Effects of backfilling at shield work in soft cohesive soil

Effets du remblai lors du creusement au bouclier dans des argiles

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SYNOPSIS Rational design of the injection method to the tail void for backfill is required to protect surface and subsurface installations from the damage caused by ground movements associated with shield tunneling in the soft ground. In this paper, the effects of backfill injection at shield work in soft cohesive soil are examined using the results of finite element analysis in view of the consolidation of disturbed cohesive soil. It is concluded that the most effective method is to inject the suitable backfill materials at the same time as the occurrence of the tail void.

INTRODUCTION

It is very important to prevent ground settlement associated with shield work in soft ground. Much of the magnitude of settlement can be related with the tail void (clearance between the tailpiece and lining). It is inevitable that large settlement could occur, unless suitable injection to the tail void for backfill might be performed. There are two types of settlements associated with unsuitable injection to the tail void at shield work in soft cohesive soil. The first is the instantaneous settlement accompanied by invasion of surrounding soil into the tail void on account of delayed timing for injection. The second is the longtime settlement owing to consolidation of cohesive soil disturbed by ground displacements mentioned above. Moreover, when the greater volume of backfill materials than that of the tail void may be injected, the surrounding soil will be pushed back and the ground surface will heave. Then the consolidation settlement due to soil disturbance caused by this heave of the ground could occur. The instantaneous ground displacement and consolidation settlement due to soil disturbance result in final settlements after backfilling.

In this study the ground movements associated with shield tunneling and backfill injection are obtained from finite element analysis in view of the consolidation of disturbed cohesive soil. In the analysis, shield work in typical alluvial deposit is supposed. It is investigated what differences in final settlements can be resulted from the variation of the timing for backfill injection or soil conditions.

CONSOLIDATION OF DISTURBED COHESIVE SOIL

The displacements and strains of cohesive soil associated with shield tunneling and backfill injection seem to be great enough to break the bonds between particles and change their microstructure, as Peck suggested (1969). Hence, disturbed zone of soil can be created surrounding the tunnel and delayed settlement of the ground surface will take place owing to consolidation of disturbed cohesive soil.

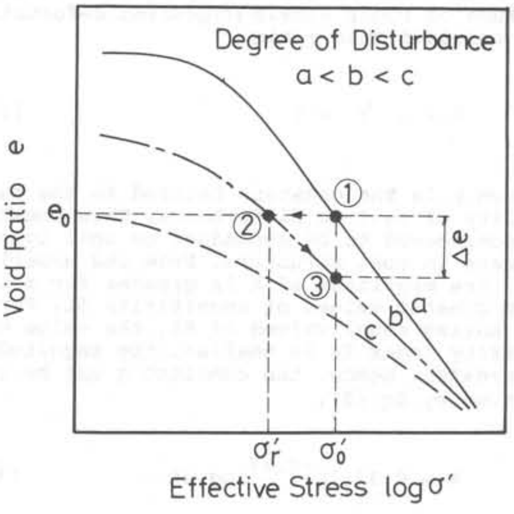

Fig.1 Change of Consolidation Curve due to Soil Disturbance

The mechanism of this consolidation of cohesive soil due to its disturbance is illustlated as follows. In Fig.1, typical oedometer test results are shown for undisturbed soil a ,slightly disturbed soil b and completely remolded soil c. If shield tunnel is driven in soft cohesive soil corresponding to the normally consolidated state at point ① on undisturbed line a , the cohesive soil adjacent to the tunnel will be disturbed under constant void ratio e_0 . The state of this soil will move to point ② on line b , since the effective stress decreses to σ'_r due to soil disturbance. The state of total stress applied

to the surrounding soil seems to recover the initial K_0 condition (at rest) gradually after backfilling. Therefore, the effective stress increases up to σ'_0 along line b and the state of soil will arrive at point ③. In other words, the void ratio of the soil decreases by Δe under constant effective overburden pressure σ'_0 and the consolidation of disturbed soil can take place.
Volume decrease α owing to this consolidation of disturbed cohesive soil can be represented by Eq.(1).

$$\alpha = \frac{\Delta e}{1+e_0} = \frac{Cc'}{1+e_0}\cdot\log\frac{\sigma'_0}{\sigma'_r} = \frac{Cc'}{1+e_0}\cdot\log R \quad (1)$$

where Cc' is the compression index for line b and R $(=\sigma'_0/\sigma'_r)$ is the measure for the magnitude of soil disturbance, named disturbance ratio.
This consolidation of disturbed cohesive soil has been studied in detail by the authors (1983).
It has been shown from a number of experiments and theoretical considerations that the disturbance ratio R can be defined by Eq.(2), using the magnitude of shear strain γ(%) during deformation under constant void ratio.

$$R = k\cdot\gamma + 1 \qquad (2)$$

in which k is the constant related to the susceptibility of soil to disturbance. This constant k is considered to be dependent on soil type or differece in soil structure. From the experiments, the magnitude of k is greater for soils having greater values of sensitivity St. For soils having equal values of St, the value of plasticity index Ip is smaller, the magnitude of k is greater. Hence, the constant k can be represented by Eq.(3).

$$k = 0.33\cdot Ip^{-0.37}\log St \qquad (3)$$

The values of the compression index Cc' of disturbed soil have been examined experimentally. It is appropriate to use the value of Cc' for natural soil obtained by Eq.(4).

$$Cc' = 0.3\cdot Cc \qquad (4)$$

where Cc is the value of compression index of natural soil at undisturbed state.
Therefore, volume decrease α owing to the consolidation of disturbed cohesive soil can be obtained by Eq.(5), by substituting Eqs.(2), (3), and (4) into Eq.(1).

$$\alpha = \frac{0.3Cc}{1+e_0}\cdot\log((0.33\cdot Ip^{-0.37}\log St)\gamma + 1) \quad (5)$$

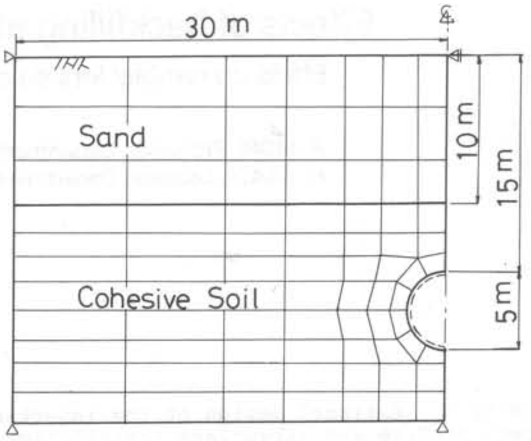

Fig.2 Finite Element Model

TABLE I Input Data for Analysis (instantaneous)

Young's Modulus E (kN/m^2)	Poisson's Ratio		Unit Weight γ_t(kN/m^3)
	Sand	Cohesive Soil	
294Z + 1764	0.333	0.475	15.7

TABLE II Input Data for Analysis (consolidation)

Type	Ip	St	Cc	e_0
I	30	10	0.4	1.4
II	30	20	0.5	1.6
III	30	30	0.7	2.0
IV	30	30	1.0	2.0

FINITE ELEMENT ANALYSIS

Finite element model used in this analysis is shown in Fig.2. This model corresponds to typical alluvial deposit, where the upper layer is 10 m thick saturated sand and the lower is saturated cohesive soil. Shield tunnel (Diameter = 5 m) is driven in the cohesive soil, thereafter backfill injection to the tail void is performed. The ground movements associated with shield tunneling are obtained from finite element analysis under plane strain condition, where the material of ground is assumed to be isotropic-elastic. Input data used in the analysis of instantaneous ground displacements associated with shield tunneling are shown in Table I . In Table II input data necessary to obtain the consolidation settlement are shown, where four types of cohesive soil are supposed. Each of them has different magnitudes of volume decrease α owing to consolidation, when disturbed to the same degree (same magnitude of shear strain).

At first, the instantaneous ground movements accompanied by invasion of the surrounding soil into the tail void on account of delayed timing for injection are obtained, where 5 cases of timing for injection are supposed. In each case the initial total stress applied to the soil adjacent to the tail void can be released to a given degree and the surrounding soil may invade the tail void according to this stress change. Therefore, the delayed timing for injection can be represented by the degree of stress release at the tail void or the volume of soil invaded into the tail void. At the same time, the magnitude of shear strain γ_i for each element in the cohesive soil can be calculated. Hence, the magnitude of consolidation settlement due to soil disturbance caused by ground movements associated with the stress release at the tail void can be obtained by using Eq.(5).

It is assumed that the tail void will be completely filled with backfill materials and the injecting pressure may be applied uniformly to the inner surface of the soil. The injection volume of backfill materials will be varied by changing the magnitude of injecting pressure within 1.7 times of the overburden pressure at the crown of the tunnel. In each case, the ground displacement (the magnitude of shear strain γ_b) associated with backfill injection can be obtained.
The magnitude of shear strain γ_b caused by backfill injection is added to the value of shear strain γ_i caused by stress release at the tail void for each element in the cohesive soil. As a result, the consolidation settlement can be obtained by summing up α over the disturbed area of cohesive soil, after backfilling.

INFLUENCES OF INJECTION TIMING AND SOIL TYPE

In Fig.3, the relations between the magnitudes of surface settlements at center line and the degrees of stress release for each type of cohesive soil are shown. In this figure, tail void contraction is the ratio of the volume of the soil invaded into the tail void to the inherent volume of the tail void. Hence, 100 % of tail void contraction corresponds to the situation that the tail void is filled completely with the surrounding soil.
It is evident that the magnitude of final settlement increases owing to the consolidation of disturbed cohesive soil caused by ground movements on account of delayed timing for backfill injection, dependent on soil type.
The values of ground loss in 5 cases of stress release are shown in Table III for each soil type. The ratio of the ground loss owing to the consolidation of disturbed cohesive soil to the instantaneous ground loss accompanied by invasion of the surrounding soil into the tail void seems to be constant for the same type of cohesive soil.

TABLE III Values of Ground Loss in 5 Cases of Stress Release for Each Soil Type

Stress Release(%)		10	20	30	40	50
Instantaneous(m^3)		0.067	0.135	0.202	0.269	0.336
Type I	Delayed*)(m^3)	0.051	0.102	0.151	0.200	0.247
	Ratio (%)	76	76	75	74	73
Type II	Delayed(m^3)	0.077	0.152	0.225	0.297	0.367
	Ratio (%)	115	113	111	110	109
Type III	Delayed(m^3)	0.106	0.209	0.309	0.406	0.501
	Ratio (%)	158	155	153	151	149
Type IV	Delayed(m^3)	0.151	0.298	0.441	0.580	0.716
	Ratio (%)	225	221	218	216	213

*)Delayed means ground loss due to consolidation.

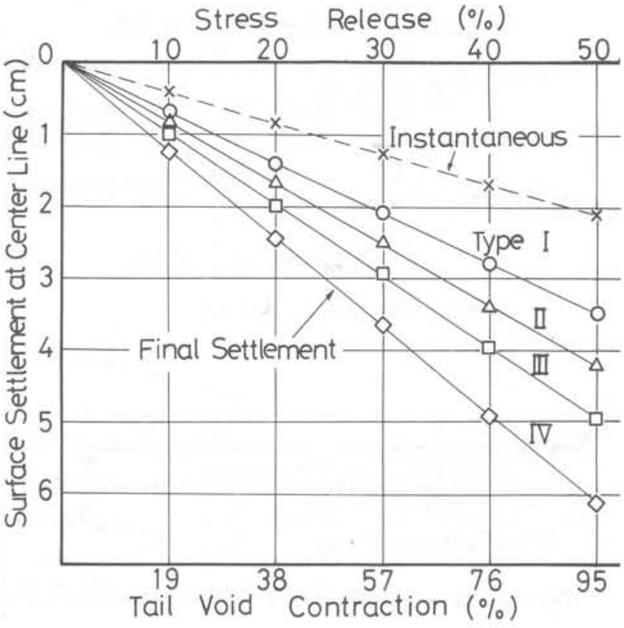

Fig.3 Relations between Surface Settlements at Center Line and Degrees of Stress Release

SURFACE DISPLACEMENTS AND INJECTION VOLUME

The instantaneous and final surface displacements are shown in Figs.4(a) and (b), when the backfill materials equivalent to 99 % and 193 % of the inherent volume of the tail void are injected in case of 30 % of stress release (57 % of tail void contraction). Although the ground surface will heave immediately after backfill injection, delayed settlement will occur owing to the consolidation of disturbed cohesive soil.
The relations between the injection volume of backfill materials and the instantaneous and final surface displacements at center line in case of 10 % of stress release are shown in Fig.5.

It is noted that the greater magnitude of consolidation settlement takes place, the greater volume of backfill materials is injected. The preventive efficiency of backfill injection against ground settlement is sufficient in every type of soil and every degree of stress release within 100 % of injection volume. It is interesting to note that the influences of backfill

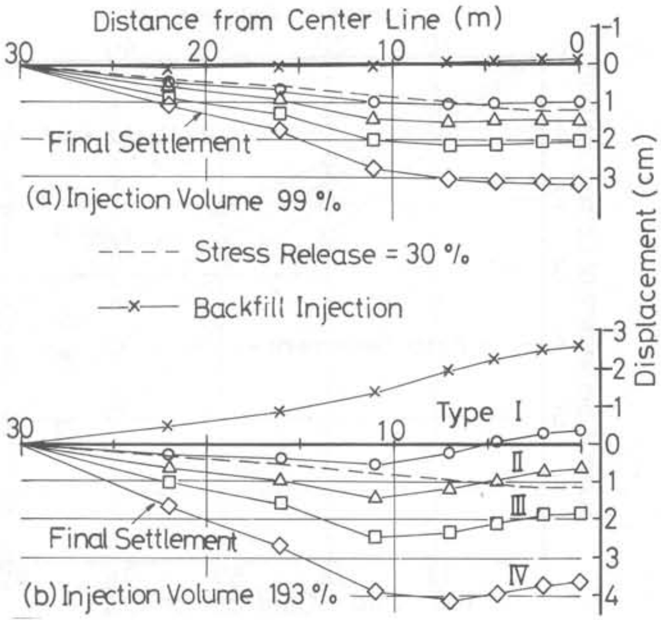

Fig.4 Instantaneous and Final Surface Displacements associated with Backfill Injection

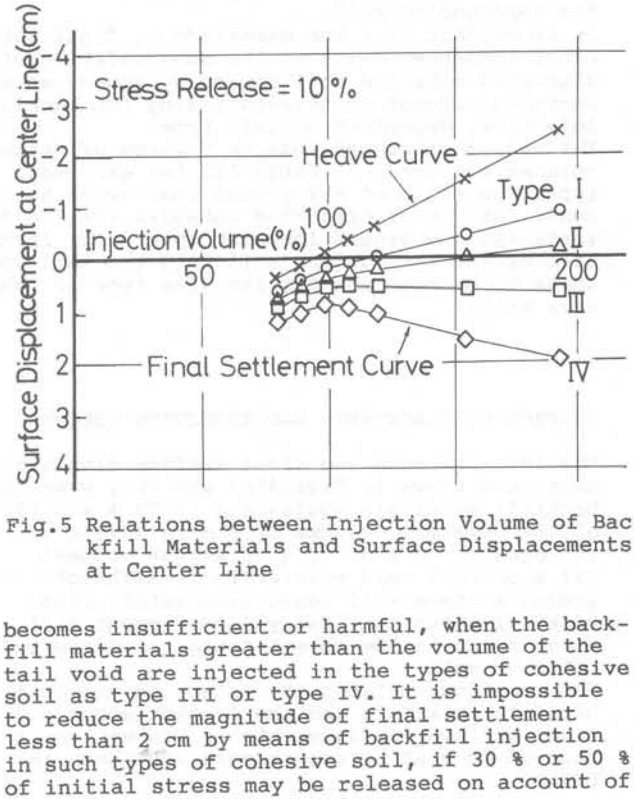

Fig.5 Relations between Injection Volume of Backfill Materials and Surface Displacements at Center Line

becomes insufficient or harmful, when the backfill materials greater than the volume of the tail void are injected in the types of cohesive soil as type III or type IV. It is impossible to reduce the magnitude of final settlement less than 2 cm by means of backfill injection in such types of cohesive soil, if 30 % or 50 % of initial stress may be released on account of delayed timing for injection.
Therefore, it is most effective to inject the suitable backfill materials at the same time as the occurence of the tail void. Even if it is supposed to be injected ideally in practice, the geometric shape of injected materials isn't necessarily uniform. Moreover, the ground movements take place at the cutting face of the tunnel. As a result, the consolidation settlements could occur due to soil disturbance caused by these ground movements. Hence, it seems practical to regard these situations as equivalent to the delayed timing for backfill injection.

CONCLUSION

In this study, the ground displacements associated with shield tunneling and backfill injection in the soft ground are obtained from finite element analysis in view of the consolidation of disturbed cohesive soil under various conditions.
Based on the results of this finite element analysis, it is concluded that :

1. Large delayed settlements could occur owing to consolidation of the disturbed cohesive soil adjacent to the tunnel associated with shield tunneling and backfill injection.

2. The magnitude of final settlement can not be reduced by injecting the backfill materials greater than the inherent volume of the tail void dependent on types of cohesive soil, if the timing for backfill injection may be delayed.

3. It is most effective to inject the suitable backfill materials at the same time as the occurence of the tail void.

It is indispensable to examine the results obtained here from the viewpoint of the measurements in the field. However, it is very difficult to pick up the magnitudes of ground movements associated with backfill injection only.
Therefore, it is significant to investigate the ground movements using the method adopted in this analysis. The results obtained here seem to be useful guidelines for the injection method to the tail void for backfill at shield work in the soft cohesive soil.

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REFERENCES

MORI, A., and H. AKAGI (1983). Consolidation phenomena of normally consolidated clays due to the disturbance caused by undrained shear. Proc. J.S.C.E., No.335, July, 117-125 (in Japanese).

Peck, R.B. (1969). Deep excavation and tunneling in soft ground. State of the Art Report, 7th Int.Conf.Soil Mech.Found.Engg., 225-290, Mexico.