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Numerical simulation of deformational behavior of a shallow NATM tunnel excavated in a sandy ground
砂質地盤中の NATM トンネル掘削における変形挙動の数値解析例

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This paper attempts to identify deformation behavior of a shallow NATM tunnel in soft and sandy ground using a strain softening model. By comparing the calculated deformation with obtained data from field measurement, parametric studies are carried out in order to identify characteristics of the ground behavior observed during construction. The results of a series of calculations are discussed and the attempt is made to identify both the design input parameter and the mechanism governing the development of the surface settlement profile and ground movement.

Key Words : Shallow NATM tunnel, soft and sandy ground, strain softening model

1. INTRODUCTION

Currently an increasing number of tunnels under low overburden are excavated according to the principles of the New Austrian Tunneling Method (NATM). This method, referred to as a City NATM or Urban NATM, is applied under soil or soft rock conditions in urban area[1]. In urban tunneling, the existence of nearby buildings and structures around towns and cities implies a need to keep these ground movements below allowable limits to avoid structural or functional damage. In recent years, numerical methods for design purposes are often used to predict deformational behavior around tunnel. Satisfactory prediction of ground movement by numerical simulation requires following conditions;

1) Selection of the most suitable values for the design parameters of the adopted constitutive law.[2),3)]
2) Sensible choice of the correct mode of deformation behavior around ground and tunnel.[4)]
3) Reasonable modeling of combined behavior of ground-support interaction system and excavation process.[3)]
4) Proper treatment of the effect of underground water at tunneling problem in sandy ground.

In this paper, prediction analysis for shallow NATM tunneling is discussed in view of the above conditions 1 and 2. This paper focuses on aspects of the identification of ground movement of shallow NATM tunnels in soft ground using a strain softening model. At first, important parameters governing the behavior of a shallow NATM tunnel in soft ground were identified and included in an analysis to understand the elastic behavior, nonlinear ground behavior. Secondly, possible ground movements of shallow tunnel were identified using a strain softening analysis considering adequately controlled strain softening pattern.

2. A CHARACTERISTIC OF DEFORMATIONAL BEHAVIOR IN SHALLOW TUNNELS

Fig. 1 shows a soil displacement and strain distribution derived from the results of displacement measurements takes from a subway tunnel in Washington D.C.[5)]. Wong and Kaiser[4)] calculated the boundaries between different modes of behavior near tunnel based on the analytical solutions.

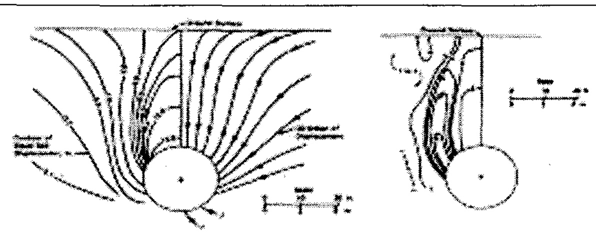

Fig. 1 Soil displacement and strain distribution around a subway tunnel

Fig. 1 shows a typical deformation behavior around a shallow tunnel often characterized by formation of shear bands developing from tunnel shoulder reaching, sometimes, to the ground surface. And, this mechanism is affected by depth and K_0.

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3. CHARACTERISTICS OF STRAIN SOFTENING MODEL

There have been series of approaches taken for simulation of tunnel excavation such as finite element methods. Adachi et al[6] made use of classical slip line theory to define geometrical distribution of joint elements. Okuda et al[7] applied a back analysis procedure to identify deformation mechanism, in which anisotropic damage parameter *m* was employed. A strain softening analysis was conducted by Sterpi[8] in which strength parameters (cohesion and friction angle) were lowered immediately after the initiation of plastic yielding. This approach was applied for the interpretation of field measurements by Gioda and Locatelli[9] who succeeded to simulate the actual excavation procedure with accuracy. The authors concluded that the essential features to be taken into the numerical procedure would be reduction of shear stiffness and strength parameters after yielding (namely, strain softening). Following is a brief summary of the procedure employed in this work[10]. A fundamental constitutive relation between stress σ and strain ε are defined by an elasticity matrix D:

$$D = \frac{E}{1-\nu-2\nu^2}\begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & m(1-\nu-2\nu^2) \end{bmatrix} \quad (1)$$

where $\sigma = D\varepsilon$ holds. E and ν stands for Young's modulus and Poisson's ratio, respectively. The anisotropy parameter m is defined as:

$$m = m_e - (m_e - m_r)\left[1 - Exp\{-100\alpha(\gamma - \gamma_c)\}\right] \quad (2)$$

where m_e is the initial value of m, m_r is the residual value, α is a constant, γ is maximum shear strain, γ_c is the maximum shear strain at the onset of yielding. The constitutive relationship is defined for conjugate slip plane direction $(45^0 \pm \phi/2)$ and transformed back to the global coordinate system. Strength parameters, namely cohesion, c, and friction angle, ϕ, are reduced from the moment of initiation of yielding to reduced values. This implies that the admissible space for stress is gradually shrunk as strain-softening process takes place. The validity of strain softening model is assessed by comparison with results from model test and field observations. In Fig. 2, the strain distribution at collapse is shown in comparison with experimental result and strain softening analysis[11]. Fig. 3 shows a surface settlement and slope derived from the results of measured and calculated value taken from case study of shallow NATM-tunneling in sandy ground[14]. According Figs. 2 to 3, the strain softening model would enable a better understanding of deformation characteristics of the ground medium not only in identifying local plastic zones, but also surface settlement mechanism.

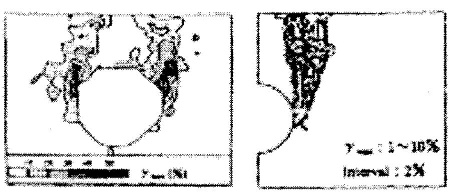

Fig. 2 Maximum shear strain distribution

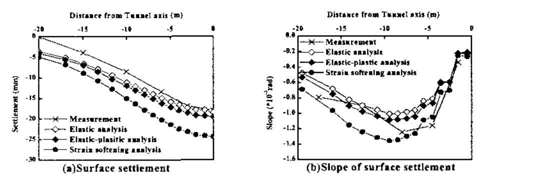

Fig. 3 Surface profile resulted by strain softening analysis

4. GENERAL CHARACTERISTICS OF THE TUNNEL

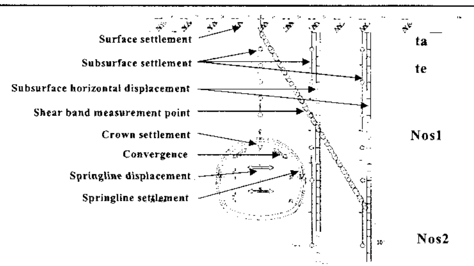

Fig. 4 Measurement point cross-section

The Rokunohe tunnel, 3810m long, is located at the northern end of the Honshu, between Hachinohe and Shin-Aomori. Condition of the ground consists of unconsolidated sand layers. The tunnel passes through, with some 60m of overburden, town road and prefectural road intersection. During the tunnel construction, various measurements on tunnel and ground were carried out to confirm the stability of the tunnel and the adequateness of the excavation method as shown in Fig. 4. Table 1 show the properties of Nos.1 layer obtained by laboratory test.

5. Numerical analysis

5.1 Outline

Geometry and boundary conditions of the finite element meshes are shown in Fig. 5. Shotcrete and steel support were modeled as plane elements. Excavation of the full tunnel face is modeled by gradually applying the nodal forces associated with excavation. Stress release ratio at excavation stage was 40%, while that at the support stage was 60%.

Table 1 Test result

[illegible]		[illegible]			[illegible]	[illegible]	[illegible]
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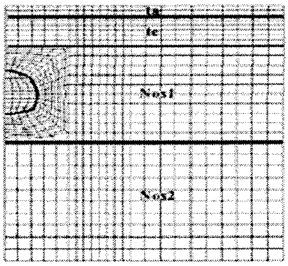

Fig. 5 Finite element mesh

Table 2 Material parameters of ground in FEM

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 3 Properties of support members in FEM

Support parameter (Plane element model:shotcrete and steel support)	Initial support, $E(MN/m^2)$	5000
	Invert support, $E(MN/m^2)$	

Table 4 Pattern of strain soften model

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

Table 5 Pattern of strain soften model

[illegible]	[illegible]		[illegible]	
	α	$\Delta\gamma$	α	$\Delta\gamma$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

In the first step of the analysis, the initial stress state prior to tunnel excavation has been calculated by $K_0 = \nu/(1-\nu)$, by selecting the Poisson's ratio that creates the desired K_0-value. Tables 2, 3 show the properties of ground and support members as initial input parameters.

5.2 Identification of Young's modulus and horizontal stress ratio

Firstly in the analysis, the ground was assumed to show elastic behavior to identify of Young's modulus, E, and horizontal stress ratio, K_0.

The former research[13)] showed that E is much affected by subsurface settlement above tunnel and K_0 is much affected by horizontal displacement. Fig. 6 shows the surface settlement and subsurface settlement at the arrival of upper section with varied E and K_0. The analysis in which E is twice the initial value, E_i, and K_0 is set to 1.2, produces a good agreement between the curves of the evaluated and observed displacement.

5.3 Identification of the strain softening parameter

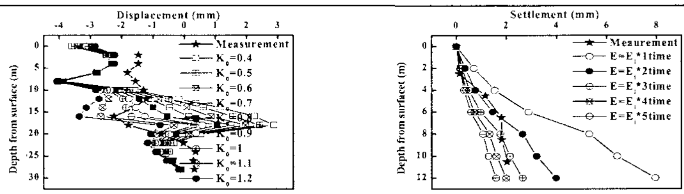
Key parameters of strain softening analysis are strength reduction ratio and increment of shear strain during strength reduction down to residual values. It is difficult to find strain softening parameters by laboratory test. This paper tries to identify probable ground movement of shallow tunnel considering adequately controlled strain-softening constitutive relationship. The representative patterns of strain softening parameters were chosen as seen in Table 4. Strength reduction ratio, α, means the ratio of residual strength parameters to initial ones. This analysis is conducted for comparison between the calculated and measured displacement in order to identify strain softening parameters or patterns at the arrival lower section. Fig. 7 shows the surface settlement and other displacement at the arrival of lower section. Among several cases considered, Patten 7 agrees with the measured results better than the other patterns.

5.4 Discussion on result from various numerical analyses

Fig. 8 shows comparison of field data and numerical analysis results using elastic, elastic-plastic and strain softening analysis (Pattern 7). As seen, the strain softening model usually gives the surface subsidence profiles in better agreement compared with other models at final stage. But, surface settlement and its slope was underestimated at the lower section excavation. And, this model overestimated subsurface settlement and horizontal displacement at final stage. Fig. 9 shows crown settlement and convergence plotted against excavation step. To improve nonlinear behavior at lower section excavation, additional analyses (Patters 10, 11, 12) were conducted considering change of reduction ratio of strength under tunnel springline for deformation behavior of the ground after the arrival lower section as seen in Table 5. Fig. 10 shows the comparison between the measured displacement and those obtained by the strain softening analysis (Pattern 7, 10, 11 and 12). Pattern 12 very closely matched the magnitude and distribution of the observed surface settlement, slope, subsurface settlement and horizontal displacement at each excavation step compared with other patterns.

6. CONCLUSIONS

An important subject of this paper is to propose an improved simulation method based on actual deformation data obtained while excavating a NATM tunnel. Comparison of the calculated deformation with obtained data from field measurement was carried out. Key parameters governing the behavior of a shallow NATM tunnel in soft ground were identified and included in an analysis to understand the nonlinear ground behavior. Firstly, those models lead to the following results.



(a)Horizontal displacement (b)Subsurface settlement above Tunnel

Fig. 6 Identification of Young's modulus and horizontal stress ratio parameter at the arrival upper section

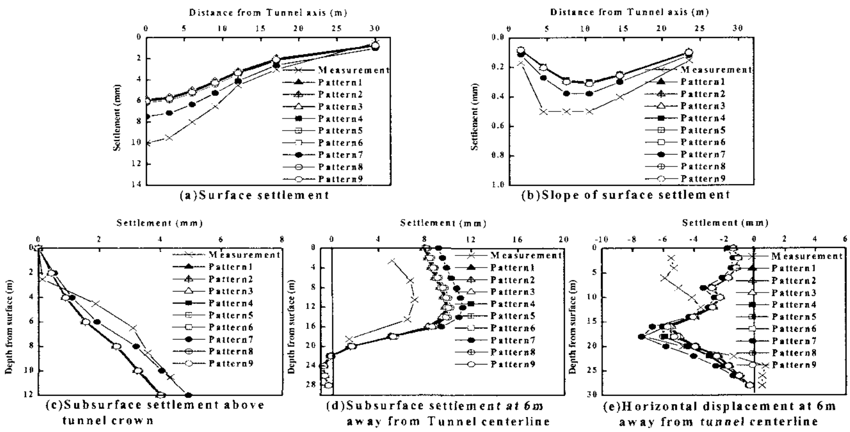


Fig. 7 Identification of strain-softening parameter at the arrival lower section

1) The elastic analysis in which E is twice the initial value, E_i, and K_0 is set to 1.2, produces a good agreement between the curves of the evaluated and observed displacement at the arrival of upper section.
2) The representative patterns of strain softening parameters was searched for from the comparison between the calculated and measured displacement in order to identify strain softening parameters or patterns at the arrival of lower section. Results from Pattern7 agree well with the measured results better than the other patterns.
3) In a case of 30% reduction of strength parameters, additional analysis considering change of reduction ratio of strength under tunnel springline for deformation behavior of the ground after the arrival lower section closely matched the magnitude and distribution of the observed surface settlement, slope, subsurface settlement and horizontal displacement at each excavation step compared with other patterns.

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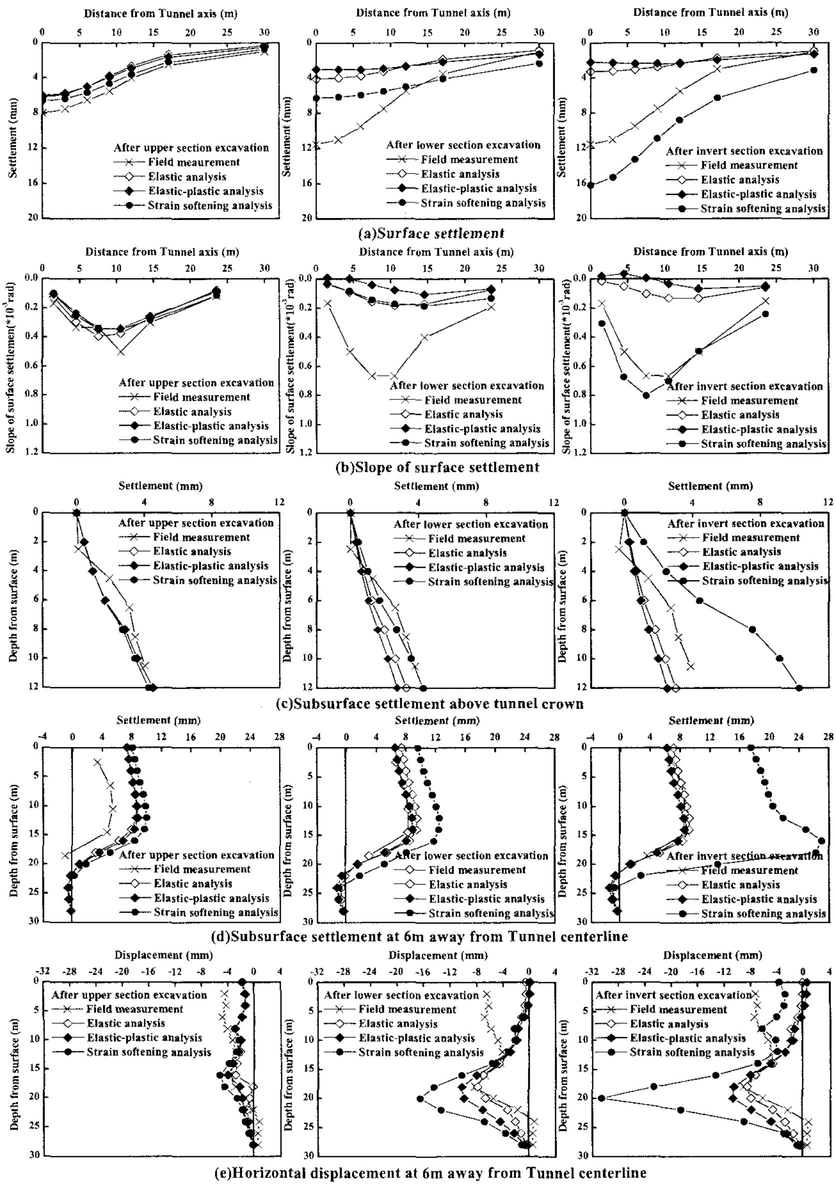


Fig. 8 Comparison between the measured ground movements and those obtained by strain softening analysis

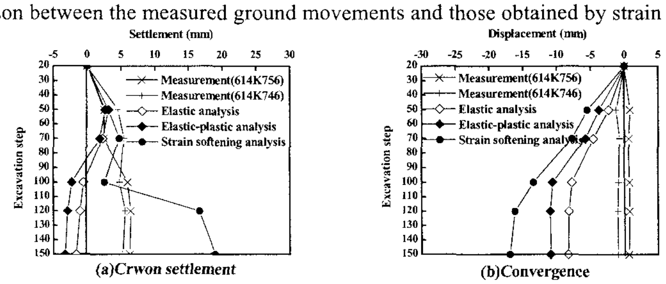
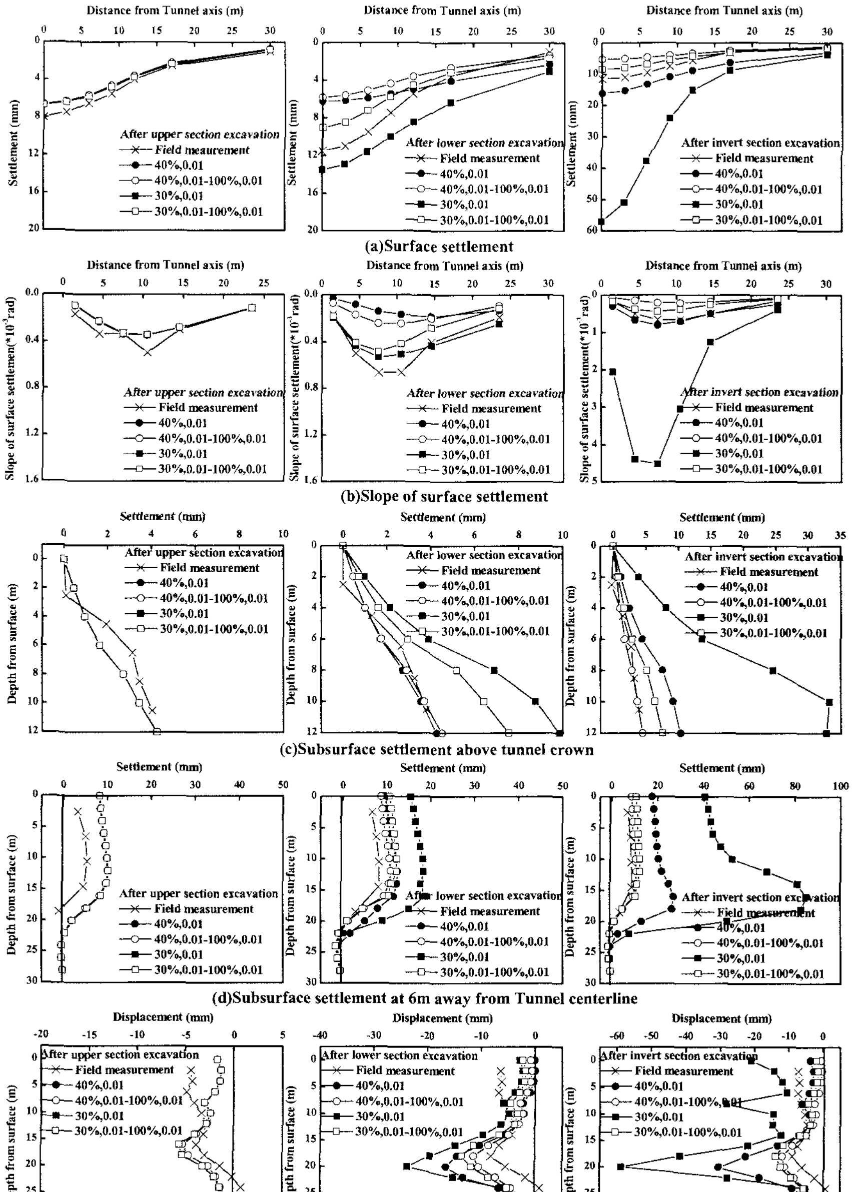


Fig. 9 Comparison between the measured tunnel movements and those obtained by strain softening analysis



(a)Surface settlement

(b)Slope of surface settlement

(c)Subsurface settlement above tunnel crown

(d)Subsurface settlement at 6m away from Tunnel centerline

(e)Horizontal displacement at 6m away from Tunnel centerline

Fig. 10 Comparison between the measured displacement and those obtained by the strain softening analysis (parameters; change of reduction ratio of strength under tunnel springline after the arrival lower section)