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Ground movements around tunnels in soft ground

Z.-C. Moh & R. N. Hwang
Moh and Associates Inc., Taipei, Taiwan

D. H. Ju
CDPO, Department of Rapid Transit Systems, Taipei Municipal Government, Taiwan

ABSTRACT: It has been found that the use of the existing correlations under-estimates the widths of troughs of subsurface settlements over tunnels in the regions near tunnels. Based on observations made during the construction of Taipei Rapid Transit Systems, a new equation is proposed with due consideration given to the variation of subsurface settlements with depth.

1 INTRODUCTION

It is generally accepted that ground settlements over tunnels, refer to Fig. 1, may reasonably be represented by an error function of the form (Martos, 1958; Peck, 1969):

$$\delta = \frac{vA}{2.5i}\exp\left(\frac{-x^2}{2i^2}\right) \qquad \text{Eq. 1}$$

where δ = settlement, v = ground loss, A = sectional area of tunnel, x = horizontal distance to tunnel center, i = trough width parameter and is the transverse distance to the point of inflection. Based on observations on tunnels driven in the United Kingdom, O'Reilly and New (1982) proposed the following equation:

$$i_o = kz_o \qquad \text{Eq. 2}$$

where

i_o	=	width parameter at surface
z_o	=	vertical distance from surface to center of tunnel
k	=	0.4 (stiff clays) to 0.7 (soft, silty clay)
	=	0.2 and 0.3 (granular materials)

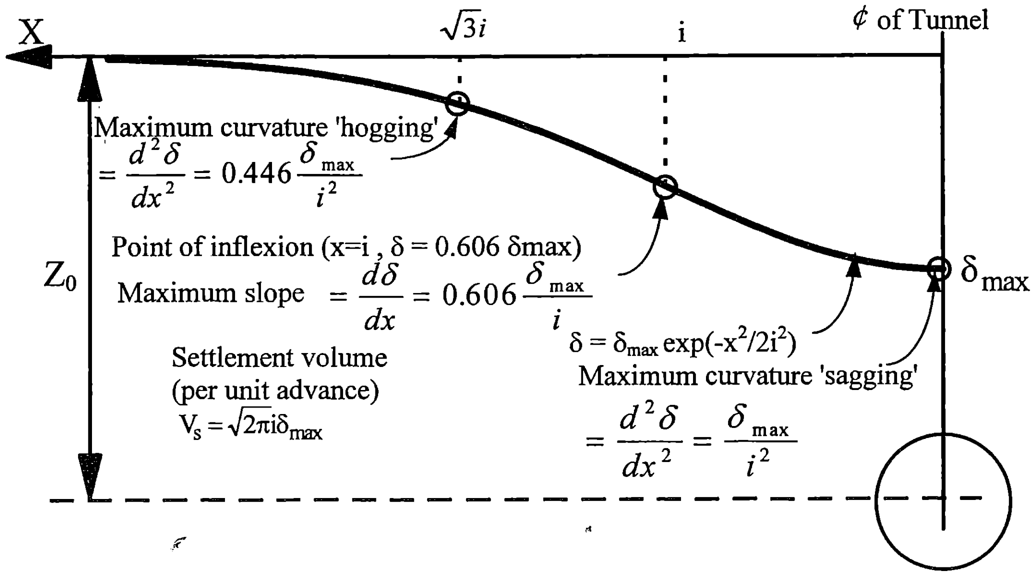

Fig. 1 Idealized Settlement Trough over Tunnel

It has been claimed that no significant correlation exists between i_o and tunnel diameter. Numerical analysis also shows that at distance of more than about one tunnel diameter, i.e., $z_o > 1.5D$, from the periphery of the tunnel the shape of the settlement trough is not significantly dependent on the tunnel diameter and the loss of ground may be considered to occur at a point sink located at the tunnel axis (Glossop, 1977).

Clough and Schmidt (1981) proposed the following relationship for soft ground:

$$i_o = \left(\frac{D}{2}\right)\left(\frac{z_o}{D}\right)^{0.8} \quad \text{Eq. 3}$$

where D = tunnel diameter. This equation can be rewritten as

$$i_o = 0.5D^{0.2}z_o^{\ 0.8} \quad \text{Eq. 4}$$

It is then clear that the depth to the center, z_o, is by far dominating than the tunnel diameter, D, on the trough width parameter, i_o. In any case, i_o is expected to be dependent on soil properties and it is thus necessary to establish relationships based on local experience.

Either Eq. 2 or Eq. 3 has been used with success for surface settlements. For subsurface settlements, the use of either equation, with z_o replaced by (z_o-z) where z is the depth at which the trough is to be determined, has been found to yield troughs which are much steeper than what have been observed (Moh and Hwang, 1993; Mair, Taylor and Bracegirdle, 1993) and attempts have been made to develop new equations for estimating subsurface troughs (Mair, Taylor and Bracegirdle, 1993; Wang and Chang, 1995).

For structures over tunnels, sagging and hogging are the major causes of damages. It is a common practice at this moment to ignore structural rigidity in design and to assume that the bases of structures deform in the same way as the ground does. Therefore, the damage potentials of buildings with basements will be over-estimated if Eq. 2 or Eq. 3 is used.

2 TRTS EXPERIENCE

The construction of Taipei Rapid Transit Systems (TRTS) provides a large quantity of valuable data enabling local correlations to be established. Figure 2 shows the instrument layout and soil profile for Section B1 of Contract CH218 of the Hsintien Line (Moh and Hwang, 1993). An earthpressure balancing shield machine with an outer diameter of 6050mm was used for mining the twin tunnels of which the concrete segments are 250mm in thickness and 1000mm in length. The outer diameter of the segments is 5900mm.

Settlements obtained above the tunnel center for the case of interest are shown in Fig. 3 in a semi-log scale. Ideally, as shown in Fig. 4, settlements over tunnels can be divided into 3 phases (Hulme, Shirlaw and Hwang, 1990) and it is proposed to consider only the settlement induced in the Phases 1 and 2 in analyzing ground loss (Moh and Hwang, 1993). For convenience, ground-loss settlement is defined as the settlement corresponding to the intersection of two straight portions in the later part of a settlement curve. The subsequent settlement is considered as long-term consolidation settlement which has a different mechanism and has to be analyzed separately. Accordingly, only the settlements induced within 4 days after the passing of the shield are considered in the following discussions.

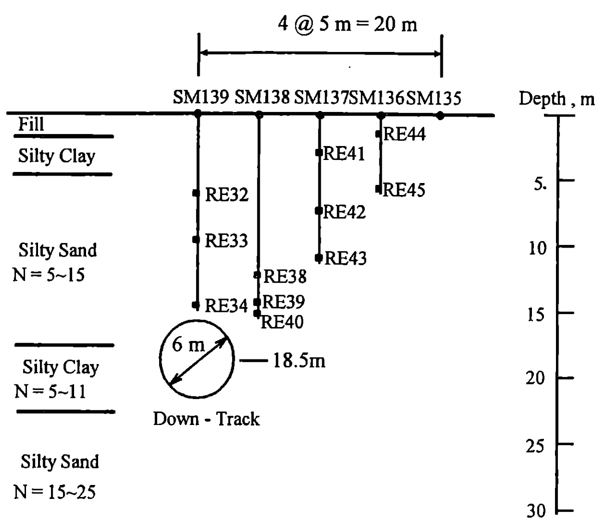

Fig. 2 Profile and Instrument Layout at Section 218B1

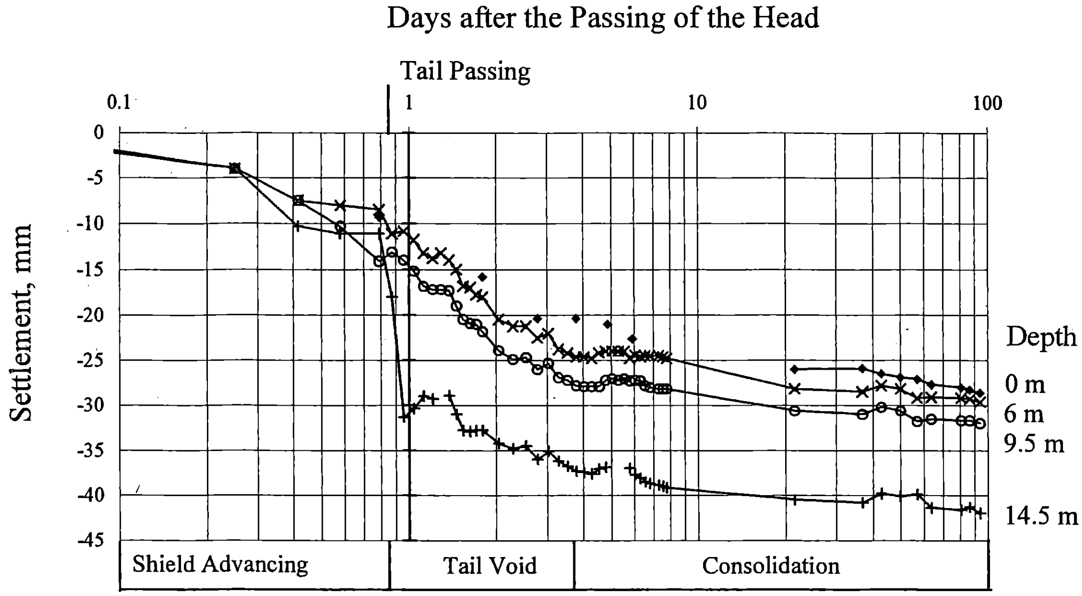

Fig. 3 Settlements at Center, Section 218B1

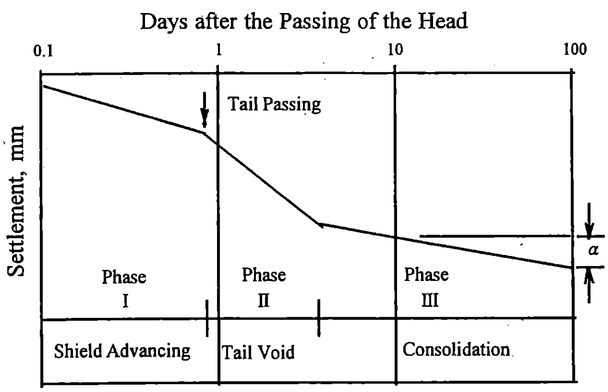

Fig. 4 Idealized Settlement Time Curve

2.1 Surface Settlements

Figure 5 shows the settlement readings interpreted from settlement curves, with ground-loss settlements on the right-hand side and consolidation settlements on the left. It has been found that, refer to Fig. 6, the data points for surface settlements are bound by two curves with i_o= 6.4m and 8.4m and the average i_o value of 7.4m is coincidentally the value obtained by using Eq. 3. For an i_o value of 7.4m, the ground loss, v, is found to be 1.3% and this value is used throughout this study.

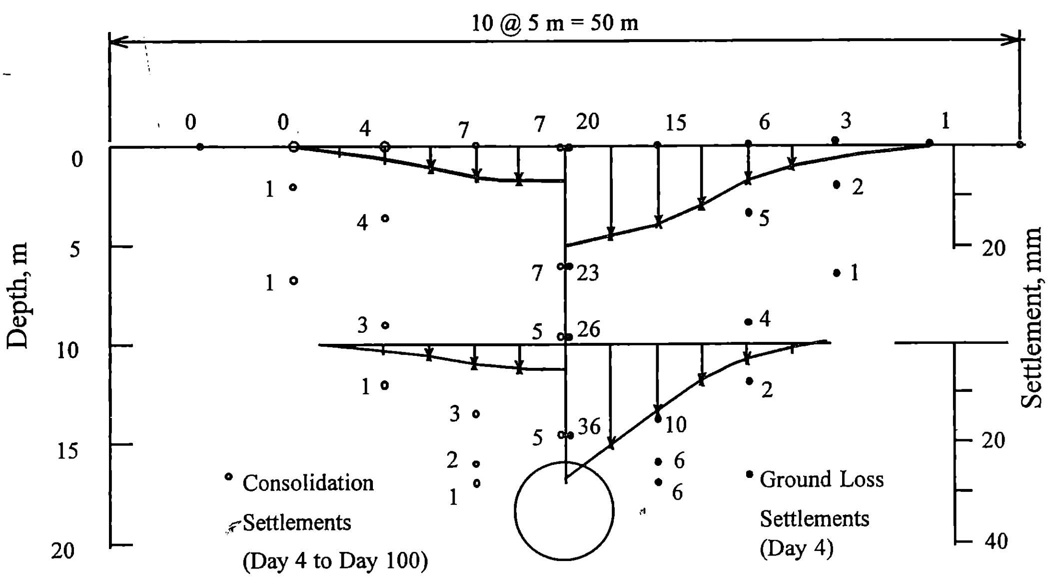

Fig. 5 Ground-Loss and Consolidation Settlements

If Eq. 2 is used, k will be of an order of 0.4 to yield an i value of 7.4m. The subsoils above the tunnel crown consist of sands with a very high silt content of 25 to 30% and k = 0.4 proposed by O'Reilly for stiff clays appears to be reasonable for the case of interest.

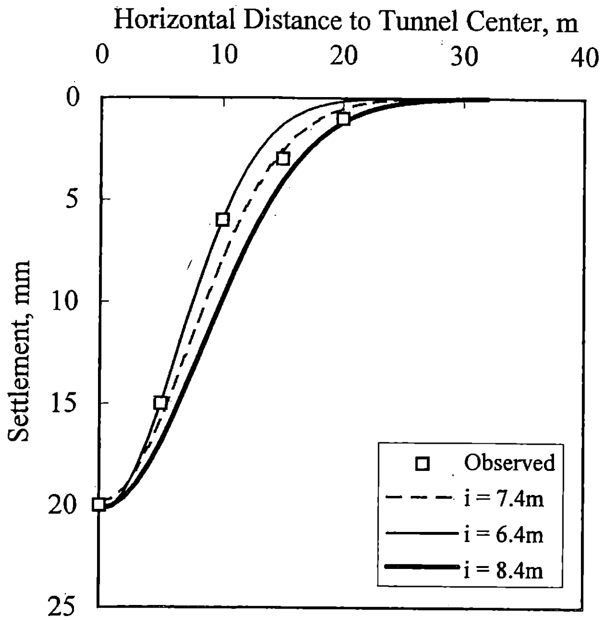

Fig. 6 Settlement Troughs at Surface

2.2 Subsurface Settlements

Subsurface settlement at any particular depth can be obtained by interpolating the readings given in Fig. 5. The results at a depth of z = 10m below surface are compared with those computed using Eq. 2 (for k = 0.4) and Eq. 3 in Fig. 7. As can be noted that the use of either Eq. 2 or Eq. 3, with z_o replaced by (z_o-z), under-estimates the width of the trough at this depth, resulting in a much steeper trough than what was observed.

Assuming that:

(a) Eq. 1 holds true for all the depths
(b) trough width parameter, i, at a depth of z can be generalized in the form of :

$$i_z = bD\left(\frac{z_o - z}{D}\right)^m \qquad \text{Eq. 5}$$

where b and m are constants to be determined based on regression analyses. For $b = k$, m = 1, this equation will give the same results at surface as Eq. 2 and for b = 0.5, m = 0.8, it will give the same results as Eq. 3.

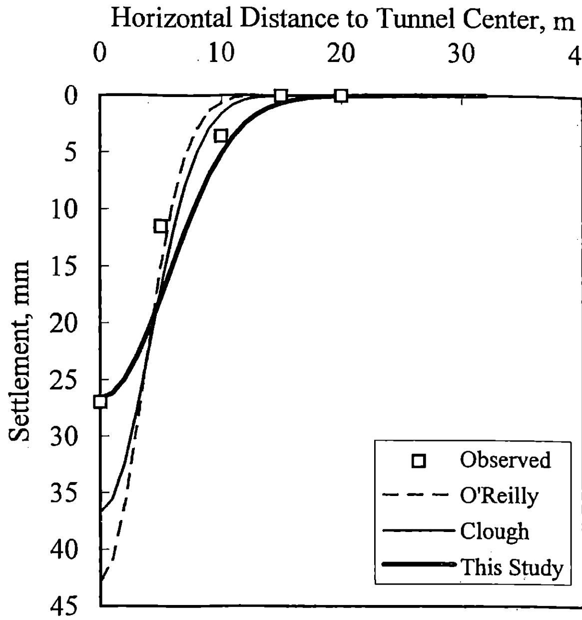

Fig. 7 Settlement Troughs at Depth of 10m

For settlements directly above the center, i.e., x = 0, substituting Eq. 5 in Eq. 1 gives:

$$\delta = \frac{vA}{2.5b} D^{m-1}(z_o - z)^{-m} \qquad \text{Eq. 6}$$

Since $A = \frac{\pi}{4}D^2$, Eq. 6 reduces to:

$$\log\delta = -m\log(z_o - z) + c \qquad \text{Eq. 7}$$

where

$$c = -0.5 + (1+m)\log D + \log v - \log b$$

The exponent $-m$ is thus the slope of log(δ) versus log(z_o-z) curve.

The ground-loss settlements directly above the center of the tunnel shown in Fig. 5 are plotted versus depth in Fig. 8, with hollow symbols for sands and solid symbols for clays. A m value of 0.4 is found to fit the data for sandy ground. For clayey ground, m = 0.8 appears to work better. However, for clays, data are limited to a single case (Section T5 of CN256 of the Nankang Line) at this moment.

Once exponent m is established, coefficient b in Eq. 5 can be obtained by fitting the settlement trough at surface. As discussed previously, refer to Fig. 6, that an i_o value of 7.4m offers the best fit. Accordingly, b can be computed from Eq. 5 by using this i_o value and is found to be about 0.8. Eq. 5 can then be rewritten as:

$$i_z = 0.8D\left(\frac{z_o - z}{D}\right)^{0.4} \qquad \text{Eq. 8}$$

The settlements computed by using Eqs. 2, 3 and 8 are compared with the observed settlements in Table 1 and it can be noted that the use of Eq. 8 leads to a much better agreement with the observed settlements below surface. This is even more evident by comparing the settlement trough at the depth of 10m given in Fig. 7.

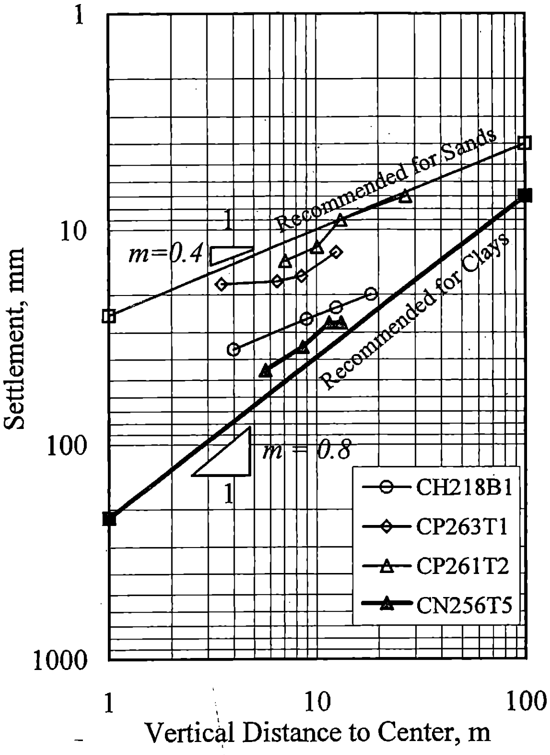

Fig. 8 Determination of Parameter m

3 DISCUSSIONS

The trough width parameters computed for various depths using Eqs. 2, 3 and 8 are compared in Fig. 9. The i_o value of 7.4m adopted at surface throughout this study is coincidentally the one obtained by using Eq. 3. Since Eq. 8 was established by matching this i_o value at surface and the k = 0.4 in Eq. 2 was determined in the same way, it is not surprising for all the three curves to meet at surface.

Of the two parameters in Eq. 8, m , which in a sense is a "subsurface trough width parameter", was determined by plotting settlements at various depths above the tunnel center and is unaffected by the i values. However, parameter b still has to be determined by the boundary condition that $i = i_o$ as $z = z_o$, therefore,

$$i_o = bD\left(\frac{z_o}{D}\right)^m \qquad \text{Eq. 9}$$

Table 1 Computed and Observed Settlements

Instrument	Depth (m)	x (m)	Observed Settlement (mm)	Computed Settlement O'Reilly Eq. 2 (mm)	Computed Settlement Clough Eq. 3 (mm)	Computed Settlement This Study Eq. 8 (mm)
SM139	0	0	20	20	20	20
SM138	0	5	16	16	16	16
SM137	0	10	6	8	8	8
SM136	0	15	3	3	3	3
SM135	0	20	1	1	1	1
RE32	6	0	23	29	27	23
RE33	9.5	0	26	40	35	26
RE34	14.5	0	36	90	66	36
RE38	13.5	5	10	4	9	18
RE39	16	5	6	0	0	15
RE40	17	5	6	0	0	11
RE41	3.5	10	5	6	7	7
RE42	9	10	4	1	2	6
RE43	12	10	2	0	0	4
RE44	2	15	2	2	2	2
RE45	6.5	15	1	0	0	1

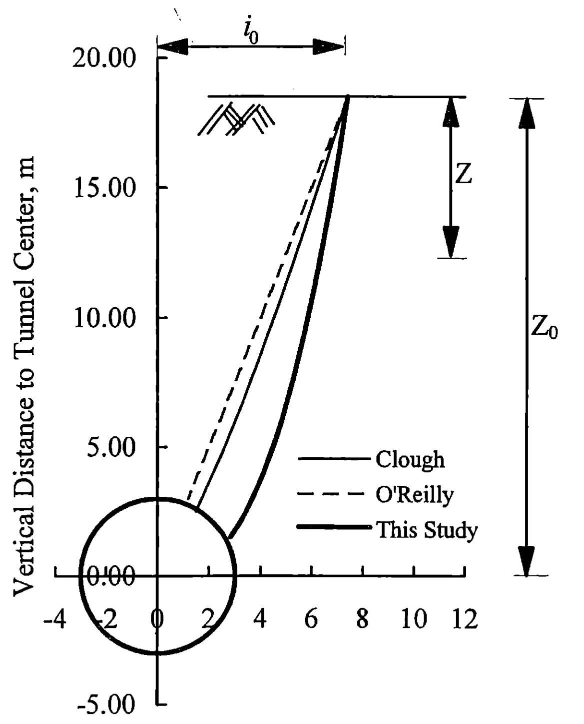

Fig. 9 Trough Width Parameter

Dividing Eq. 5 by Eq. 9 gives:

$$i_z = i_o\left(\frac{z_o - z}{z_o}\right)^m \qquad \text{Eq. 10}$$

Theoretically, any reliable relationship can used for estimating i_o for surface troughs. However, because some degree of dependency of i_z on D is expected in regions close to tunnel, Eq. 3 is preferred to Eq. 2 in which such dependency is totally missing. Accordingly, substituting Eq. 3 in Eq. 10 yields:

$$i_z = \left(\frac{D}{2}\right)\left(\frac{z_o}{D}\right)^{0.8}\left(\frac{z_o - z}{z_o}\right)^m \qquad \text{Eq. 11}$$

For clays with $m = 0.8$, it can be shown that Eq. 11 is identical to Eq. 3 with z_o replaced by $(z_o - z)$.

4 CONCLUSIONS

The foregoing discussions lead to the following conclusions:

(a) The use of equations suggested by O'Reilly & New (1982) and Clough & Schmidt (1981) under-estimates the trough widths for subsurface settlements over tunnels and may lead to over-estimation of damage potentials of buildings with basements.

(b) Equation 11 is recommended for computing subsurface settlements over tunnels.

(c) For tunnels driven in silty sands, $m = 0.4$ will be appropriate and for tunnels driven in silty clays, $m = 0.8$ is recommended.

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