

CONSOLIDATION SETTLEMENTS DUE TO TUNNELLING

by

R. N. Hwang, C. B. Fan and G. R. Yang

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R. N. Hwang

Project Manager, Moh & Associates, 11Fl, 35, Lane 11, Kwangfu N. Rd, Taipei, Taiwan

C. B. Fan

Deputy Director, SDPO, DORTS, 9Fl, 16, Nanking E. Road, Section 4, Taipei, Taiwan

G. R. Yang

Senior. Engineer, Moh & Associates, 11Fl, 35, Lane 11, Kwangfu N. Road, Taipei, Taiwan

ABSTRACT: Consolidation settlements and ground loss settlements due to tunneling have totally different mechanisms and are thus affected by different factors. It is therefore necessary to study them separately. However, since the beginning and the ending of consolidation are difficult to ascertain, a consistent definition of consolidation settlement is needed for studies to be meaningful. A procedure is proposed herein for such a purpose and an example is given to illustrate its application.

1. INTRODUCTION

In analyzing ground settlements due to tunneling, Peck's approach is usually followed (Peck, 1969) and settlement troughs are assumed to have normal distributions such that:

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

where d = ground settlement at surface, v = ground loss, A = sectional area of the tunnel, x = offset from center. The distance to the point of inflection, i , can be calculated from the following empirical formula (Clough and Schmidt, 1981):

$$i = \left(\frac{D}{2}\right) \left(\frac{z}{D}\right)^{0.8} \quad (2)$$

where D = tunnel diameter and z = depth to springline of the tunnel. In using the above equations, it is the understanding that only short term settlements are supposed to be considered.

However, it has never been made clear exactly how long the observation period should be. This will not be a problem for cohesionless materials in which excess pore pressures dissipate rather quickly and consolidation settlements finish in a very short time. In other words, all the settlements are short-term settlements. For cohesive soils, however, it is a different story. Because of the high excess pore pressures induced in the soil mass surrounding the tunnel and the slow rate of dissipation of these pressures, consolidation of soft clays may be a predominant source of settlements and it may drag on for weeks, if not months. The lack of a consistent definition of the observation period is responsible for, at least partly, the inconsistent conclusions reached in many research studies.

Settlements over tunnels due to tunneling consist mainly of the following three parts:

- Phase 1: those due to face advancement, overcutting and shield advancing
- Phase 2: those due to the closure of tail void, and
- Phase 3: those due to consolidation

Usually it takes only a few hours for the shield to pass a section and during this period ground displacements are unsteady because of the stop-and-go movements of the shield. Furthermore, it is difficult to ascertain exactly when the tail passes and how soon the ground will respond to the creation of the void. Therefore, Phase 1 and Phase 2 settlements are difficult to distinct unless settlements are monitored, say, hourly, and sufficient number of cases are studied. For the time being, out of no choices, these two phases of settlements are combined as "ground loss" settlements. On the other hand, because sufficient data have been collected, it is now possible to single out consolidation settlements from others for studying factors affecting their magnitudes. The eventual goal of this exercise is to find ways to improve shield driving technique and thus reduce ground settlements.

2. CASE STUDIED

In Contract CH218 of the Hsintein Line of the Taipei Rapid Transit Systems (TRTS), an earth pressure balancing shield machine was used to drive the twin tunnels running between Tai Ta Hospital (R12) Station and CKS Memorial Hall (G11) Station. The outer diameter of the shield is 6050mm and that of the lined tunnel is 5900mm. At Section B-1, which is the section of interest, the tunnel axis is at a depth of 18.5m below the ground surface. The head of the shield passed the section at 11:57 of November 9, and the tail passed the section, roughly 16 hours later, at 3:42 of November 10, 1992. The average earth pressure recorded by the pressure cells installed in the earth chamber was 2.1 kg/cm² during shoving. A total of 1870

liters of grout was injected at the back of the concrete segments and this quantity corresponds to 117% of the theoretical tail void of 1598 liters (with a minimal copy cut of 10mm).

Ground Conditions and Instrumentation

The site is located in the T2 Zone of the Taipei Basin. A typical soil profile for the T2 Zone is given in Fig. 1. The ground conditions at the Contract CH218 site are shown in Fig. 2. In brief, the upper third of the tunnel is in silty sand (SM) which belongs to Sublayer 5, while the lower portion of the tunnel is in silty clay (CL), which belongs to Sublayer 4 of the Sungshan formation.

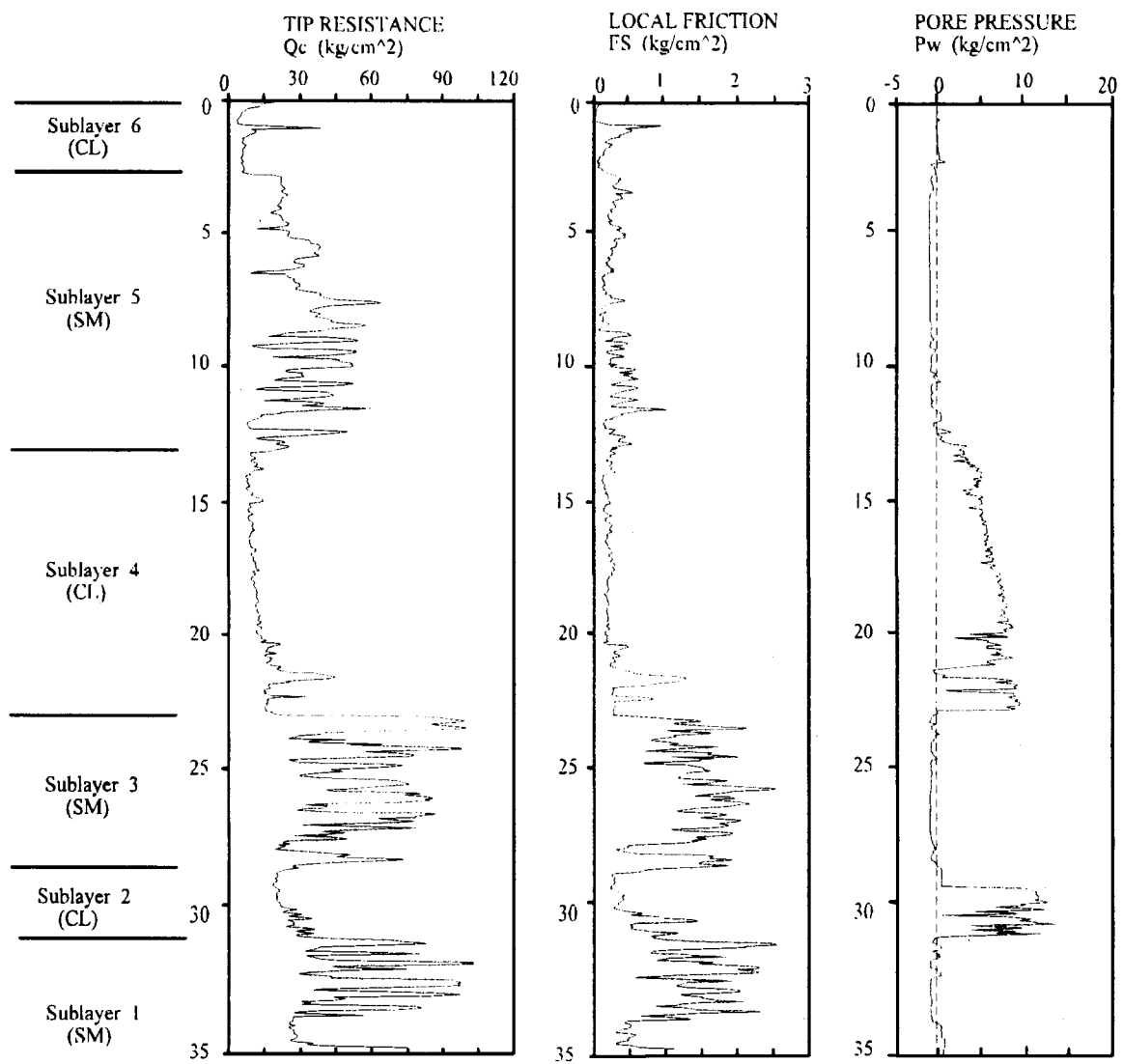


Fig. 1 Soil Profile for T2 Zone of Taipei Basin

The layout of instruments installed at the site is given in Fig. 2. Settlements markers (SM) were installed at 5m intervals along a transversal section at the surface for establishing the settlement trough. Besides, a total of 11 rod extensometers (RE) were installed in four boreholes which were at distances of 0m, 5m, 10m and 15m away from the center of the Down-Track tunnel. With all these instruments, it is possible to establish the displacement field of the soil mass within the influence zone.

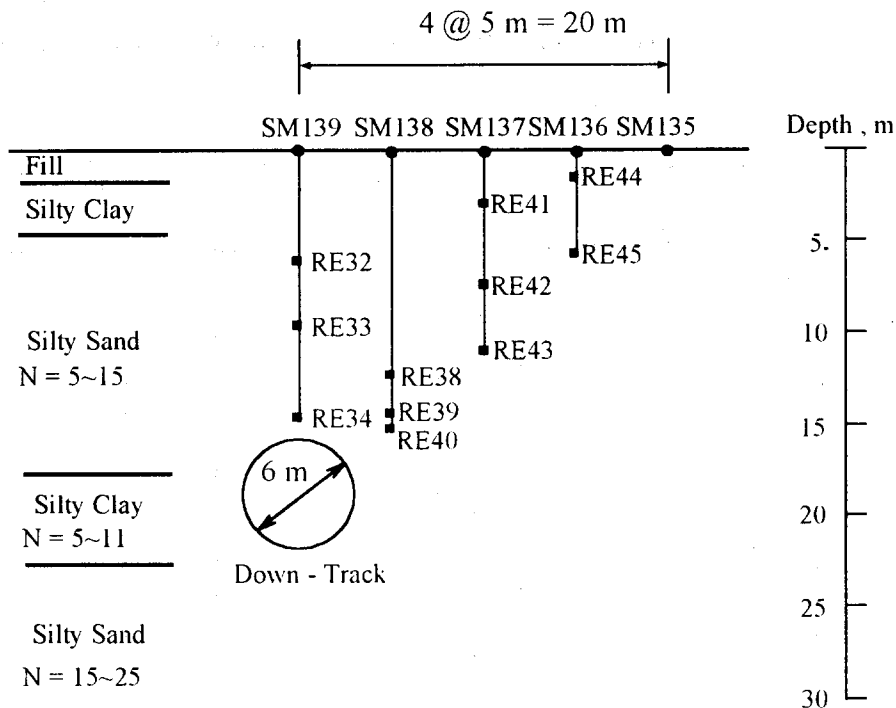


Fig. 2 Soil Profile at the Site and Instrument Layout

Observations

Settlement readings obtained at the center of the Down-Track tunnel are shown in Fig. 3. As can be clearly noted that settlements increase as depth increases. The majority of the settlements occurred after the passing of the tail of the shield. The extensometer installed at a depth of 14.5m, or 1m above the tunnel crown, suddenly sank by 20mm immediately as the tail passed. The two extensometers at shallower depths and the settlement marker at the surface did not respond accordingly, conceivably, due to the arching effects.

Figure 4 is an idealization of the settlement curves. The first straight segment corresponds to Phase 1 settlements caused by the advancement of the shield. As the tail passed the section, settlements speeded up, conceivably, due to the closure of tail void. At an elapse time of about 3.5 days, settlements slowed down considerably. The settlements after this date can be

assumed to be a result of consolidation caused by dissipation of excess pore pressure induced by shoving of the shield (Hulme, Shirlaw and Hwang, 1990) and the settlements occurred prior to this data can be assumed to be due to the so-called "ground loss". This is a somewhat arbitrary assumption and is, strictly speaking, incorrect because consolidation started as soon as pore pressure was induced, even before the passing of the head. However, from an engineering point of view, this assumption provides a convenient and consistent way for analyzing a very complicated phenomenon.

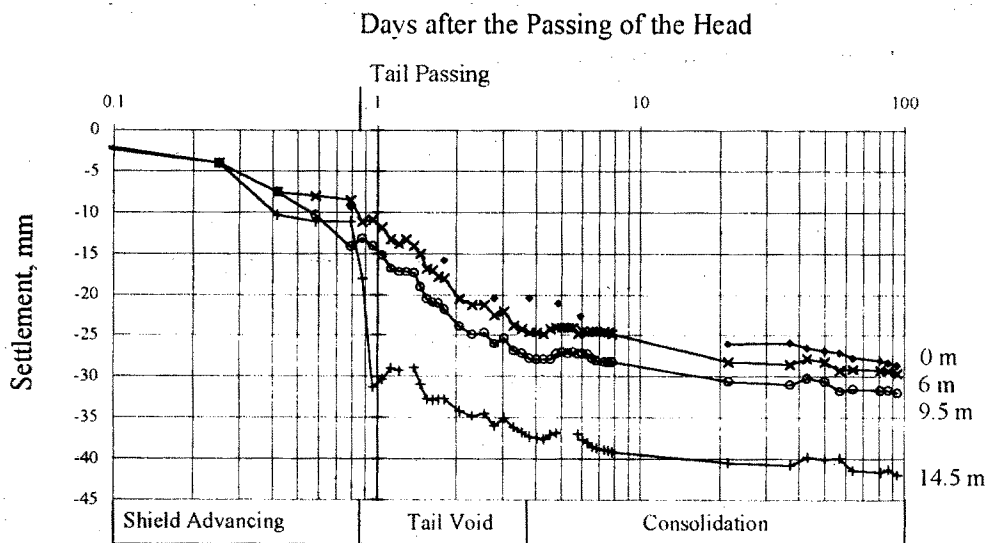


Fig. 3 Settlements at Center

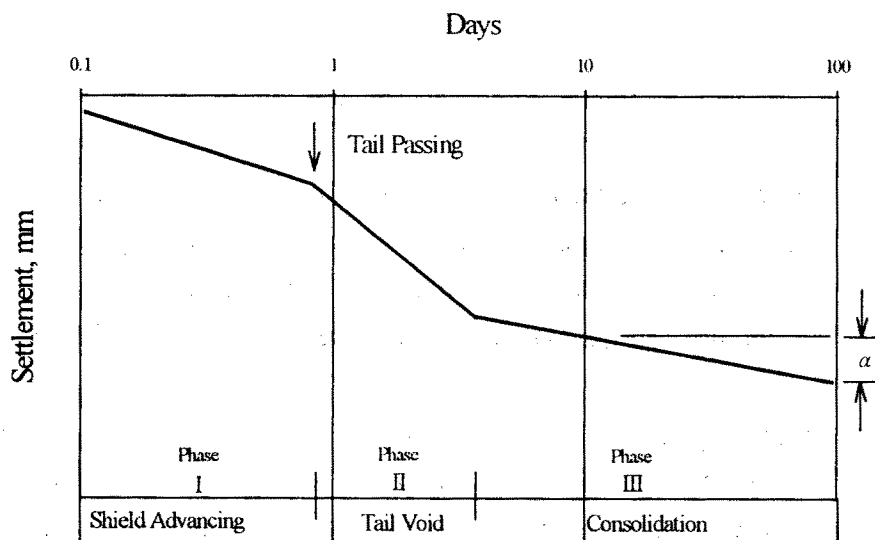


Fig. 4 Idealized Ground Settlement Curve

Experience indicates that consolidation sometimes may drag on for months. In the case studied, since some environment factors come into play, settlement readings became unsteady after an elapse time of 100 days. The consolidation settlements at this date are compared with the ground loss settlements, side by side, in Fig. 5. It is interesting to note that, opposite to ground loss settlements, consolidation settlement at the center of the tunnel is the greatest at the surface and decreases as the depth increases. It is quite reasonable for this to be so because the consolidation settlement at the surface is an accumulation of the consolidation settlements of all the underlying layers. For this reason, it is obvious that consolidation settlements can not be analyzed in the same way as ground loss settlements.

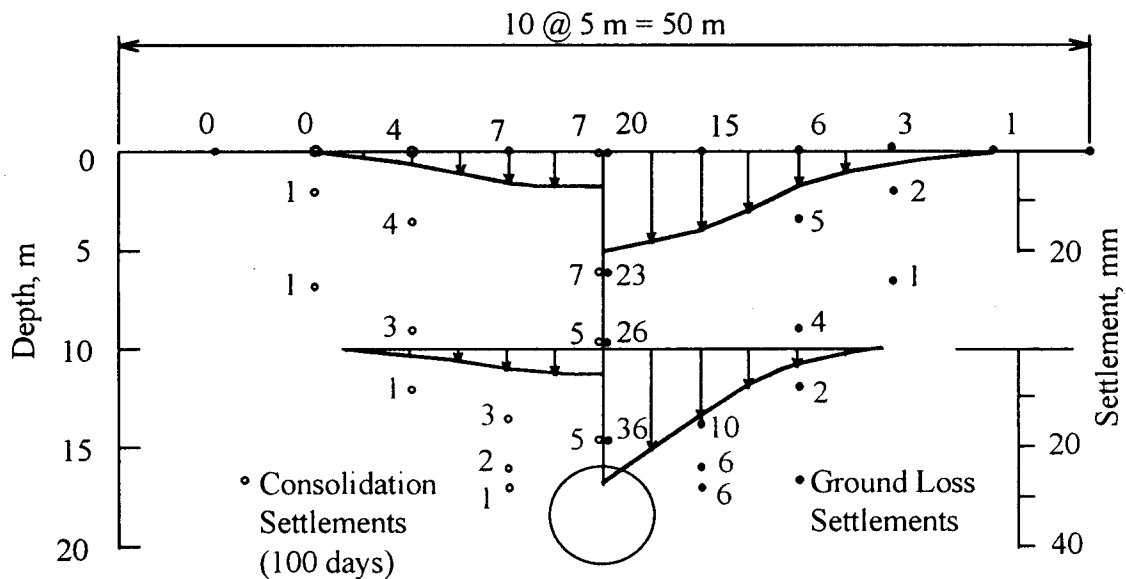


Fig. 5 Settlements and Settlement Troughs

The trough for ground loss at the ground surface shown in Fig. 5 corresponds to a ground loss, v (Eq. 1), of 1.3%. Using a ground loss of 1.3%, Eqs. (1) and (2) give a settlement of 35mm, which is far greater than the 26mm recorded by extensometer RE33, at the depth of 9.5m. This indicates that the use of Eqs. (1) and (2) is conservative at large depths.

The settlements at other depths can be computed by interpolating data obtained by extensometers. The troughs for settlements at a depth of 10m below the ground surface are compared with the troughs of surface settlements in Fig. 5. As discussed in Hulme, Shirlaw and Hwang (1990), the source of consolidation settlement is not limited to the dissipation of

excess porewater pressures induced by tunneling operation, and leakage into tunnel may also be important. Leakage into tunnel may lower the groundwater table and result in wide-spread settlements. Therefore, the shape of settlement trough is an indicator of the watertightness of a tunnel. In a conference paper accompanying to this, prepared by Hwang, Wu and Lee, it is reported that the excess pore pressures induced by the shoving of shield in clay may be significant within a distance of one diameter from the edge of tunnel, i.e., 9m from the center in the case studied. The fact that consolidation settlements shown on the left-hand side of Fig. 5 do not stretch too far beyond this distance proves that leakage is minimal.

4. INDEX OF CONSOLIDATION SETTLEMENT

In most of cases, the commencement of consolidation is difficult to decide because settlement readings are usually taken weekly or even less frequently. Furthermore, because tunnels are usually under busy roads, settlement readings are affected by traffic vibrations. The ending of consolidation settlements is even more difficult to decide because settlement may drag on for months and the second tunnel is likely to arrive before consolidation finishes. Even without the influence of the second tunnel, other sources of disturbance will soon come into play.

To have a fair comparison of the performance of tunnel drives, a consistent procedure is desired. In lack of detailed data, consolidation settlements may be assumed to start at an elapse time of 10 days after the passing of the shield. Furthermore, it is proposed to use the slope of the settlement curve in the consolidation phase as an index for consolidation settlement. In other words, the index of consolidation settlement, α , is defined as the settlement in a cycle in the log-t plot. More conveniently, as illustrated in Fig. 4 the index of consolidation settlement is simply the difference in settlements between the 10th day and the 100th day after the passing of the tail. However, it is more preferable to plot the elapse time after the passing of the head of the shield, instead of the tail, because the Phase 1 settlements occurred during the passing of the shield are of interest as well. The error introduced will be insignificant because the tail usually passed within 24 hours after the passing of the head.

The indices of consolidation, i.e., the α values, as read from Fig. 3 decrease from 5mm at surface to 3mm at the depth of 14.5m. In this particular case, the differences among these curves are not obvious because of the small values of α . Indices of consolidation are predominately affected by the permeability of soils surrounding the tunnel. In the case studied, at the tunnel crown is a thick layer of silty sand which has a moderate permeability of an order of 1×10^{-6} m/sec. The shield is roughly 7m in length and it took 16 hours for the shield to pass the section. It is anticipated that, at this slow rate of advancement, much of the excess

pore pressure induced by the movement of the shield had dissipated during shoving and therefore the subsequent consolidation was minimal. There are certainly other factors which are important. As large quantity of data have been collected during the construction of the TRTS, it is hope that all these factors can someday be identified and their effects quantified.

5. SUMMARY

In lack of detailed data, consolidation settlements can be assumed to start at an elapse time of 10 days after the passing of the shield, and consolidation settlements can be expressed in terms of indices of consolidation settlement, α , which is defined as the settlement in a log cycle, or, simply the difference between the settlements on the 10th and the 100th days after the passing of the head of shield. This provides a convenient and consistent way for analyzing consolidation settlements.

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