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Factors affecting settlements above shield driven tunnels

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SYNOPSIS: It is well known that factors such as tail clearance and ground disturbance due to excavation influence the ground settlements in shield tunneling. However, since very little is known about the quantitative influence of these factors, a quantitative estimation is required. In this study, the ground settlements estimated by an error function curve for a settlement trough equal to the tail clearance area were compared with actual measurements of the settlements. The influence of various factors were then investigated from the results.

1. INTRODUCTION

Shield tunneling is often used when constructing urban underground structures. Some urban traffic and communication systems such as subways and telephone cables are already underground.

It is important to be able to estimate the ground movement and the influence on nearby structures when shield tunneling is used. Some methods of estimating ground movement have been developed, but shield tunneling technology has also progressed and some auxiliary methods, such as backfill grouting and new excavation systems have been improved. These new auxiliary methods are thought to be effective for reducing ground settlement, but the quantitative influence of these methods is not clear.

It is well known that certain factors influence the ground movements in shield tunneling, such as tail clearance, ground disturbance due to excavation and backfill grouting. However, since very little is known about the precise influence of these factors on ground movements, the influence needs to be estimated quantitatively. It is also necessary to reconsider the ground movements measured above shield tunnels constructed in the past.

In this study, ground movements calculated by an error function curve for a settlement trough equal to the tail clearance area of cross section were compared with the settlement actually measured in three shield tunnels on alluvial silt layers. The effects of factors such as tail clearance, ground disturbance, and backfill grouting on the ground settlements were then investigated from the results.

2. PROFILE OF SITE

Ground movements were measured in three shield tunnels on alluvial silt layers. However, the shield tunneling machines and backfill grouting methods were different in each case.

The profile and ground classifications of site A are shown in Fig.1 and Fig.2. The profile and ground classifications of site B and site C are shown in Fig.3 and Fig.4 respectively. Table 1 shows the profile of the shield tunneling machine and backfill grouting method in each site.

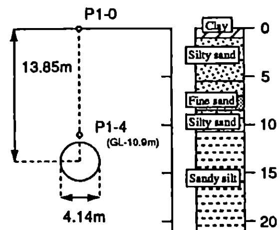

Fig.1 Site A Section No.1

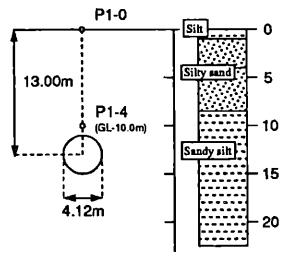

Fig.2 Site A Section No.2

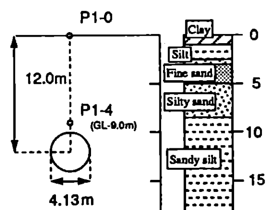

Fig.3 Site B

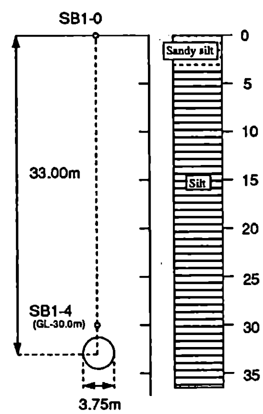

Fig.4 Site C

3. GROUND MOVEMENT

Ground movement is strongly dependent on the advance of the cutting face of shield tunneling (Ohta 1985). In this study, ground movement was considered on the basis of the relationship between the ground movement and the advance of the cutting face. Fig.5 shows the data for ground movements. In Fig.5, the vertical axis shows the ground movement and the horizontal axis shows the position of the cutting face. The position of the cutting face is taken as the outer diameter D of the shield tunnel. The position is negative when in front of the measured section, and positive when the cutting face goes through the measured section. So, 0D means that the cutting face matches the position of the measured section, and -5D means that the cutting face is 5D in front of the measured section.

Table 1. Profile of shield tunneling machine and backfill grouting method

Site	Section No.	Shield machine (Diameter:m)	Backfill grouting method	Year
A	1	Soil pressure type Diameter (Outer:4.14, Inner:4.0)	After shield tunnel driving	1980
	2	Blind shield (Outer:4.12, Inner:4.0)	After shield tunnel driving	1980
B	-	Soil pressure balanced type shield (Outer:4.13, Inner:4.0)	After shield tunnel driving	1980
C	-	Mud pressure balanced type shield (Outer:3.75, Inner:3.6)	During shield tunnel driving	1988

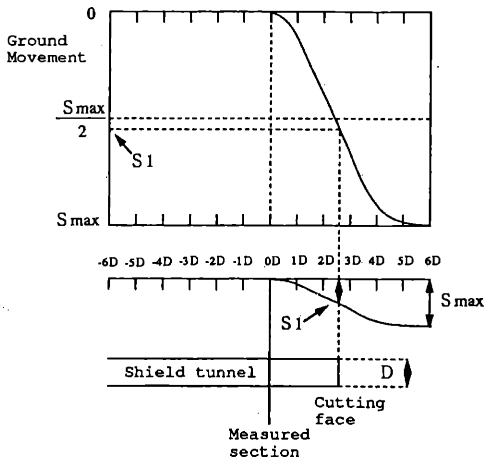

Fig.5 Ground movement data

3.1 Ground movements of site A

Fig.6 shows the ground movements at the measured points (P1-0) and (P1-4) in section No.1 of site A. In this figure, ground heaving is observed at the point +8D in (P1-0). Ground settlement occurs from the point 0D to +16D. At the point +16D, 90% of maximum ground settlement occurs. At the point +5D, ground settlement reduces temporarily and large ground settlement occurs again from the point +7D. Ground settlement at the point +5D is about 50% of maximum ground settlement. From an analytical study of the relationship between the ground settlement and the advance of the cutting face (Ohta,1985), ground settlement, which occurs from -5D to +5D, is thought to be caused by tail clearance. So, ground settlement from -5D to +5D is thought to be mainly caused by tail clearance in Fig.6. And ground settlement from +5D to +16D is thought to be mainly caused by ground disturbance due to excavation.
Fig.7 shows the ground settlements at section No.2 of site A. The shield tunneling machine is the soil pressure type shield. In this case, less ground movement occurs than in section No.1 until the cutting face arrives at the measured section. The ground of No.1 is thought to be disturbed more than the ground of No.2 due to excavation (Mori,1983), causing more ground settlement in No.1 than No.2.

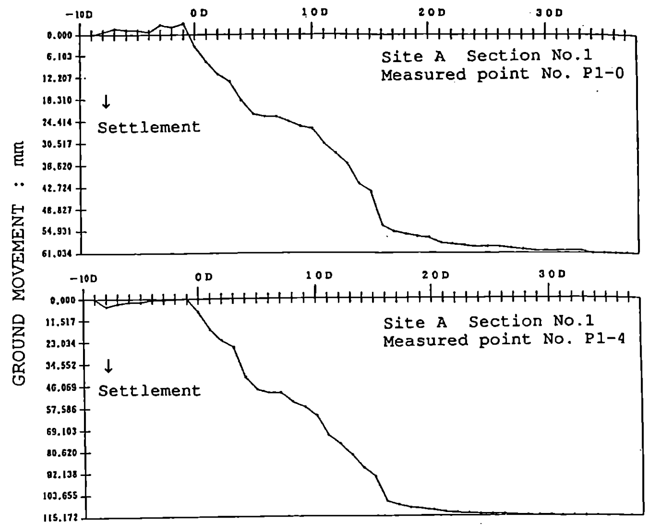

Fig.6 Ground movements of Site A, Section No.1

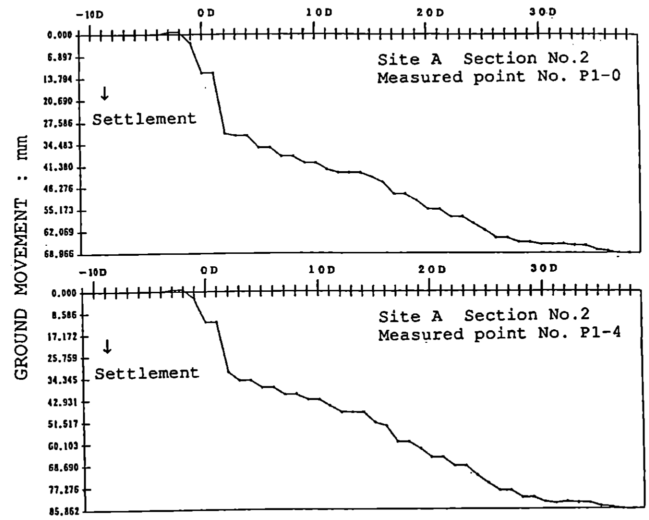

Fig.7 Ground movements of Site A, Section No.2

3.2 Ground movements of site B

Fig.8 shows the ground movements at the measured points (P1-0) and (P1-4) in the section of site B. The soil pressure balanced type shield is used in this site. In this case, there is little ground heaving in front of the measured section and the maximum ground settlement is less than that of site A. At the point +5D, ground settlement reduces temporarily and ground settlement is 80% of maximum settlement. This indicates that the settlement caused by ground disturbance of site B is less than that of site A. So, the soil pressure balanced type shield can be excavated with little ground disturbance and is thus suitable for excavation of soft ground.

3.3 Ground movements of site C

Fig.9 shows the ground movements at the measured points (SB1-0) and (SB1-4) in the section of site C. The mud pressure balanced type shield and the backfill grouting during shield tunnel driving are used in this site. In this

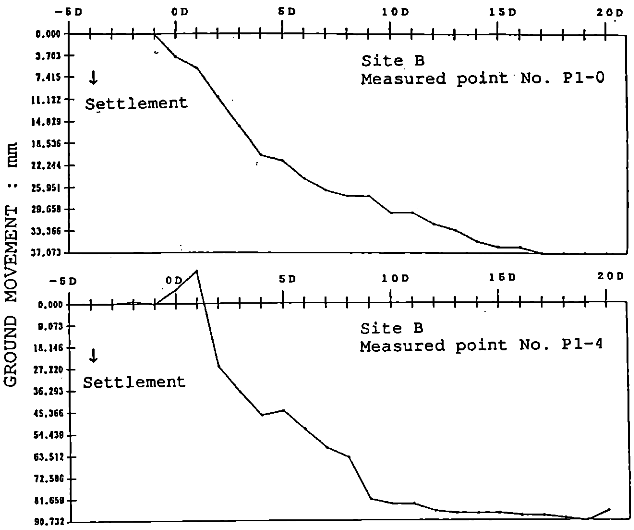

Fig.8 Ground movements of Site B

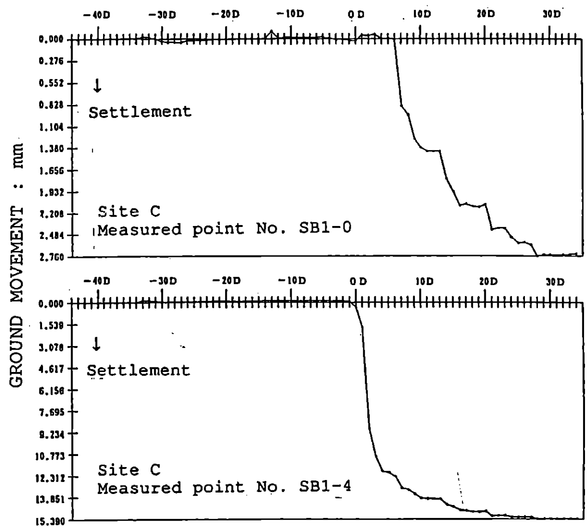

Fig.9 Ground movements of Site C

case, the maximum settlement is less than the tail clearance because the backfill grouting during shield tunnel driving can effectively fill the tail clearance.

4 ESTIMATED SETTLEMENT AND MEASURED SETTLEMENT

Conventional estimations of ground settlement have already been made. Peck(1969) reported state-of-the-art estimations of ground settlement, noting that the ground settlement curve can be represented by an error function curve, as shown in Eq.(1),

$$S(x) = S_{max} \cdot \exp\left(-\frac{x^2}{2 \cdot i^2}\right) \quad \text{Eq.(1)}$$

where Smax is maximum ground settlement, i is the distance between the center line of the tunnel and the inflection point of the settlement trough curve, and x is the distance between the point and the center line of the settlement trough curve.
It is necessary to determine the value of Smax and i in order to estimate the ground settlement curve by Eq.(1). Methods for determining the value of Smax and i were proposed by Attewell (1981). O'Reilly and New (1982) also proposed a similar method. In this study, Attewell's method was used to determine the value of Smax and i, while Eq.(2) and Eq.(3) were proposed by Attewell.

$$\frac{i}{R} = K \cdot \left(\frac{Z}{2 \cdot R}\right)^n \quad \text{Eq.(2)}$$

$$S_{max} = \frac{V}{(2 \cdot A)^{0.5} \cdot i} \quad \text{Eq.(3)}$$

where R is the outer radius of the tunnel, Z is the depth of the center of tunnel, V is the sectional area of the settlement trough, and A is the sectional area of the inner tunnel. The value of K and n was proposed as 1 for clayey ground by Attewell.
A ground settlement curve S(x) can be obtained by combining Eq.(1), Eq.(2) and Eq.(3).
In this study, the sectional area of the settlement trough V is thought to be equal to the sectional area of the tail clearance V_T (refer to Fig.10). Thus, the ground settlement curves estimated by the above method gives the settlement curves caused by tail clearance. The influences of shield tunneling machines and the backfill grouting methods were considered by comparing actual measured settlement and the settlement curves estimated by Eq.(1) for $V=V_T$.

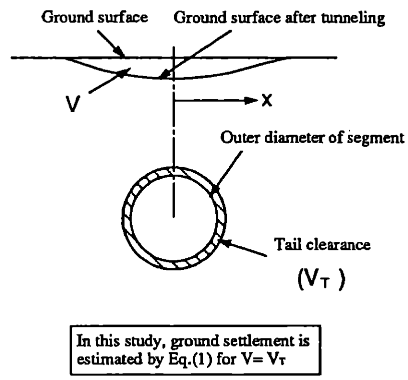

Fig.10 Estimating ground settlement

The results for site A, section No.1 and No.2 are shown in Fig.11 and Fig.12 respectively. In these cases, ground settlement estimated by Eq.(1) for $V=V_T$ are less than the measured ground settlements. The measured settlement is thought to be larger because settlement caused by ground disturbance due to excavation is large in these cases, as described in section 3.1.
Fig.13 shows the results for site B. In this case, the estimated settlement is almost equal to the measured settlement. The settlement caused by ground disturbance of site B is less than that of site A from the viewpoint of ground movement as mentioned in section 3.2. So, the estimated settlement is almost equal to the measured settlement.
Fig.14 shows the results for site C. Here, the estimated settlement is larger than the measured settlement. Backfill grouting during shield tunnel driving was used in site C, while backfill grouting after shield tunnel driving

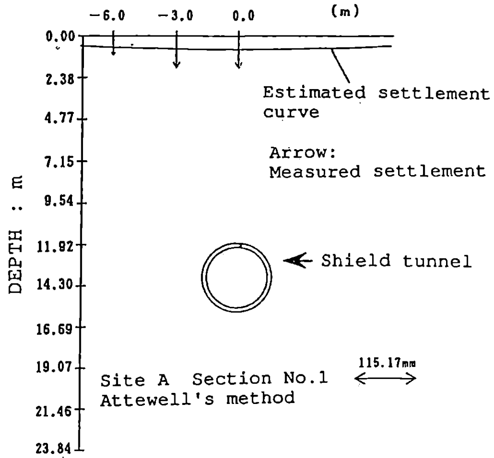

Fig.11 Estimated settlement of Site A, Section No.1

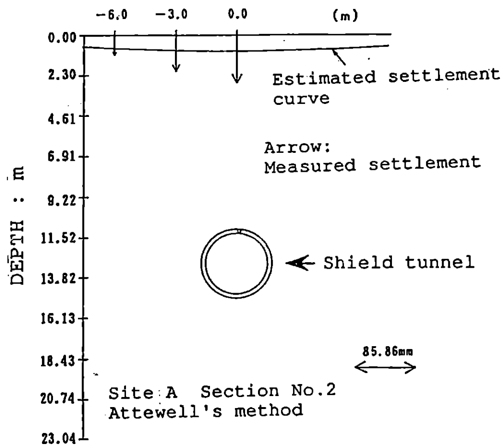

Fig.12 Estimated settlement of Site A, Section No.2

was used in other sites. Backfill grouting during shield tunnel driving is therefore more effective for reducing the settlement than after shield tunnel driving.

This study shows that the influence of various factors on ground settlement can be estimated quantitatively by comparing the settlement measured in the field with the settlement estimated by an error function curve in which the settlement trough V is equal to the tail clearance area V_T.

5 CONCLUSIONS

The following conclusions can be drawn from this study.

1) The influence of various factors on ground settlement could be estimated quantitatively by comparing the settlement measured in the field with the settlement estimated by an error function curve in which the settlement trough is equal to the tail clearance area.

2) The blind shield and soil pressure type shield, which are now out of date in Japan, often disturb the ground during excavation, and settlement caused by ground disturbance was larger than settlement caused by other factors. The ground disturbance for the newest shield machines such as the mud pressure balanced

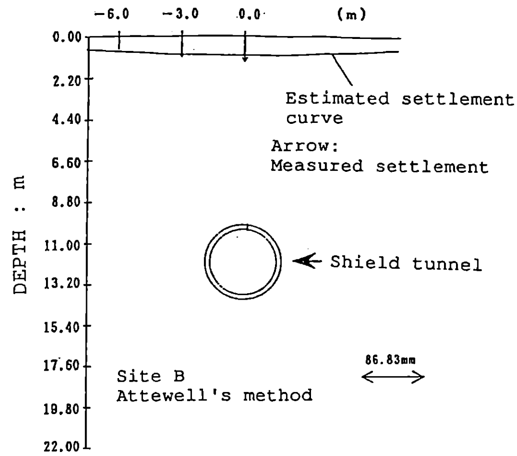

Fig.13 Estimated settlement of Site B

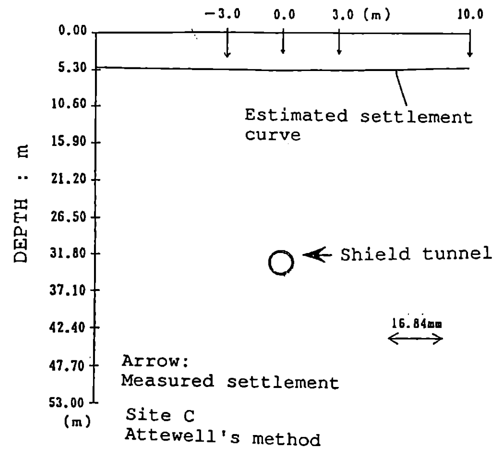

Fig.14 Estimated settlement of Site C

shield was small and settlement caused by tail clearance was the largest factor.

3) Backfill grouting during shield tunnel driving is more effective than backfill grouting after shield tunnel driving for reducing settlement.

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