PREDICTION OF LONG-TERM SETTLEMENTS INDUCED BY SHIELD TUNNELING

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ABSTRACT

Prediction of settlements over tunnels is important for protecting adjacent structures. Proposed herein are three mathematical models for predicting long-term settlements over tunnels due to shield driving based on short-term settlement readings, *i.e.*, (1) the Logarithmic Model, (2) the Hyperbolic Model and (3) the Hybrid Model. Prediction was made for settlements at four sections based on the readings obtained in the first stage construction of the Taipei Rapid Transit Systems and the results were compared to confirm the validity of these three models.

Key words: Settlement, tunnel, tunneling, consolidation, shield.

1. INTRODUCTION

As more and more mass rapid transit systems are to be constructed in cities, settlements over tunnels have become a serious concern because buildings adjacent to tunnels may be endangered should ground settlements exceed limits tolerable by their structures. This is particularly true if tunnels are to be driven directly underneath buildings. The uneasiness of the residents frequently leads to protest against the projects and sometimes may even result in court injunctions. Therefore, prediction of ground settlements is vital to the progress and success of tunneling projects.

2. MATHEMATICAL MODELS

Three models are introduced herein for predicting long-term settlements over tunnels: namely, the logarithmic model, the hyperbolic model and the hybrid of these two.

2.1 The Logarithmic Model

The use of earth-pressure balancing shield machines and slurry shield machines nowadays practically reduces the advance ground movements over tunnels before the arrival of shield machines to minimal (say, a few millimeters), therefore, settlements can be assumed to start after the passing of shield machines. Moh and Hwang (1993) divided settlements into 3 phases: (1) shield advancing, (2) closure of tail void after the passing of the tail, and (3) consolidation. Normally, shield machines are 6 m to 8 m in length and, with normal rates of progress of 8 to 10 rings per day, will pass the sections of interest in a day or less. Major part of settlements would occur as the tail passes and the surrounding soils close in toward the segments. Grouts should be injected to fill up the voids behind the tails, the sooner the better, to reduce ground settlements.

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Settlements in Phase 3 can be approximated by straight lines, in semi-log plots, as depicted in Fig. 1, and the slopes of these lines can be considered indices for comparing settlements obtained in different ground conditions (Hwang, *et al.*,1995). For convenience, settlements in Phases 1 and 2 were first called "immediate settlements" collectively, with the understanding that they might take quite a few days to occur, and the subsequent settlements were called "consolidation settlements". The terms of "immediate settlement" and "consolidation settlement" are somewhat ambiguous because considerable consolidation may have occurred in Phases 1 and 2 and settlements in Phase 3 may involve mechanisms other than consolidation of soils. They were onetime renamed to "primary settlement" and "secondary settlement". But, again, these two terms could be mis-interpreted to imply "primary consolidation" and "secondary consolidation". Therefore settlements in various phases are now simply referred to, as depicted in Fig. 1, as "Phase 1 settlement", "Phase 2 settlement" and "Phase 3 settlement", *etc*, herein without referring to the speediness nor the mechanism of settlements.

The slope of the line corresponding to Phase 3 settlements, denoted as α, is called "index of Phase 3 settlement" and can be used to predict future settlements based on the records already obtained. It is the settlement over one full cycle in the semi-log plot, or, simply the difference between the settlements obtained on the 100th day and the 10th day after the passing of the shield machine. Such a definition has the merit that settlement increases, roughly, by 0.5α each time the elapse time increases by a factor of 3, for example, from 10 days to a month, from a month to 100

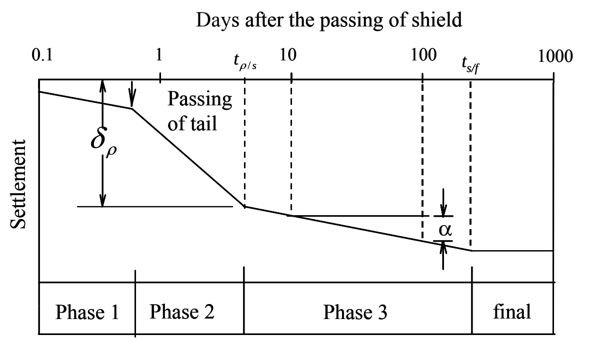

Fig. 1 Logarithmic Model for simulating settlement curves

days, from 100 days to a year, so on and so forth. Accordingly, long-term settlements beyond the observation period can be obtained by extending this straight line and can be expressed as follows:

$$\delta_t = \delta_p + \log\left(\frac{t}{t_{p/s}}\right) \cdot \alpha \quad (1)$$

where

- δ_t = settlement on the t-th days after the passing of the shield
- δ_p = Phases 1 and 2 settlement
- t = elapse time after the passing of shield
- $t_{p/s}$ = time corresponding to the transition of Phase 2 settlement and Phase 3 settlement
- α = index of Phase 3 settlement
- $t_{s/f}$ = time corresponding to the transition of Phase 3 settlement and final settlement

Based on the experience learned from the first stage construction of the Taipei Rapid Transit Systems (TRTS), the transitions between Phase 2 and Phase 3 settlements occurred, in general, at elapse times between 7 days to 10 days after the passing of shield. For practical purposes, it can be assumed that the transitions always occur on the 10th day. Accordingly, Eq. (1) can be rewritten as:

$$\delta_t = \delta_{10} + \log\left(\frac{t}{10}\right) \cdot \alpha \quad (2)$$

or

$$\delta_t = \delta_{10} + (\log t - 1) \cdot \alpha \quad (3)$$

As depicted in Table 1, the α values obtained in the first stage TRTS construction are found to vary in a very narrow range, say, between 5mm to 9mm, except in the T1 Zone, with a weighted average of about 6mm (Chen, *et al*., 2002). They are obviously affected by ground conditions as evidenced by the fact that small values are obtained in the T1 Zone in which subsoils are predominantly silty sands and the largest values are obtained in the K1 Zone in which subsoils are predominantly silty clays. If the α value for a certain tunnel falls beyond this range, it is very likely due to reasons other than tunneling, such as grouting, lowering of groundwater table, leakage of lining, or other construction activities. It is therefore possible to predict the final settlements based on short-term settlements with confidence. This may not hold true elsewhere because, for example, a limited number of case histories do suggest that the α values for tunneling in Singapore marine clay are much larger, say, in the range of 10 mm to 20 mm.

2.2 The Hyperbolic Model

In normal cases, as illustrated in Fig. 2, settlements over tunnels will increase at reducing rates as time goes by and will reach their limits eventually. Fujita (1982) and Fang, *et al*., (1993) suggested to express settlement curves by hyperbolic functions, as illustrated in Fig. 2, as follows:

$$\delta_t = \frac{t}{a + bt} \quad (4)$$

in which "*a*" and "*b*" are two constants to be established by curve fitting. Equation (4) can be rewritten as:

$$\frac{t}{\delta_t} = a + bt \quad (5)$$

As such, "*a*" will be the ordinate of the intercept of (t/δ)-versus-(t) plot with the y-axis and "*b*" will be the slope of the line. The constant "*a*" is in fact the inverse of the rate of initial settlements while constant "*b*" is the inverse of the ultimate settlement, *i.e.*,

$$\delta_{\text{ultimate}} = \frac{1}{b} \quad (6)$$

As to be illustrated in Section 3.2, these two constant can easily be obtained by regression analysis once data are available. Table 2 shows the maximum settlements proposed by Fujita (1982) and Table 3 shows the "*a*" values proposed by Fang, *et al*., (1993,2001) for tunnels driven by using different types of shields in different ground conditions. It, however, should be noted that these studies were performed based on data obtained in the early days and recently experience indicates that ground settlements over tunnels have been greatly reduced as tunneling technology advanced.

The initial condition for Eq. (4) is $\delta = 0$ as $t = 0$. This condition may or may not be valid because there could be settlement or heave as the shield passes the section. However, as to be illustrated in Section 3.2, the discrepancies, if any, will not be critical as the final settlements are insensitive to the settlements in the early stages.

Table 1 Indices of Phase 3 settlements in the Taipei basin (after Chen, *et al*., 2002)

Zone	No. of sections	Average (mm)	Standard deviation (mm)
T1	16	2.0	0.7
T2	21	5.4	2.7
TK2	4	5.5	0.9
K1	44	8.9	4.3
H1	6	5.2	2.0
YH	12	6.8	2.8
B1	19	7.4	3.6
B2	74	5.1	2.8
C	6	5.0	1.6
	202	6.04	

Table 2 Ground settlements over tunnels driven by using different types of shields in different ground (after Fujita, 1982)

	Surface settlement (mm)			
	Open	Blind	Slurry	Earth pressure balancing
Clay	100 ± 30	40 ± 20	40 ± 20	60 ± 25
Clay + Sand	100 ± 30		90 ± 30	20 ± 10
Sand			40 ± 25	20 ± 10

Table 3 "*a*" values for tunnels driven by using different types of shields in different ground (after Fang, *et al.*, 1993)

	Type of shield		
	Earth pressure balancing	Slurry	Open
Clay	0.15 ~ 0.25 (13 cases)	0.19 ~ 0.57 (4 cases)	
Soft Clay	0.05 ~ 0.09 (5 cases)		0.19 (1 case)
Sand	0.05 ~ 0.11 (2 cases)	0.06 (2 cases)	

2.3 The Hybrid Model

The Logarithmic Model, as indicated by Eq. (1) has the discrepancy that settlements continue forever. This is definitely unrealistic. It is anticipated, in normal conditions, settlement curves will show the tendency of leveling off, as illustrated in Fig. 1, if the observation periods are sufficiently long. If this does happen, Phase 3 settlements, together with subsequent settlements may be better expressed as hyperbolic functions in a semi-log scale as depicted in Fig. 3. This can easily be achieved by letting:

$$u = \log(t) \tag{7}$$

$$\delta_t = \frac{u}{c + du} \tag{8}$$

in which "*c*" and "*d*" are two constants to be obtained by curve fitting and the same procedures used for the Hyperbolic Model, refer to Section 3.2, can be used to obtain final settlements. To be consistent with the Logarithmic Model, only Phase 3 settlements are considered to avoid unnecessary influences by the Phases 1 and 2 settlements on the results. However, unlike the case for the Logarithmic Model, which simplifies settlement curves into straight lines so the transition between Phase 2 and Phase 3 can readily be identified, the starting point of Phase 3 settlements is not defined in the Hybrid Model. As mentioned in Section 2.1, it can be assumed that Phase 3 settlements start on the 10th day unless data indicate otherwise.

The initial condition for Eq. (8) is $\delta = 0$ as $t = 1$. This condition may or may not be valid as there could be settlements or heaves one day after the passing of the shield. However, similar to the case of Hyperbolic Model, the discrepancies, if any, are not critical as the final settlements are insensitive to the settlements in the early stages.

3. CASE STUDY

To illustrate the applications of these 3 models, settlement readings obtained at 4 sections in Contract 218 in the first stage construction of the Taipei Rapid Transit Systems are analyzed. As can be noted from Fig. 4, the data for Sections C1 and C2 are rather poor in quality with abrupt drops at an elapse time of about 45 days followed by unexpected heaves. Such phenomena are, however, by no means rare in reality as the ground may be disturbed by various construction activities, such as grouting, pumping of groundwater, *etc*. The observation periods of 3 months for these two sections are also short in comparison with those for Sections B1 and B2, but are already longer than the observation periods in normal cases as monitoring is usually terminated in one month or even less after the passing of shields. In contrast, the quality of data for Sections B1 and B2 is exceptionally good and the observation periods are exceptionally long. This provides an extraordinary opportunity to illustrate the applications of the 3 models. On the other hand, the data for Sections C1 and C2 are

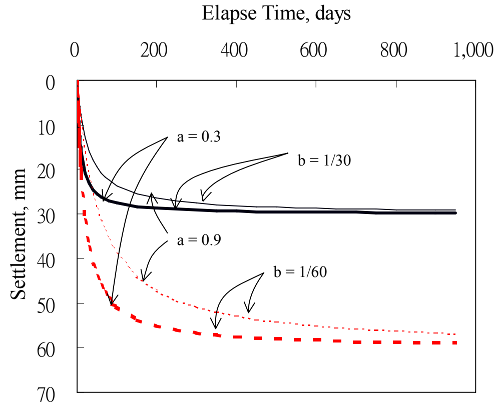

Fig. 2 Hyperbolic Model for simulating settlement curves

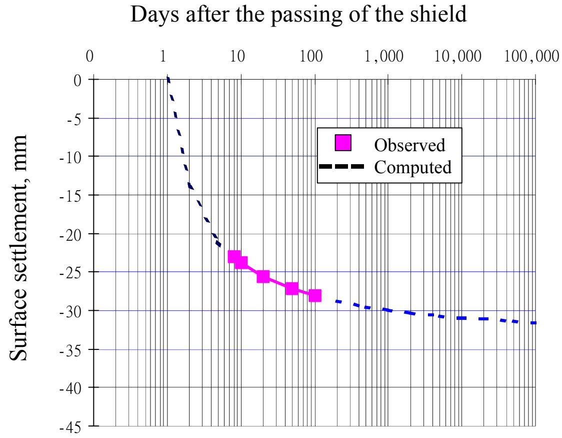

Fig. 3 Hybrid Model for simulating settlement curves

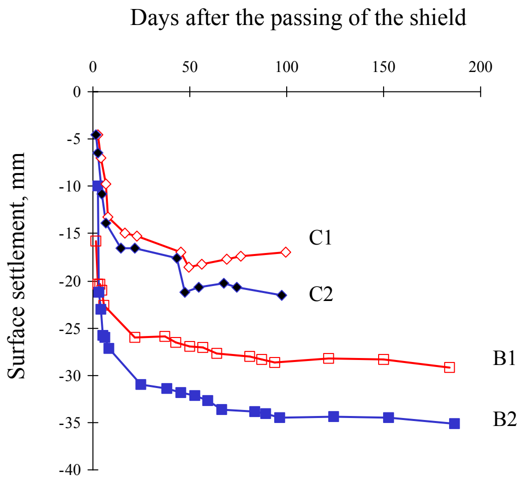

Fig. 4 Settlement readings obtained in Contract 218 of TRTS

deliberately included to illustrate the difficulty normally encountered in interpreting instrument readings and how the quality of data will affect the results.

The site is located in the T2 Zone in the Taipei Basin. Since ground conditions are irrelevant to the mathematic schemes proposed herein, readers are advised to refer to Woo and Moh (1991) and Lee (1996) for geological settling of the Taipei Basin and ground conditions in the T2 Zone if so desired.

3.1 Settlements Predicted by using the Logarithmic Model

The settlement readings shown in Fig. 4 are plotted in a semi-log scale in Fig. 5. As can be noted, settlements obtained in Sections B1 and B2 in the period of 7 days and 100 days after the passing of the shield machine indeed appear to be roughly linear. Straight lines can be determined visually to represent these settlements and can be extended to obtain long-term settlements after the observation periods.

As mentioned above, the quality of the data for Sections C1 and C2 is rather poor with abrupt drops and unexpected heaves. Such a discrepancy is even more pronounced in semi-log plots. Considerable judgment has to be applied to determine the lines representative of Phase 3 settlements. However, no matter how these lines are drawn, the differences made will be within 5mm at an elapse time of, say, 1,000 days. Differences of this magnitude are deemed to be acceptable for all practical purposes. The indices of Phase 3 settlements, *i.e.*, the α values, are 4.42 mm, 6.18 mm, 4.68 mm, and 6.57 mm for Sections B1, B2, C1, and C2, respectively. These values fall in the range for the T2 Zone as depicted in Table 1.

3.2 Settlements Predicted by using the Hyperbolic Model

Figure 6 illustrates the procedure of obtaining the two constants "*a*" and "*b*" in Eq. (4) by regression analyses. The data obtained at Sections B1 and B2 are used as examples and ultimate settlements of 29.06 mm and 35.36 mm, respectively, are obtained. Figure 7 shows the settlement curves obtained for all the 4 cases shown in Fig. 4. As can be noted that a fairly good agreement is achieved between the observed settlements and the computed settlements within the observation periods.

As can be noted from Fig. 6, the ordinates of the y-intercepts of the regression lines, *i.e.*, the constant "*a*" in Eq. (5), are governed by settlements in the early stages while the slopes of these lines, *i.e.*, the constant "*b*" in Eq. (5), are governed by settlements in the latter stage and have very little to do with settlements in the early stage. Since ultimate settlements are the inverse of constant "*b*", they are insensitive to settlements in the early stage. For the same reason, it is expected that the ultimate settlements computed will not be significantly affected by the inherent initial condition of $\delta = 0$ as $t = 0$ mentioned in Section 2.2.

3.3 Settlements Predicted by using the Hybrid Model

As illustrated in Section 3.1, settlement curves for Sections B1 and B2 in the period between the 7th day and the 100th day after the passing of the shield can be represented by straight lines if plotted in a semi-log scale. Subsequent readings, however, do show the tendency of leveling off as depicted in Fig. 5. Accordingly, it may be a good idea to simulate Phase 3 settlements and subsequent settlements by hyperbola in a semi-log scale.

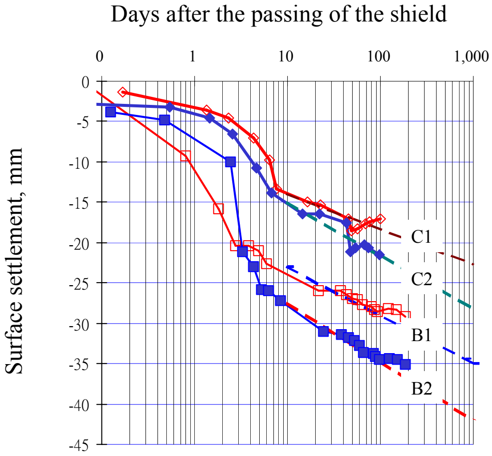

Fig. 5 Settlements predicted by using the Logarithmic Model

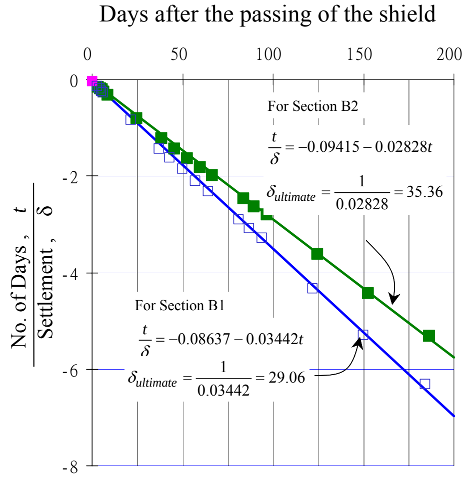

Fig. 6 Regression analysis using the Hyperbolic Model

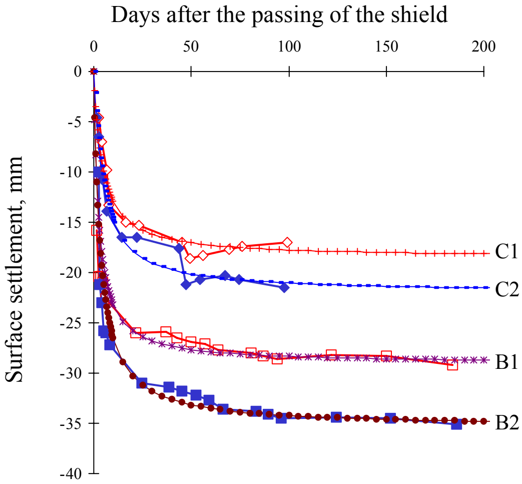

Fig. 7 Settlements predicted by using the Hyperbolic Model

In analyses using the Hybrid Model, the 2 constants "*c*" and "*d*" in Eq. (8) can be determined by adopting the procedure depicted in Fig. 6 with "*t*" transformed to "*u*" by using Eq. (7). Although it has been suggested that, to be consistent with the Logarithmic Model, Phases 1 and 2 settlements be excluded, analyses were also performed with Phases 1 and 2 settlements included to see whether the inclusion of these settlements makes differences. Figures 8 and 9 show the 2 sets of settlements obtained for Sections B1 and B2, respectively, and Figs. 10 and 11 show those for Sections C1 and C2, respectively. As can be noted by comparing these figures with Fig. 5, settlement curves are indeed better simulated by hyperbola, instead of straight lines, in a semi-log scale.

Unlike the case of Hyperbolic Model, the inclusion of early settlements does make some differences on the results. The ultimate settlements, except for Section C2, obtained are larger if early settlements are included. This is only of academic interest because it is not suggested to include Phases 1 and 2 settlements in analyses in any case.

4. COMPARISON OF RESULTS

4.1 Ultimate Settlements

Ultimate settlements can be obtained mathematically by following the procedure illustrated in Fig. 6 if the Hyperbolic Model is used. The same procedure is applicable if the Hybrid Model is used with the variable "*t*" transformed to "*u*" by using Eq. (7). In analyses using the Logarithmic Model, however, settlements theoretically go on forever and ultimate settlements cannot be defined. It has been proposed that the settlements projected to an elapse time of 300 days (or a year) after the passing of the shield be assumed as the final settlements to be considered (Hwang, *et al*., 1995). For practical purpose, it can be assumed that:

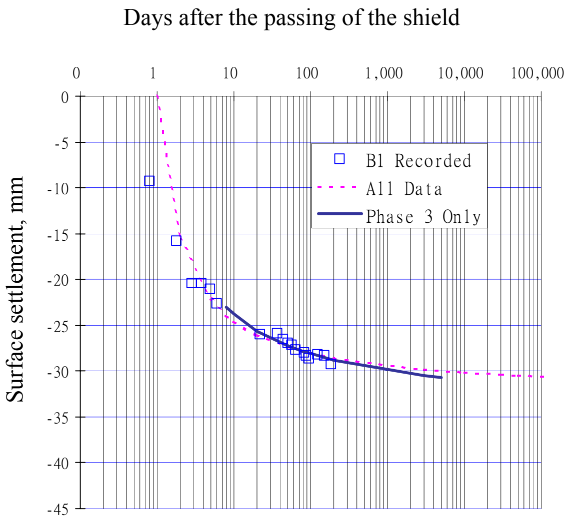

Fig. 8 Prediction of long-term settlements at Section B1 using the Hybrid Model

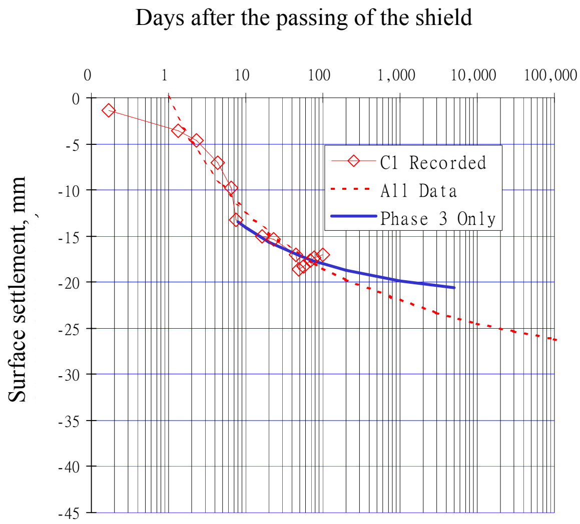

Fig. 10 Prediction of settlements at Section C1 using the Hybrid Model

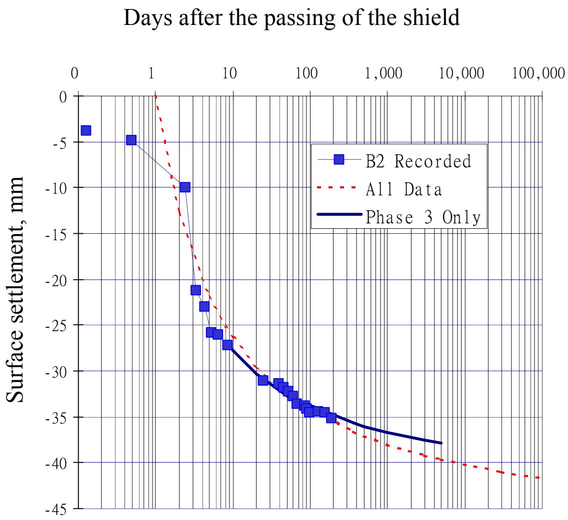

Fig. 9 Prediction of settlements at Section B2 using the Hybrid Model

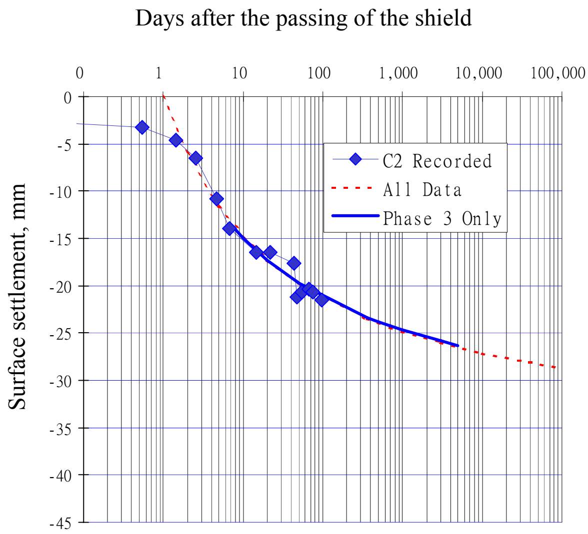

Fig. 11 Prediction of settlements at Section C2 using the Hybrid Model

$$\delta_{final} = \delta_{10} + 1.5\alpha \qquad (9)$$

This final settlement in 300 days is assumed to be the ultimate settlement for the Logarithmic Model for comparing with those for the Hyperbolic Model and the Hybrid Model.

The settlements computed by using the 3 models are compared in Figs. 12 and 13 for Sections B1 and B2, respectively, and in Figs. 14 and 15 for Sections C1 and C2, respectively. The ultimate settlements obtained are summarized in Table 4. As can be noted, the results obtained by using the Logarithmic Model and Hyperbolic Model become very close while the use of the Hybrid Model gives somewhat larger ultimate settlements in comparison.

Table 4 Ultimate settlements predicted by using the 3 models

Section	Predicted ultimate settlements (mm)		
	Logarithmic (300 days)	Hyperbolic	Hybrid
B1	30.14	29.06	34.27
B2	36.38	35.36	43.70
C1	20.50	18.53	24.87
C2	24.70	22.03	36.59

In Figs. 12 and 13 and Table 4, Phases 1 and 2 settlements were included in analyses using the Hyperbolic Model but were excluded in analyses using the Logarithmic and Hybrid Models. To investigate whether the differences in results were caused by this inconsistency, analyses were repeated by using the Hyperbolic Model with Phase 1 and 2 settlements excluded. The results are compared with those presented above in Table 5. The differences in the two cases are within 1 mm and are negligible for practical purposes. It is therefore concluded that the inclusion of Phases 1 and 2 settlements has little influence on the results.

4.2 Final Settlements to be Considered

Settlements over tunnels increase with time and may drag on for a very long period. Therefore, it is unfair to compare settlements at different elapse times. Theoretically, ultimate settlements shall be considered in evaluating ground response to tunneling. However, since the purpose of studying settlements over a tunnel is to see whether structures adjacent to the tunnel may be endangered, it is unreasonable to expect these structures to last forever. Furthermore, settlements due to consolidation beyond a certain period are overshadowed by settlements due to factors not related to tunneling, for examples, lowering of groundwater table, heavy traffic on surface, cutting and/or filling of the ground, *etc*. It is thus necessary to decide a reasonable time span so settlements due to tunneling in various cases can be evaluated on the same basis.

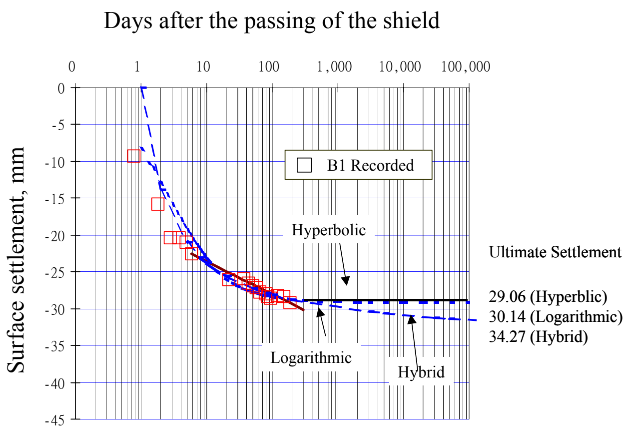

Fig. 12 Comparison of settlements at Section B1

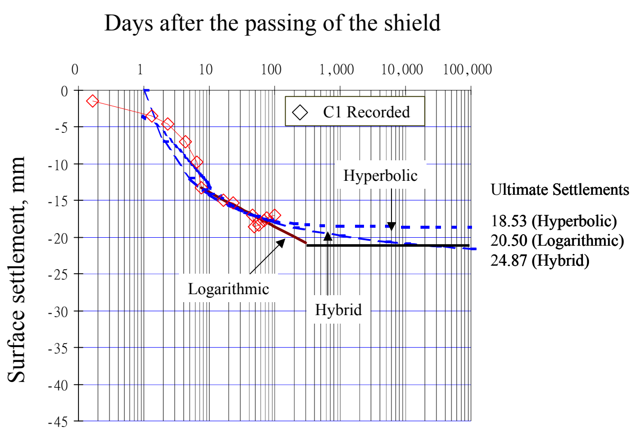

Fig. 14 Comparison of settlements at Section C1

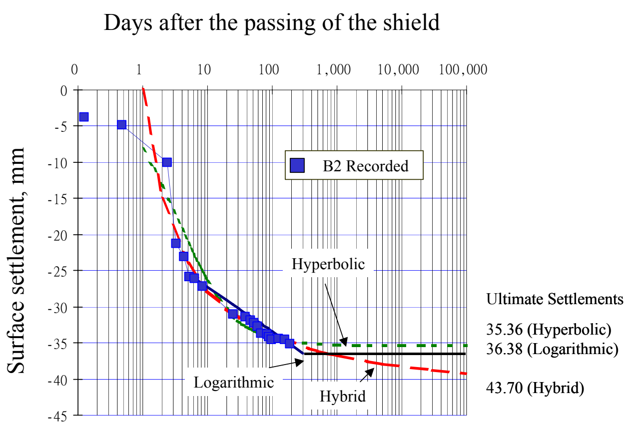

Fig. 13 Comparison of settlements at Section B2

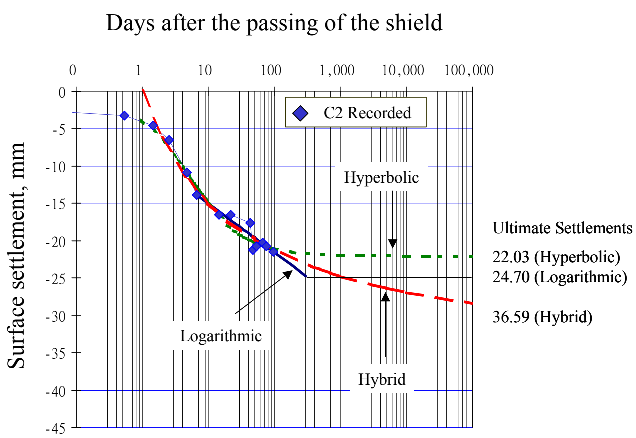

Fig. 15 Comparison of settlements at Section C2

Table 5 Ultimate settlements predicted by using the Hyperbolic Model with and without Phases 1 and 2 settlements

	Predicted ultimate settlements (mm)	
Periods of readings	0 ~ 185 days	7 ~ 185 days
Section B1	29.06	29.41
Section B2	35.36	35.59
Section C1	18.53	18.16
Section C2	22.03	22.56

From a practical point of view, a period of 3 years is sufficiently long as damages to adjacent buildings, if any, would have occurred much sooner than that. Secondly, construction contracts would normally have completed within this period and it will be impractical to expect monitoring to continue. As can be noted from Figs. 12 and 13, provided the data are of good quality, all the three models give essentially the same results at the end of this period. The final settlements at the end of this 3-year period are summarized in Table 6. Since there is no reason to believe any of the 3 models is superior to the others, the averages of the 3 sets of results are considered to be representative of the true response of the ground. As can be noted, the differences between the settlements predicted by using these 3 models and the averages are within 3%, for Sections B1 and B2. For Sections C1 and C2, the differences are within 7%.

4.3 Validity of the Predictions Based on Settlements in 60 Days

The observation periods for Sections B1 and B2 lasted for 185 days. It will be interesting to see how well these 3 models predict settlements based on data obtained only in the early days. The settlements estimated by using these 3 models with readings taken in the 60-day period are depicted in Figs. 16 and 17 for Sections B1 and B2, respectively. The settlements at the end of the 185-day period obtained in the two cases are summarized in Table 7. As can be noted that the results obtained by using all the 3 models are very close, say, within 2mm, or 6% of the recorded settlements. Therefore, it is concluded that these 3 models are equally capable. As can be noted by comparing Fig. 12 with Fig. 16 and comparing Fig. 13 with Fig. 17, extension of period of monitoring from 60 days to 185 days does narrow down the differences in the long-term settlements predicted by using the 3 models.

Again, it will be interesting to see how well the 3 models predict the final settlements in 3 years based on readings obtained in such a short period. The average settlements shown in Table 6 are considered to be the target settlements and the settlements obtained based on readings taken in the 60-day period are compared with the target settlements in Table 8. As can be noted that the differences between the predicted settlements and the target settlements increase from 3%, as given in Table 6 to 7%. The longer the period of observation is, the less the predicted settlements will deviate from the averages.

Table 6 Settlements in 3 years

Section	Predicted final settlements (mm) (% of Averages)			
	Logarithmic	Hyperbolic	Hybrid	Average
B1	30.14 (101.6%)	28.99 (97.7%)	29.88 (100.7%)	29.66
B2	36.38 (100.7%)	35.25 (97.6%)	36.69 (101.6%)	36.11
C1	20.78 (105.5%)	18.45 (93.7%)	19.83 (100.7%)	19.69
C2	24.70 (103.9%)	21.93 (92.3%)	24.69 (103.9%)	23.77

Table 7 Settlements in 185 days predicted by using readings obtained in 60 days

Section	Settlements recorded on the 185th day	Predicted settlements (mm) (% of recorded settlements)		
		Logarithmic	Hyperbolic	Hybrid
B1	29.20	29.98 (102.7%)	27.63 (94.6%)	28.08 (96.2%)
B2	35.10	36.09 (102.8%)	33.33 (95.0%)	33.97 (96.8%)

Table 8 Settlements in 3 years predicted by using readings obtained in 60 days

Section	Predicted final settlements (mm) (% of Targets)			
	Target (1)	Logarithmic	Hyperbolic	Hybrid
B1	29.66 (100%)	31.02 (104.6%)	27.82 (93.8%)	28.99 (97.7%)
B2	36.11 (100%)	37.54 (104.0%)	33.68 (93.3%)	35.42 (98.1%)

Notes: (1) average settlements in Table 6

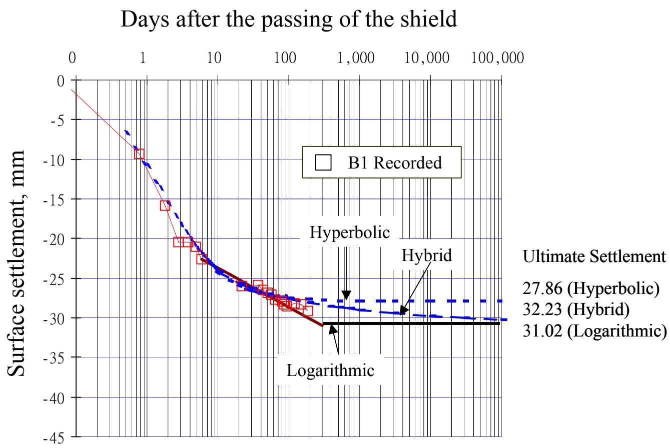

Fig. 16 Long-term settlements at Section B1 based on readings obtained within 60 Days

4.4 Validity of the Predictions Based on Settlements in 30 Days

More than often, monitoring of ground settlements was terminated in a month or even less. At a normal rate of progress of 8 to 10 rings per day, the shield would have advanced by 250 m (assuming rings are 1 m in length) in a month. Then, people tend to take easy and become less interested on settlements. It will be interesting to study whether such a short period is sufficient for predictions to be accurate.

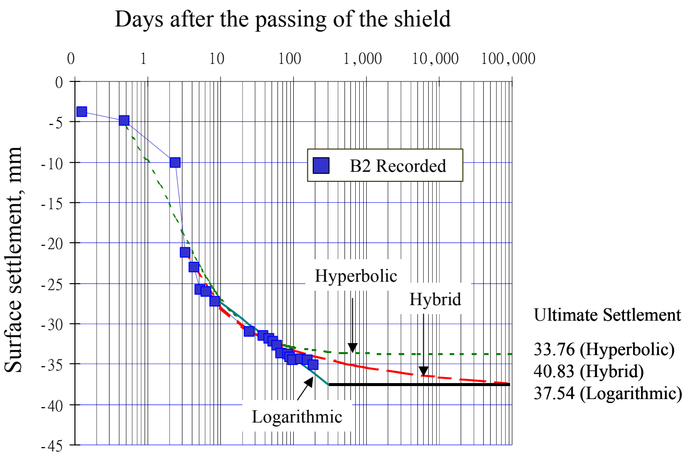

Fig. 17 Long-term settlements at Section B2 based on readings obtained within 60 days

Table 9 shows the settlements computed for Sections B1 and B2 as compared to what was observed in 185 days. It should be noted that only two sets of readings were available in analyses using the Logarithmic and the Hybrid Models for Section B1, one on the 7th day and one on the 22nd day after the passing of the shield. For Section B2, 3 sets of readings were available in the analyses and they were taken on the 7th, 9th and 25th days after the passing of the shield. Usually, readings are taken weekly after the shield passes, therefore, the readings are very limited within a month. Even so, it is rather surprising to note by comparing Table 9 with Table 7 that the settlements in 185 days computed by using the Hyperbolic and Hybrid Models based on readings obtained in 30 days are essentially the same as those computed based on readings obtained in 60 days. On the other hand, the results obtained by using the Logarithmic Model appear to be overly conservative due to the fact that linear extrapolation of extremely limited data, 2 sets of readings for Section B1 and 3 sets for Section B2, tends to over-estimate settlements.

Table 9 Settlements in 185 days predicted by using readings obtained in 30 days

Section	Settlements recorded on the 185th day	Predicted settlements (mm) (% of recorded settlements)		
		Logarithmic	Hyperbolic	Hybrid
B1	29.20	32.93 (112.8%)	27.70 (94.9%)	28.42 (97.3%)
B2	35.10	40.18 (114.5%)	33.40 (95.2%)	34.51 (98.3%)

5. DISCUSSIONS

Based on the data presented above, settlement curves are better represented by hyperbola, either in a linear or a semi-log scale, and the process of simulating settlement curves by hyperbola is rather simple with the aid of modern software packages. However, prediction of long-term settlements is strongly influenced by the quality of data, particularly the data toward the end of the observation period, and the duration of observation period. On the other hand, straight lines can be drawn manually to represent Phase 3 settlements in semi-log scale and, with engineering judgment, discrepancy in the quality of data can be compensated.

6. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

(1) Because settlements over tunnels are time dependent, a reasonable time period has to be determined so the performance of tunnelling can be evaluated on the same basis and settlements in 3 years can be considered to be the final settlements if the Hyperbolic Model or the Hybrid Model is used.

(2) Since the Logarithmic Model has the drawback of overshooting as Phase 3 settlements are extended linearly, in the semi-log scale, to obtain subsequent settlements, it is suggested that the settlements in 300 days, instead of 3 years, be taken as the final settlements.

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