} \right) (1 + x_{(\max)}^2)^c \quad (2)$$

$$x_{(\max)} = \frac{-b - \sqrt{b^2 - 16ac}}{4a} \quad (3)$$

and

$$a = 0.358 - \frac{0.35}{(d_B^* - H)d_B} \quad (4)$$

$$b = b' + b^*$$

$$c = c' + c^*$$

H = excavation depth in meters

d_B = depth to bedrock in meters

d_B^* = adjusted depth to bedrock parameter

The parameter to adjust depth to bedrock, d_B^* , can be calculated as followings.

1. For wide excavations: $B > (d_B - H)$

$$d_B^* = d_B \quad (5)$$

2. For intermediate-width excavations : $(d_B - H) \geq B > 2(L - 10 - H)$

$$d_B^* = (3.5H + B + d_B) / 3 \quad (6)$$

3. For narrow excavations : $B \leq 2(L - 10 - H)$

$$d_B^* = (4.5H + B + L) / 3 \quad (7)$$

where

B = width of excavation in meters

L = length of retaining wall in meters

The above process seems to be tedious and therefore Jen (1998) developed a series of charts to simplify the process of determining parameters b' , b^* , c' and c^* , as shown in Figures 2.1 to 2.4.

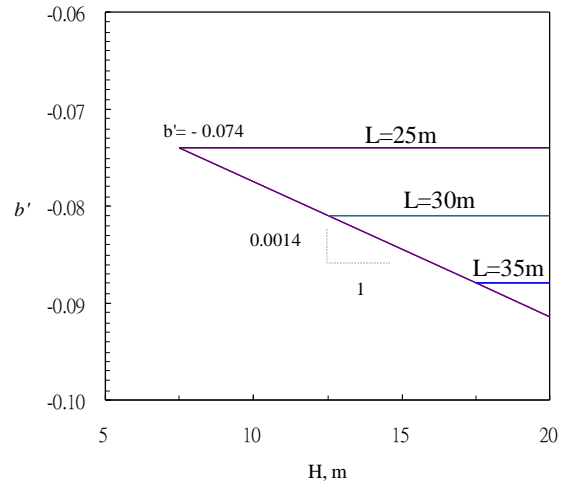


Figure 2.1. Determination of Coefficients b' (after Jen, 1998)

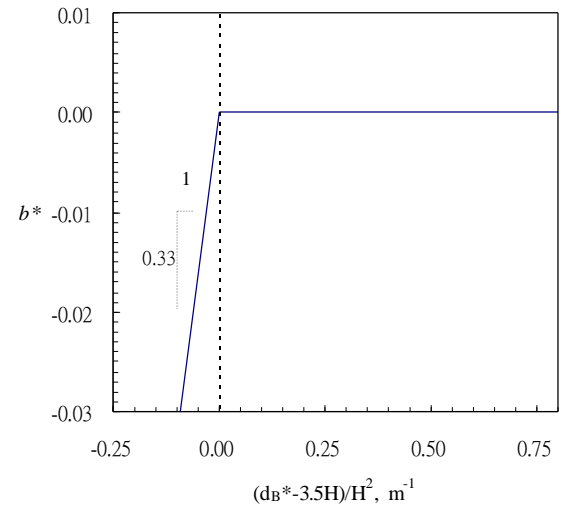


Figure 2.2. Determination of Coefficient b^* (after Jen, 1998)

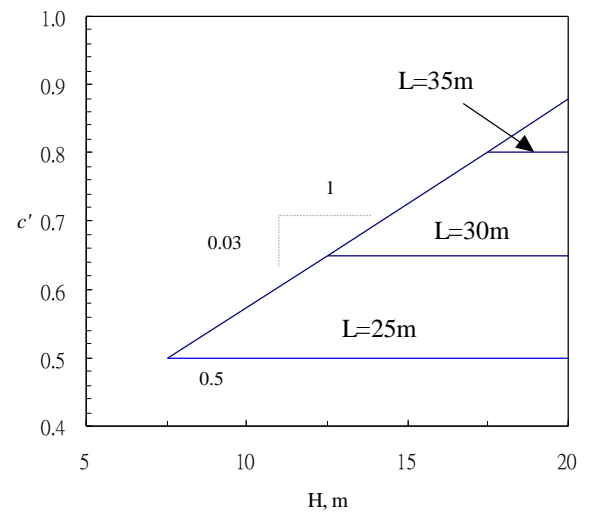


Figure 2.3. Determination of Coefficient c' (after Jen, 1998)

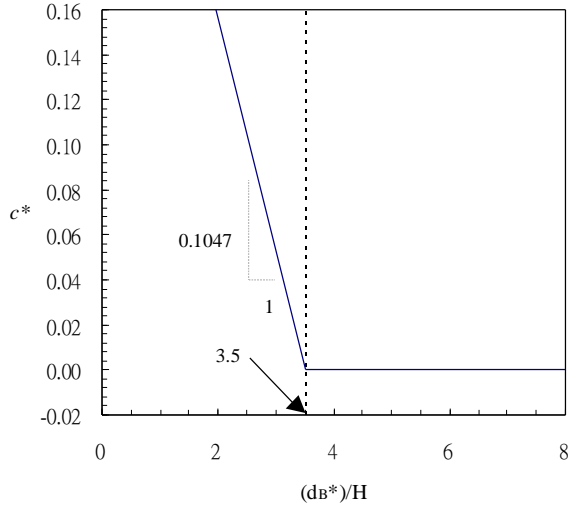


Figure 2.4. Determination of Coefficient c^* (after Jen, 1998)

2.2 Maximum surface settlement

According to Jen's studies, maximum surface settlement, $\delta_{v(max)}$, is a function of depth to the bedrock, soil properties, and stiffness of the support system. The maximum settlement can be obtained as follows.

$$\delta_{v(max)} = \mu\lambda\omega(\delta_{v(max)}^*) \quad (8)$$

where

$\delta_{v(max)}$ = maximum settlement in cm

μ = factor for bedrock depth

λ = factor for soil profile

ω = factor for stiffness of support system

$\delta_{v(max)}^*$ = maximum settlement for a given soil stress history and can be express as following.

$$\delta_{v(max)}^* = \left(\frac{B}{2m} + 1 \right) n \quad (9)$$

where

$m = f(L, B)$, see Table 1

$n = i - (H^2 - 7.5^2)j$, see Table 1

Table 1. Values of m , i and j .(after Jen,1998)

	B/2<15 for all	B/2≥15m	
	L	L=25m	L=40m
m	7	27	30
i	-0.35	-0.7	
j	0.0055	0.0115	

Once $\delta_{v(max)}$ is obtained, the entire settlement trough can be obtained by using Equation 1.

The adjustments of $\delta_{v(max)}$ (Equation 8) for the effect of bedrock, soil profile (overlying cohesionless soil and OCR varying with depth), and the support system stiffness are more complicated and are not discussed herein.

3. CASE STUDIES IN TAIPEI SILT

Jen's method has been used in two cases as a preliminary study to investigate its applicability in Taipei Silt.

3.1 Boston Blue Clay and Taipei Silt

Boston Blue Clay(BBC) and Taipei Silt (Chin et al., 1994) can both be categorized as normally to lightly overconsolidated lean sensitive clay. The physical properties of Boston Blue Clay generally fall in the ranges of those of Taipei Silt. In addition, laboratory tests have been performed at MIT using tube samples from Taipei (Whittle et al., 1993). The test program included several CRS consolidation tests and CKoU triaxial compression and extension tests. Test results were used to derive the input parameters of MIT-E3 model. A comparison between Boston Blue Clay and Taipei Silt is shown in Table 2.

Table 2. Comparisons between Boston Blue Clay and Taipei Silt

	$w_L(\%)$	PI(%)	s_{uTC}/σ'_{vc} (1)	s_{uTE}/σ'_{vc} (2)
BBC	40~42 ⁽³⁾	16~20 ⁽³⁾	0.33 ⁽⁵⁾	0.13 ⁽⁵⁾
Taipei Silt	25~40 ⁽⁴⁾	8~16 ⁽⁴⁾	0.29 ⁽⁶⁾	0.19 ⁽⁶⁾

(1)Undrained strength ratio for K_0 -consolidated triaxial compression test

(2)Undrained strength ratio for K_0 -consolidated triaxial extension test

(3)O'Neil(1985)

(4)Ou(2002)

(5)Ladd and Varallyay(1965)

(6)Whittle et al.(1993)

From a practical engineering point of view, these test results indicate that Boston Blue Clay and Taipei Silt are both lean sensitive soil with similar characteristics. Therefore it is expected that the Jen's method can be used to predict ground settlements in Taipei without any significant modification.

3.2 The Results

Settlement records are available at two sites, i.e., site A and site B, (Ou, 2002) and were adopted to compare with those estimated values by using the Jen's simplified method. The soil profiles at these two sites are depicted in Figure 3.1.

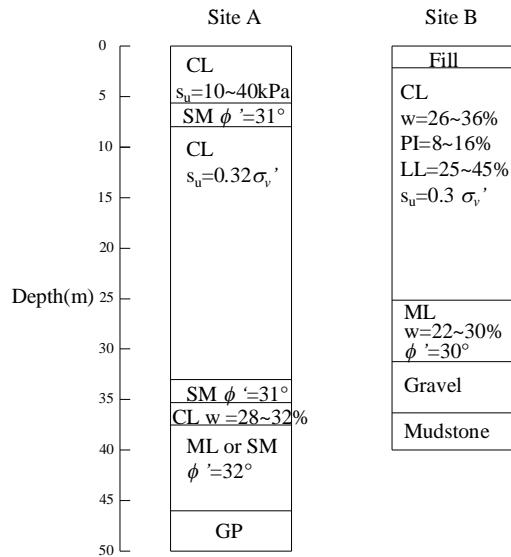


Figure 3.1. Soil Profiles at Site A and Site B (after Ou and Hsieh, 2000)

Site A is the National Enterprise Center in Taipei. For site A, the width of excavation, B , is 40m and the maximum depth of the excavation, H , is 19.7m. The length, L , and thickness of the retaining wall, t , are 35m and 0.9m, respectively. After the upper two levels of strut supports were placed, the remaining excavation was carried out by using the so-called top-down method and the walls were braced by the floor slabs.

The settlement trough estimated by using the Jen's method at site A is compared with the observed one in Figure 3.2 and the normalized settlement troughs are compared in Figure 3.3.

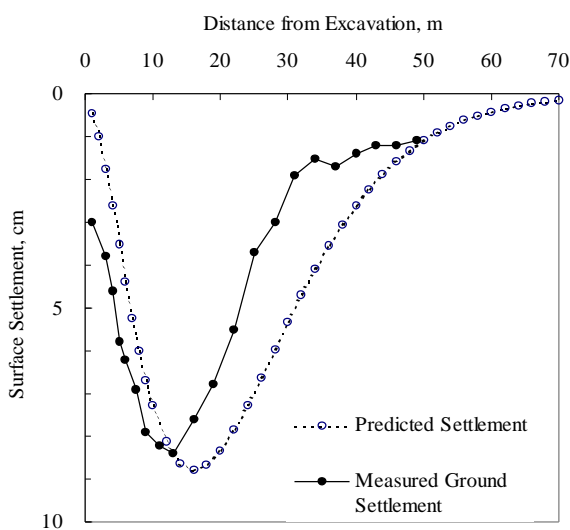


Figure 3.2. Comparison Between Ground Settlements Predicted and Measured at Site A

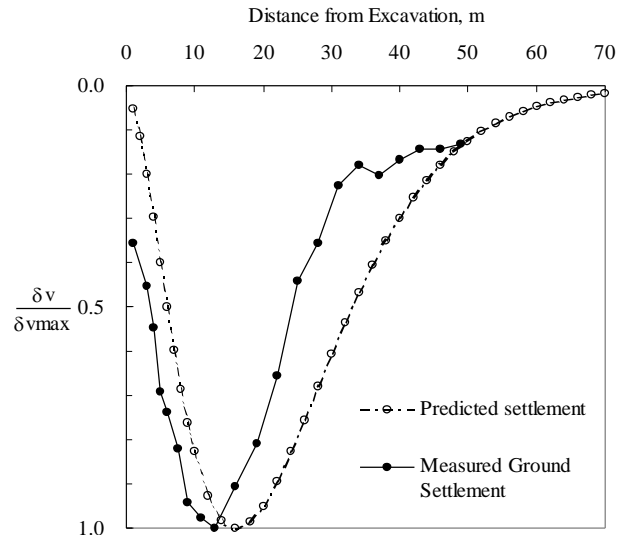


Figure 3.3 Comparison Between Normalized Settlement Troughs Predicted and Measured at Site A

Because the stress history of soil at this site is unknown, the effects of OCR were not accounted for (assuming $OCR=1$). The OCR adjustment, if there is any, tends to reduce the magnitude of predicted settlements, but will not affect the shape of the settlement troughs. As it can be noted from these two figures, the predicted settlements are in a fairly good agreement with the observed settlements at this site.

Site B is located in the K1 zone of the Sungshan formation of Taipei (i.e., very recent alluvial-lacustrine deposits, Moh and Chin, 1991). The width of excavation, B , is 35m and the depth, of the excavation, H , is 18.45m. The length, L , and thickness of the retaining wall, t , are 31m and 0.8m, respectively.

The settlement trough estimated by using the Jen's method is compared with the observed settlement trough in Figure 3.4 and the normalized troughs are compared in Figure 3.5. Similar to Site A, the effects of OCR were not accounted for. The two normalized settlement troughs appear to be in a good agreement, but the magnitudes of estimated surface settlements are significantly different from the observation. The maximum settlement was obviously over-estimated. It is, presumably, due to the omission of adjustment for the effects of OCR. This, however, has to be confirmed by further studies.

3.3 Discussions

For excavations carried out in the Taipei basin, empirical methods are the most often used method for predicting ground settlements. These empirical methods generally cannot account for all the parameters to be considered. Jen's method introduced

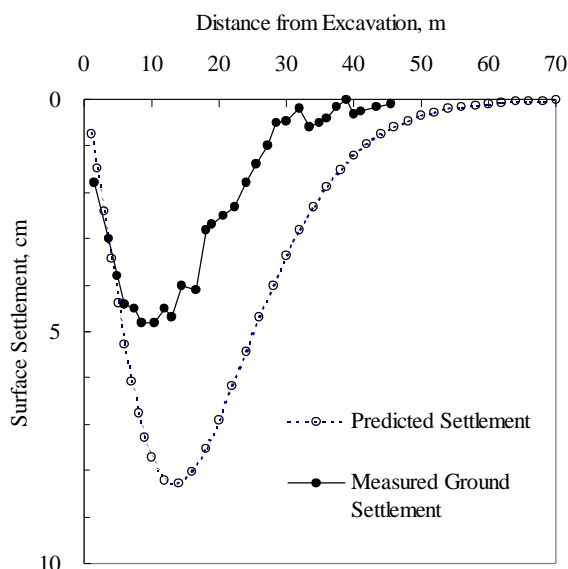


Figure 3.4. Comparison Between Ground Settlements Predicted and Measured at Site B

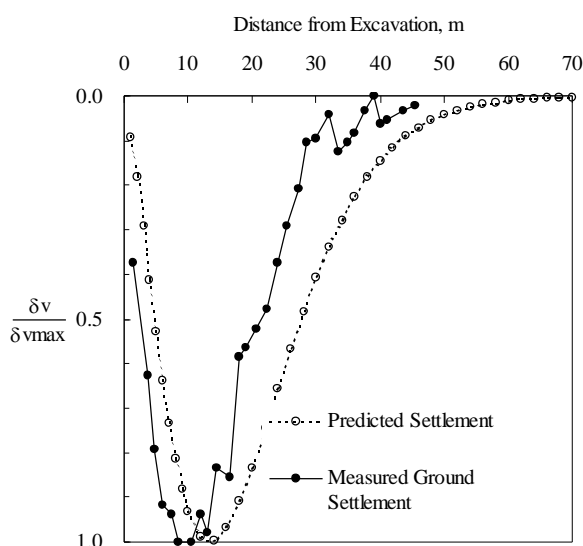


Figure 3.5. Comparison Between Normalized Settlement Troughs Predicted and Measured at Site B

herein provides engineers an alternative solution which appears to be more comprehensive and suitable for use under a variety of conditions. The results obtained in the two case studies are fairly encouraging and offers the hope that the method can be applied.

4. CONCLUSIONS

1. Two case studies are presented. At Site A, fairly good agreement was obtained between the ground settlements estimated using the Jen's method and the recorded settlements. At Site B, the maximum settlement appears to have been overestimated,

presumably, due to the fact that the effects of OCR were not accounted for.

2. The widths of settlement troughs appear to have been overestimated in both cases and therefore the distances from the walls to the tips of troughs where the maximum settlements occurred were also over-estimated.
3. For excavations in Taipei, struts are usually pre-stressed to minimize wall deflections and ground movements. The effects of pre-stressing on settlements should be further investigated.
4. The simplified method provides a very good approach for engineers to calculate the ground settlement for preliminary design. However, for detailed design, advanced numerical analyses with proper soil models are recommended.

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