Theme lecture: Monitoring and performances in tunnelling

Exposé sur le thème: Auscultation et comportement du sol dans les travaux de tunnel

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ABSTRACT: In observational methods, field measurements are essential, and their results must be used immediately after measuring to asses the stability of tunnels. In order to achieve an immediate assessment, hazard warning levels must be properly given to each measuring variable. It would be possible to understand the deformational mechanism of tunnels if measurements results are interpreted precisely. In this interpretation back analysis has a great potential. However the back analysis in geotechnical engineering should be the one which can identify not only the mechanical constants of soils and rocks, but also the mechanical model itself. In this paper, hazard warning levels are firstly discussed, and secondly the universal back analysis are described. This back analysis does not require any assumption for the mechanical model of soils and rocks.

1 INTRODUCTION

It is well known that he actual behavior of tunnels quite often differs from that predicted by numerical analysis. This difference is due to the many uncertainties involved in the modeling of complex geological formations with complex soil and rock geomechanical characteristics. The initial state of stress also causes difficulties. To obtain high accuracy in numerical analysis, input data such as geological and geomechanical parameters, initial state of stress, water table, ground permeability, etc., should be properly determined. This, however, is no easy task, even though various advanced exploration techniques have been developed and are already in use.

In order to overcome this difficulty, field measurements are carried out during construction. The design parameters used in the original tunnel design can then be assessed on the basis of the results of the field measurements, and, if necessary, both the design and excavation procedures can be modified. This design/construction method is called the observational method (Terzaghi and Peck, 1948). In this method, the most important matter is how to interpret the field measurement results for assessing the adequacy of design parameters used in the original design, as well as for monitoring the stability of tunnels during excavation.

The stability of tunnels must be evaluated immediately after taking measurements. To meet this requirement, a threshold value for each measuring item is determined beforehand so that the measurement results can be directly compared with them for assessing the tunnel stability. It is obvious that the tunnels are stable if all measured values remain within the threshold. This threshold is often called "hazard warning level", which is very useful for assessing tunnel stability at the construction site. However, it cannot be used directly in assessing the design parameters like Young's modulus, cohesion and internal friction angle which were adopted as input data for the design analysis.

In order to assess the design parameters, the measurement data must be properly analyzed. This analysis is just a reverse process in comparison with the ordinary analysis. Thus, this reverse process is called "back analysis." It should be emphasized that in back analysis in geotechnical engineering, it is extremely important to identify not only the mechanical properties like Young's modulus and the strength parameters, but also the mechanical model itself.

2 HAZARD WARNING LEVEL

It is recommended that hazard warning level be determined for each measurement item prior to the start of excavation. This will make it possible to assess the tunnel stability immediately after taking measurements simply by comparing the measured values to the hazard warning level. Obviously, when the measured values remain smaller than the hazard warning level, the stability of the tunnel is confirmed. If the measured values are predicted to become greater than the hazard warning level after a given period, then the engineers must modify the original design, and also stabilize the tunnel (see Fig. 1). This paper will discuss two ways to determine the hazard warning levels: (a) numerical approaches, and (b) critical strain approach.

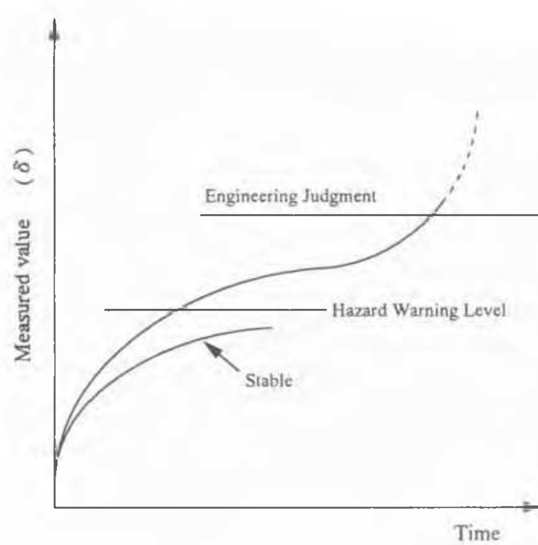


Fig. 1 Schematic diagram for measured value in relation to hazard warning level.

2.1 *Numerical approaches*

We many use a numerical approach, in such a way that the values of displacements, strains or stresses obtained by numerical analysis carried out at the design stage are used as hazard warning levels. It should be noted, however, that design engineers tend to adopt smaller values of Young's modulus and strength parameters such as cohesion and internal friction angle. This adoption of the smaller values of input data provides for larger values of displacements as output, and thus, by considering the large displacements , a conservative design can be achieved.

On the other hand, in monitoring the large displacements indicate signs of danger. Therefore, we cannot use large displacements predicted at the design stage as a hazard warning level. In other words, we should adopt the larger values for both Young's modulus and the strength parameters as input data to predict smaller displacements which can provide for conservative values of hazard warning levels (see Fig. 2).

Mechanical parameters in Design and Monitoring

Safety assessment & Warning levels

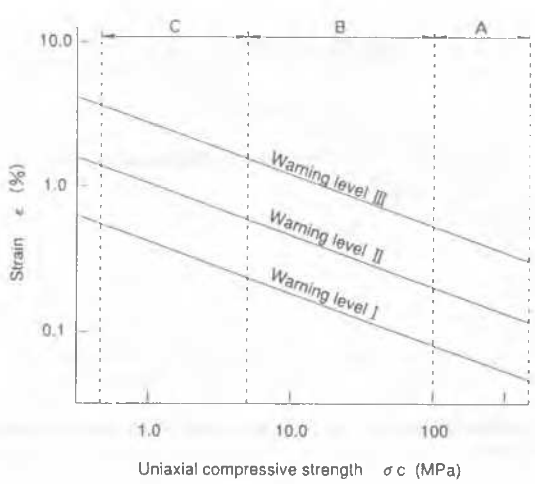
	Design	Monitoring
Young's modulus $E_s \sim E_l$	E_s	E_l
Strength $q_{us} \sim q_{ul}$	q_{us}	q_{ul}
Cohesion $c_s \sim c_l$	c_s	c_l
Friction angle $\phi_s \sim \phi_l$	ϕ_s	ϕ_l
Displacements	u_l	u_s

s: small value
l : large value

Fig.2 Relation between the mechanical parameters in design and monitoring.

2.2 *Critical strain approach*

Sakurai (1981) has proposed the critical strain of soils and rocks, which can successfully be used for assessing the results of displacement measurements in tunnels. The critical strain is defined as the ratio of uniaxial strength to Young's modulus.



	A	B	C
I	0.3~0.5	0.5~1	1~3
II	1~1.5	1.5~4	4~9
III	3~4	4~11	11~27

(Unit : cm)
(Radius of tunnel: 5.00m)

Fig. 3 Hazard warning levels for assessing the stability of tunnels.

The effects of joints existing in rock masses are supposed to be canceled out by taking the ratio of the two, though the uniaxial strength and Young's modulus are both greatly influenced by the existence of joints. In fact, the critical strain of jointed rock masses is either almost the same as or slightly larger than that of intact rock specimens. This means that we can use the critical strain obtained from laboratory tests on intact rock specimens in order to assess the stability of in-situ rock masses. It is also advantageous for critical strain that it is not much influenced by various aspects of the environments, such as moisture and temperature (Sakurai, et al 1994).

Based on the critical strain of intact rocks, Sakurai (1993) has proposed the hazard warning levels which can be used for assessing the stability of tunnels. They are classified into three different levels in relation to the degree of stability shown in Fig. 3. As an example, the hazard warming level for the crown settlement of tunnels with a radius of 5m, which is given for the corresponding level of strain is also shown in this figure.

3 UNIVERSAL BACK ANALYSIS

When the strains occurring around tunnels tend to cross the hazard warning levels, the original design parameters must be re-evaluated. For this purpose, back analysis is useful in identifying the material constants, such as Young's modulus, Poisson's ratio, cohesion and internal friction angle, from the measurement results. In tunnel practices, displacement measurements such as convergence, and bore hole extensometer measurements are commonly carried out. The initial state of stress is also determined by a back analysis of measured displacements.

It should be noted that the above mentioned back analysis is adequate only when the mechanical models of soils and/or rocks are well defined and fixed. However, the mechanical characteristics of soils and or rocks is not easily determined. This implies that it is recommended that the mechanical models should not be assumed, but rather identified by back analysis. In other words, back analysis should be capable of identifying not only the mechanical constants, but also the mechanical model itself. For this purpose, a universal back analysis procedure has been proposed, in which the mechanical model is not necessarily assumed, but non-elastic strain is introduced. In the following, the idea of this procedure is briefly described. The detailed discussion for the procedure has been given elsewhere (Sakurai, et al, 1993).

3.1 *Mathematical formulation*

The total strain occurring in the ground due to excavation can generally be divided into two parts, that is, elastic and non-elastic strains, as given in the following equation.

$$\{\varepsilon\} = \{\varepsilon_e\} + \{\varepsilon_0\} \qquad (1)$$

where $\{\varepsilon\}$: Total strain
$\{\varepsilon_e\}$: Elastic strain
$\{\varepsilon_0\}$: Non-elastic strain

In the non-elastic part, all the non-elastic strains such as the ones caused by plastic deformation, loosening due to the gravitational force as well as due to blasting, creep, and seepage of underground water are included.
Hence, Hooke's law is written as;

$$\{\sigma\} = [D]\{\varepsilon_e\} = [D](\{\varepsilon\} - \{\varepsilon_0\}) \qquad (2)$$

Taking into account Eq.(2) in the formulation of finite element analysis, the following equation is derived.

$$[K]\{u\} = \{P\} + \{P_0\} \qquad (3)$$

where $[K]$ Stiffness matrix
$\{u\}$ Displacement vector at nodal points

$$\{P\} = \int_{v1} [B]^T \{\sigma_0\} dV - \int_{v1} [N]^T \{b\} dV$$

$$\{P_0\} = \int_{v1} [B]^T [D] \{\varepsilon_0\} dV$$

where $\{P\}$ denotes external forces representing the excavation, $\{\sigma_0\}$ is initial stress, $\{b\}$ is gravitation force. $\{P_0\}$ denotes external forces equivalent to the non-elastic strain. $[K]$ is the stiffness matrix for isotropic elastic materials where Young's modulus and Poisson's ratio are only the material constants.

3.2 *Back analysis procedure*

In tunneling practice displacement measurements are most commonly carried out by using convergence meters and borehall extensometers. Therefore, in finite element analysis some of the displacements at the nodal points are known. Considering these known displacements in Eq.(3), the non-elastic strain can be back calculated. In this back analysis procedure any optimization programs can be used. If the number of measurement data is greater than the number of unknown parameters, a least squares method is most commonly used. However, in the proposed back analysis method non-elastic strains become unknown parameters, and the number of them is usually far greater than that of measurement data. Therefore, this kind of back analysis with large number of unknown parameters cannot in general be performed unless some sort of constraint is introduced to assured uniqueness of solution.

A simple way of introducing constraint is to make an assumption such that some extent around a tunnel is divided into a few regions, and each region has a constant distribution of non-elastic strains. This assumption can reduce the number of unknowns so that a least squares method can be used. An alternative way is the minimum norm method which may be one of the potential ways. The minimum norm method is a mathematical procedure by which unknown parameters can be uniquely determined from a small number of measurement data (Gao and Mura, 1992). Since the detailed description of back analyzing the non-elastic strains by using the minimum norm method have been given elsewhere (Sakurai and Akutagawa, 1995), the explanation of the method is not covered in this paper.

4 CASE STUDY

In the following, a case study will demonstrate how misleading a mechanical model can be in back analysis in tunnel practices. A double-track railway tunnel of shallow depth is concerned. The ground in which the tunnel was excavated consisted of fine grain sand deposits. Both the tunnel diameter and the height of overburden were approximately 10m. Both borehall extensometers and inclinometers were installed from the ground surface prior to tunnel excavation, so that the absolute displacements due to excavation were measured. The ground surface settlements were also measured by surveying. Using these measurement results we carried out two different back analyses; (a) elastic back analysis (b) universal back analysis.

4.1 *Elastic back analysis*

We assumed the model of the ground consisting of homogeneous and isotropic materials, so that only Young's modulus and Poisson's ratio were the material constants, and they were back calculated by an elastic back analysis. The identified material constants were used to compute the displacements around the tunnel, and the maximum shear strain distribution was then calculated, as shown in Fig. 4. It is obvious from the figure that no loosening zone appeared in the ground around the tunnel. This result is just the one we expected, because of that the

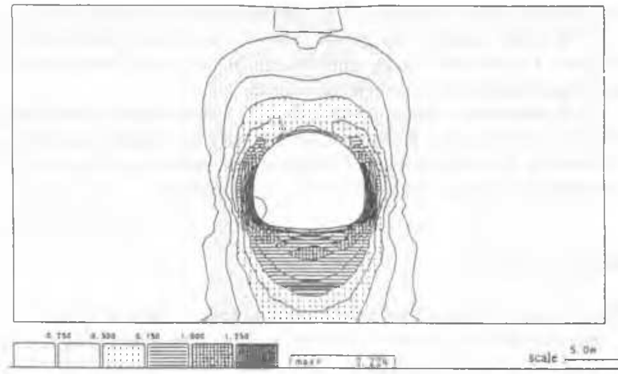


Fig. 4 Maximum shear strain distribution (isotropic elastic model).

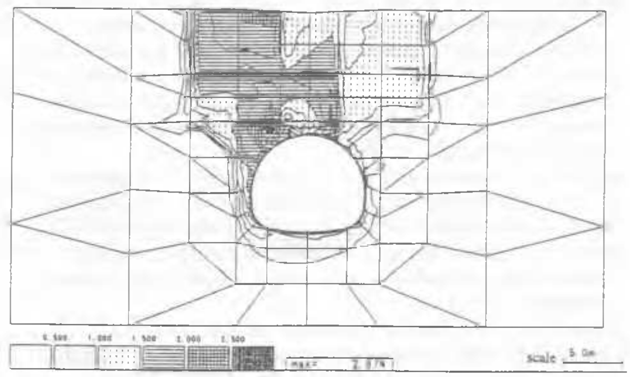


Fig. 5 Maximum shear strain distribution taking into account non-elastic strain.

mechanical model of the ground is assumed to be homogenous and isotropic, so that the existence of loosening zone was not taken into account in this back analysis.

4.2 *Universal back analysis taking into account non-elastic strain*

As already mentioned earlier, in back analysis in geotechnical engineering the mechanical model should not be assumed, but rather be determined by back analysis. To achieve this end, we used the universal back analysis procedure, in which the same mesured displacements as utilized in the elastic back analysis were used as input data. In this back analysis no mechanical model was assumed, and non-elastic strains were back calculated. Since the details of this calculation have been presented elsewhere (Sakurai, 1996), only the results of the maximum shear strain distribution is shown in Fig. 5. It is of interest that comparing the results shown in Fig. 4 with Fig 5 indicates that we can obtain two different maximum shear strain distributions being obtained from identical input data.

5 CONCLUSIONS

1. The observational method is a very promising means of achieving a rational design of tunnels. In this method, however, a crucial problem remains on how to interpret the results of field measurements taken during and after excavation.

2. For monitoring the stability of tunnels, the hazard warning levels are extremely important. The hazard warning level must be set up prior to excavation, so that the measured values can be compared directly with them for assessing the stability of tunnels.

3. The hazard warning level may be determined by numerical analyses. However, the input data must be different from those used in the design purpose.

4. Critical strain can be used for determining the hazard warning levels. It is advantageous that the critical strain of joint

rock masses can be determined by laboratory tests on intact rocks.

5. In back analysis in geotechnical engineering, mechanical models of soils and rocks should not be assumed, but rather identified from field measurement results.

6. A case study demonstrates that if a mechanical model is fixed in back analysis the results are not only inadequate, but also misleading in such a way that they provide incorrect information for modifying design and construction procedures.

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