Estimation of design parameters for earth tunnels
L'évaluation des paramètres de projet pour les tunnels en terre

T.ADACHI, Professor of Transportation Engineering, Kyoto University, Kyoto, Japan
K.KOJIMA, Research Associate of Civil Engineering, Tokushima University, Tokushima, Japan

SYNOPSIS Described is a numerical procedure to back-analyze the non-linear constitutive parameters for joint elements in simulations of particular discontinuities occurring in sandy ground during tunnel constructions. Firstly, the proposed procedure is verified with hypothetical case studies. Subsequently, the procedure is applied to actual case studies and comparisons are made with analysis results based on parameters obtained in laboratory experiments.

INTRODUCTION

In order to properly design and construct an earth tunnel under thin cover, it is very important to understand the actual behavior of the surrounding ground during the excavation phase and to establish an analytical model to describe this behavior as accurately as possible.

Since it is a well known fact that tunnel construction in cohesionless ground causes a particular pattern of discontinuous displacements, it has been proposed to use joint elements in the analysis to accommodate these discontinuities (Adachi et. al.,1985). In this paper, the ability of the method to simulate the deformation behavior of the ground surrounding the tunnel is demonstrated.

In recognition of the difficulties and uncertainties associated with the determination of earth tunnel design parameters from laboratory experiments and site explorations (especially in the case of joint stiffness parameters), the present study proposes a numerical procedure for the determination of the non-linear constitutive parameters by back-analysis based on measurements made in the ground surrounding the tunnel. Consequently, the present procedure of back-analysis based on site measurements in the early stages of an earth tunnel construction will permit the fine tuning of the design parameters, thereby improving the design of subsequent stages of construction.

DESCRIPTION OF THE PROCEDURE

Constitutive Model for Joint Elements

It is important to establish a numerical procedure to simulate the discontinuous displacement behavior observed in the ground during tunnel construction in cohesionless soil. In the present paper the finite element method with joint elements is utilized. In the joint element model proposed by Goodman et. al.(1977) material parameters can be introduced directly. Although every constitutive expression for joint elements has been used in conjunction with an elastic-perfectly plastic model based on the Mohr-Coulomb criterion, this approach is not taken in this study since it is impossible to back-analyze non-linear constitutive parameters as long as the deformation modulus is a function of stress only.

Because the stress is almost independent of the deformation modulus in a problem of homogeneous elastic media, it is impossible to back-analyze the deformation moduli from the monitored stresses. Also in a non-linear constitutive material, the deformation modulus is not a dominant factor in determination of the value of stress. As a consequence,the hyperbolic stress-strain relation is adopted in the direction tangent to the joint. As can be seen in Fig.1 the deformation modulus decreases with increasing tangential joint displacement. The tangent modulus corresponding to any point on the stress-strain curve such as shown in Fig.1 is expressed as :

$$k_s^{\,t} = \frac{k_s^{\,i}\cdot s^2}{(s+k_s^{\,i}|u|)^2} \qquad (1)$$

where k_s^t : tangent modulus of rigidity, k_s^i : initial tangent modulus of rigidity, s : shear strength, σ_n : normal stress of joint element, and u : tangential joint displacement. On the other hand, the constitutive model for normal direction

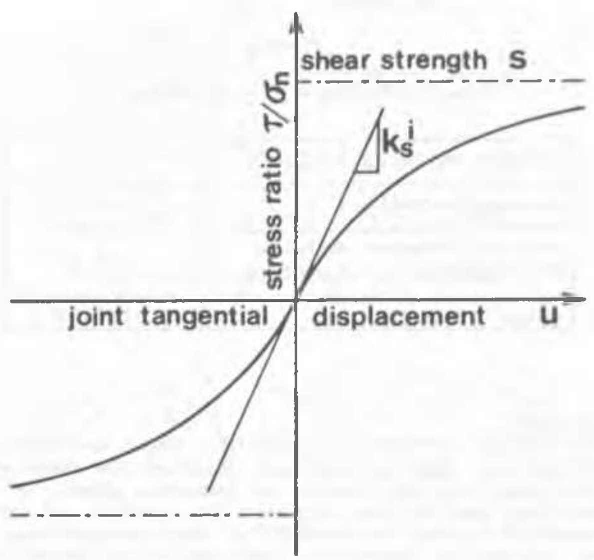

Fig.1 Stress-Displacement Relation for Joint Element

is defined such that the zero tensile strength and large stiffness in compression conditions are met.

Formulation of the Problem

The finite element method which can treat continuous-elements, beam-elements, truss-elements and joint-elements was used to model the soil. It was assumed that the material parameters for beam and truss elements are known, since they represent artificial materials. Hence the inverse-problem is to find the initial tangent modulus of rigidity k_s^i and the shear strength s for joint elements and to find the Young's modulus E and the Poisson's ratio ν for continuous elements by back-analysis from measured field displacements using the following objective function :

$$\text{minimize } J = \sum_{n}^{Nt} \sum_{i}^{Nd} (u_i^n - U_i^n)^2 \qquad (2)$$

$$E>0.0 \;,\; 0.0<\nu<0.5 \;,\; k>0.0 \;,\; s>0.0 \qquad (3)$$

where J : objective function, Nt : number of time steps, Nd : number of measured values of displacements, u_i^n : calculated displacement at the node i at time step n, and U_i^n : measured displacement corresponding to u_i^n.

It is not easy to solve the formulated optimization problem analytically, therefore the present procedure assumes that the gradient of stress is small enough and employs the conjugate gradient technique (Arai et. al.,1987).

APPLICATION TO HYPOTHETICAL CASE STUDIES

To verify the proposed procedure's validity, its performance in hypothetical case studies is demonstrated in the following. The condition of plane strain is assumed in all examples. Firstly the soil parameters given in TABLE I are used and displacements are calculated by finite element analysis. Subsequently, relevant displacements are used as if they were field measurement data and back-analysis is performed considering a geotechnical problem in which the soil parameters E, ν, k and s are unknown quantities to be found. Since the Poisson's ratio neither significantly fluctuates in a wide range nor largely affects the displacements, it is assumed to be a known parameter throughout the following case studies.

TABLE I

Material Parameters for Example-1

Young's modulus E(tf/m^2)	260.0
Poisson's ratio ν	0.3
initial tangent modulus of rigidity k_s^i(1/m)	50.0
shear strength s	0.5(ϕ'=27°)

Example-1

The example considers a hypothetical tunnel excavation in homogeneous sandy ground. Fig.2 illustrates the finite element mesh and the location of measuring points. In the bold lines show the joint elements. The simulation of tunnel excavation is done by unloading the initial element stress at the top face of tunnel in 3 steps and at the bottom face in 2 steps.

Case-1: Fig.3 shows the iteration behavior by the present

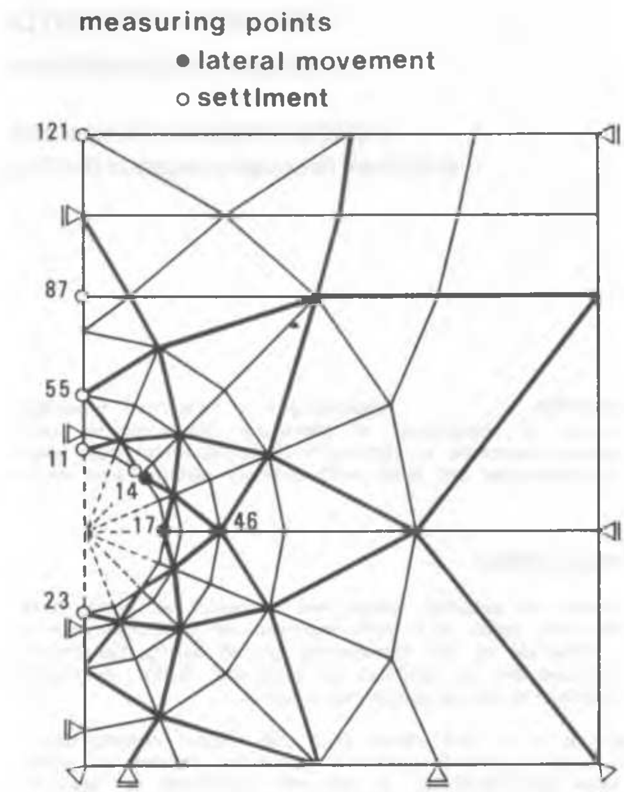

Fig.2 Finite Element Model in Hypothetical Example-1

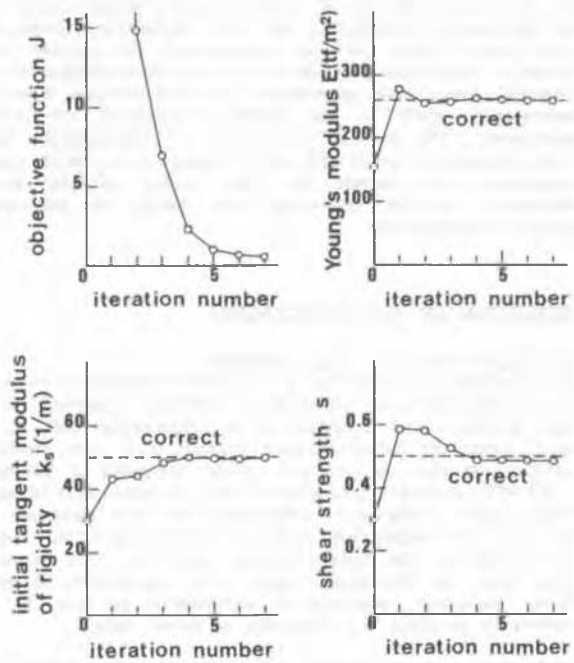

Fig.3 Iteration Behavior in Example-1 (Case-1)

procedure of back-analysis. In this case the present procedure furnishes the nearly correct values of the soil parameters.

Case-2: **Fig.4** shows the iteration behavior using the data measured during the excavation of the top portion of the tunnel. Fig.5 shows the projected displacements based on the material parameters identified by this procedure. These results indicate that the correct estimates of the parameters are successfully back-analyzed by the present procedure.

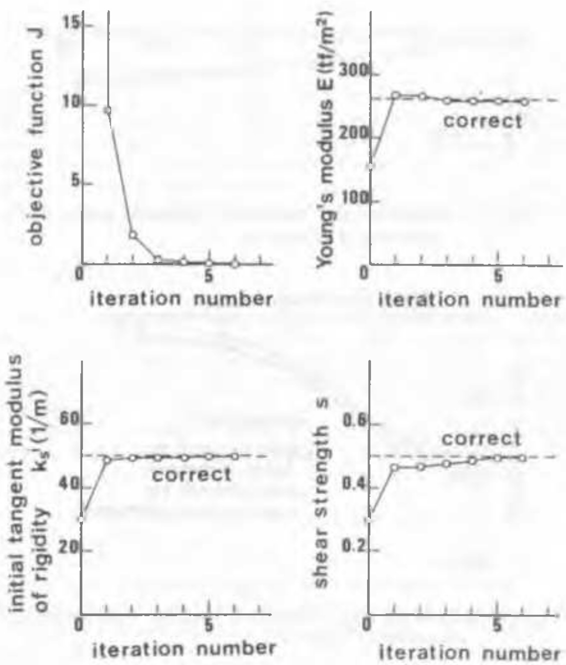

Fig.4 Itaration Behavior in Example-1 (Case-2)

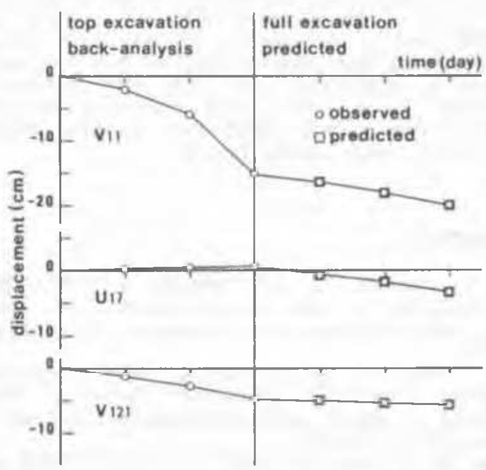

Fig.5 Predicted and Measured Displacement in Example-1 (Case-2)

APPLICATION TO ACTUAL CASE STUDIES

Example-2

The actual example given here is the cross-section of Kuriyama Tunnel of J.R. Hokusou line at Narashino, in Chiba. The section is located at 3,860 m from the Takasago Station. The tunnel is excavated in a soil deposit belonging to Narita group. Fig.6 illustrates the finite element model and the locations of measuring points. Joint elements are shown by the bold lines. Fig.7 shows the simulation of tunnel excavation. The measured displacements inside the tunnel cross-section (convergence of the cross-section) are multiplied by 10/3 to account for the release of initial stress in the soil mass prior to the arrival of the cutting face. In this example it is assumed that the Young's modulus is given by $E = E_0 \times \sigma_m$, where σ_m is the mean principal stress of the element.

Case-1: At first, the present procedure is applied using the data collected after full excavation of the cross-section. Fig.8 shows the iteration behavior of the procedure. Fig.8 also contains the soil parameters which have been obtained from laboratory tests. The calculated surface settlements based on soil parameters obtained from back-analysis are shown in Fig.9 together with those measured in the field.

Case-2: The procedure of back-analysis is applied using the data collected during the excavation of the top portion of the cross-section. Fig.10 illustrates the performance of this procedure. The projected displacements based on the back-analyzed material parameters are shown in Fig.11 together with those measured in the field. The calculated surface settlements based on the back-analyzed soil parameters are shown in Fig.12 together with those calculated by using continuous elements only (no joint element is used).

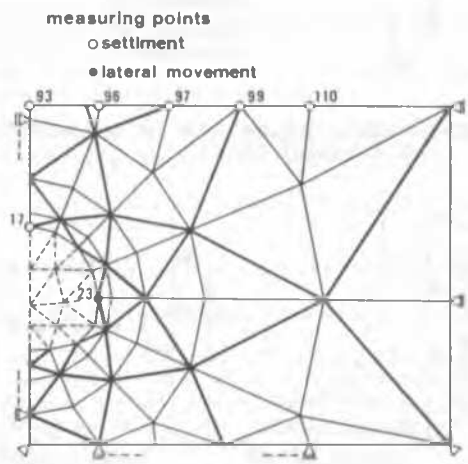

Fig.6 Finite Element Model in Example-2

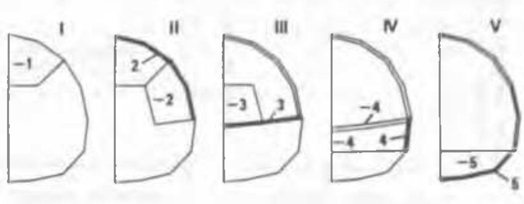

Fig.7 Simulation of Tunnel Excavation

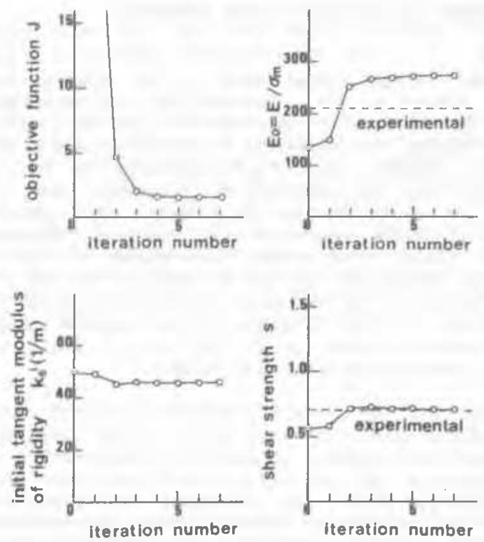

Fig.8 Iteration Behavior in Example-2 (Case-1)

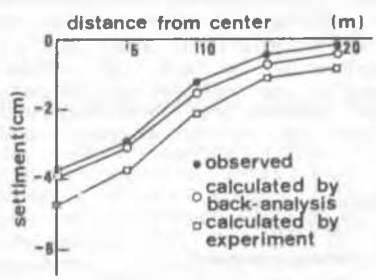

Fig.9 Calculated and Measured Surface Settelment in Example-2 (Case-1)

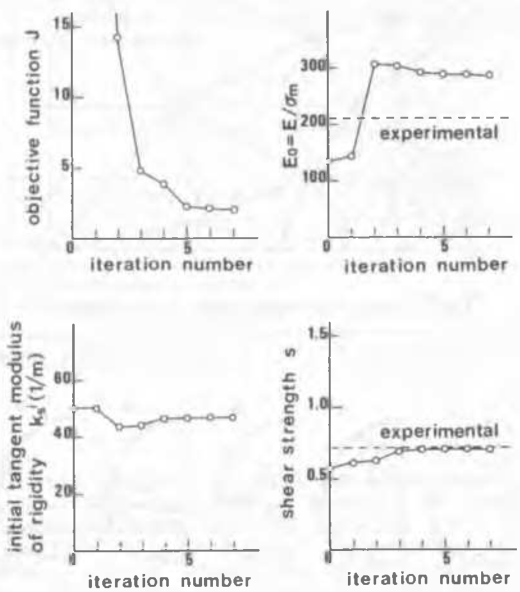

Fig.10 Iteration Behavior in Example-2 (Case-2)

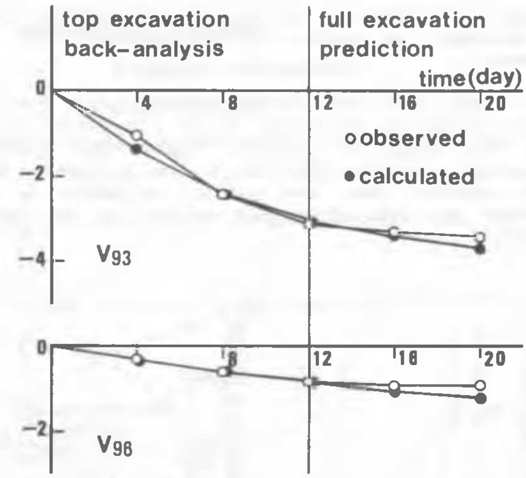

Fig.11 Predicted and Measured Displacements in Example-2 (Case-2)

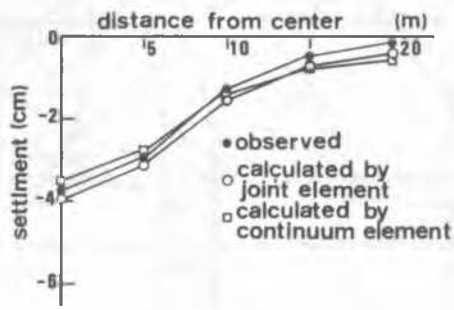

Fig.12 Calculated and Measured Surface Settement in Example-2 (Case-2)

CONCLUSIONS

A numerical procedure by back-analysis was proposed to obtain more reliable design parameters for the design of earth tunnels. It was demonstrated that the method can be successfully used to back-analyze the non-linear constitutive parameters for a joint element analysis from the monitored movements at construction sites. Thus, with observed initial displacements in an earth tunnel excavation the proposed procedure enables to make predictions of future settlements and the safety factor against failure.

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