New approach for assessing long-term stability of tunnel and remedial work

Nouvelle approche pour l'évaluation de la stabilité à long terme des tunnels et des travaux de réfection

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ABSTRACT: In this paper, a finite element analysis is conducted to investigate the long-tem stability of a tunnel excavated in a shattered zone. The analysis is based on an elasto-viscoplastic model with strain hardening and strain softening. The purpose of the present research is to investigate the mechanism of the long-term stability of the tunnel due to the time-dependent behavior of the surrounding ground. Particular attention is paid to the redistribution of stress within the ground due to strain softening and the time-dependent behavior. The constitutive model adopted in the finite element analysis not only can describe the strain-softening behavior but also such time-dependent behavior as creep failure, strain-rate dependency, and stress relaxation. The material parameters involved in the model are determined through a series of laboratory tests. From the analysis, it is possible to provide a new approach for assessing the long-term stability of tunnels and the effectiveness of the remedial work performed on the tunnels

RÉSUMÉ: Dans cet article, une analyse par éléments finis est conduite pour rechercher la stabilité à long terme de tunnels excavés dans une zone supportant une pression de confinement à la profondeur de 400m. L'étude est basée sur un modèle visco-élastique avec écrouissage et anti-écrouissage. Plusieurs années après l'achèvement de tunnels, de nombreuses fissures ont été trouvées lors d'inspections de routine. Les tests en laboratoire montrent que le matériau du sol a de fortes caractéristiques d'anti-écrouissage et de comportement dépendant du temps. L'objectif de cette présente recherche est d'identifier le mécanisme de la stabilité à long terme du comportement temporellement dépendant du sol environnant. Une attention particulière a été apportée sur la redistribution des contraintes dans le sol due à l'anti-écrouissage et au comportement dépendant du temps. Par cette analyse, il est possible d'établir une nouvelle approche permettant l'évaluation de la stabilité à long terme des tunnels et de l'efficacité des travaux de réparation effectués dans les tunnels.

1 INTRODUCTION

It is commonly known that soft rock can be linked to various geotechnical engineering problems, such as the instability of slopes, foundations, and tunnels. In general, the mechanical behavior of soft rock is elasto-plastic, dilatant, strain softening, and time dependent. Its mechanical behavior during shearing is largely dependent on the confining pressure and cementation. Cementation plays an important role in the development of shear strength. The breakdown of the soil microstructure during various processes, such as a large shearing deformation, cyclic drying-wetting, and stress release, causes a strain-softening behavior. This strain-softening behavior of soft rock is an important factor in the long-term stability of excavations. The progressive failure in an excavation problem is usually caused by the following two factors, namely, (a) the deterioration of the microstructure of the geologic materials due to swelling and weathering during and/or after the excavation, and (b) the time-dependent behavior of the geologic materials. As to the time dependency, two different types exist, that is, the apparent viscosity due to the coupling of the soil skeleton with pore water and the inherent viscosity of the soil skeleton.

The horseshoe-shaped tunnel considered in this paper was excavated in a shattered zone with an overburden of 400 m. The surrounding ground is deteriorated tuff which underwent conversion due to hot water and weathering. The laboratory tests show that the rock samples contains numerous cracks and are much weaker than the relatively fresh rock. Strong creep behavior is observed in the deteriorated rock. The cracks of the tunnel lining are mainly observed in this area. Although the cracked lining was remedied by crack-filling work, cracks still developed a certain period of time after the replacement.

For this reason, a two-dimensional finite element analysis is conducted with a strain-softening elasto-viscoplastic model (Adachi et al., 1994), based on the experimental results from laboratory tests, to investigate the creep behavior of the surrounding ground, changes in the sectional forces in the tunnel lining, and the mechanism of crack development. From the analysis, a new approach for assessing the long-term stability of tunnel and the corresponding remedial work is proposed.

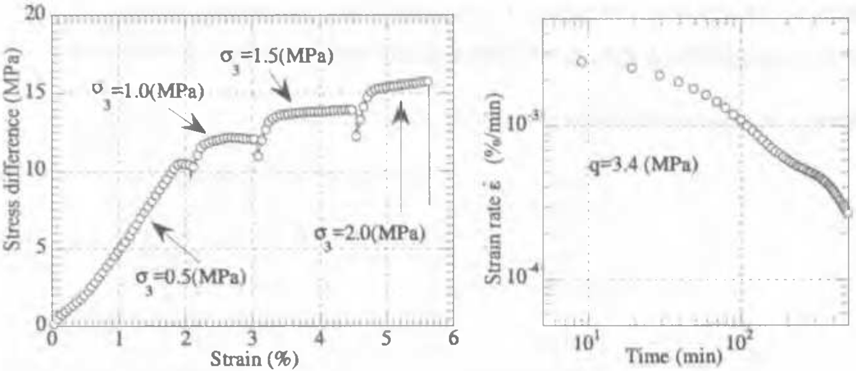
2 GEOLOGIC SURVEY AND LABORATORY TESTS

The geologic properties of the surrounding ground of the tunnel under investigation are listed below:

- The ground near the boundary between two different strata deteriorated due to weathering, because the eras of the formation of the Paleozoic strata and the tuff are different.
- The strength of the Paleozoic strata deteriorated due to conversion caused by hot water.
- The strength of the tuff also deteriorated due to conversion caused by hot water.
- Many cracks developed in the ground.

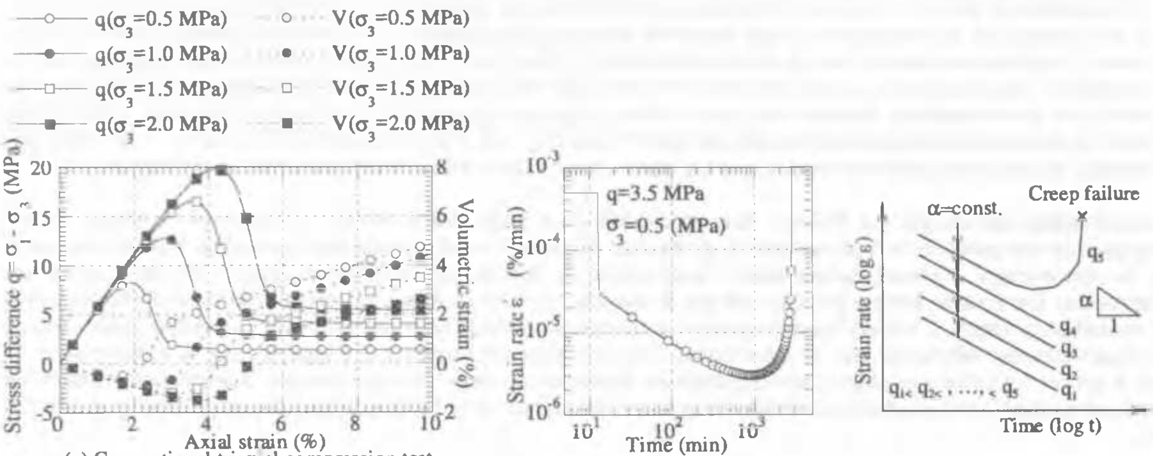
Several years after the completion of the tunnel, many cracks were discovered in the lining during a routine inspection. It was also found that cavities with 20~30 cm thick existed between the lining and the ground. The cavities might have formed during the tunnel excavation and/or during the installation of the lining. In order to investigate the mechanical behavior of the ground, a series of field and laboratory tests, such as supersonic wave propagation tests, multi-stage triaxial compression tests, uniaxial creep tests and shear creep test were conducted. It was found from the uniaxial creep tests that creep behavior existed in the deteriorated zone. Therefore, it is reasonable to think that the creep behavior of the ground contributed greatly to the cracks found in the lining of the tunnel.

Figure 1 shows the stress-strain relation obtained from the



(a) Multi-stage triaxial compression test
(b) Uniaxial creep test

Figure 1. Stress-strain-time relations obtained from laboratory tests.



(a) Conventional triaxial compression test
(b) Triaxial creep test

Figure 2. Theoretical stress-strain and strain rate-time relations.

multi-stage triaxial compression tests and the strain rate-time relation from the uniaxial creep tests. It is known from the figure that the ground shows strain softening and time-dependent behavior.

Reasons for the development of cracks in the lining include the strain softening of the surrounding ground due to the excavation and the eccentric earth pressure due to the stress redistribution caused by creep deformation of the ground and the existence of cavities between the lining and the ground.

Although the cracked lining was remedied by crack-filling work, cracks still developed in some places after the replacement. Therefore, it is necessary to properly evaluate the strength of the existing lining and to develop a suitable method by which remedial work can be judged and assessed.

3 NUMERICAL SIMULATION OF THE LONG-TERM STABILITY OF TUNNELS

Adachi et al. (1998) proposed an elasto-viscoplastic model that can describe not only the time-dependent behavior, but also the strain softening of geologic materials. The validity of the model has been confirmed by a series of conventional triaxial compression tests and triaxial creep tests on soft sedimentary rock. The model includes a feature by which the uniqueness of the solution for Valanis's (1985) sense is satisfied in the initial value problem (Adachi et al., 1995). Finite element analyses were conducted for the progressive failure of a cut slope (Adachi et al., 1994) using the model and the excavation of a tunnel with NATM (Adachi et al., 1994).

Based on the model, a finite element analysis has been carried out in this section to investigate the long-term stability of tunnels and the effectiveness of the remedial work.

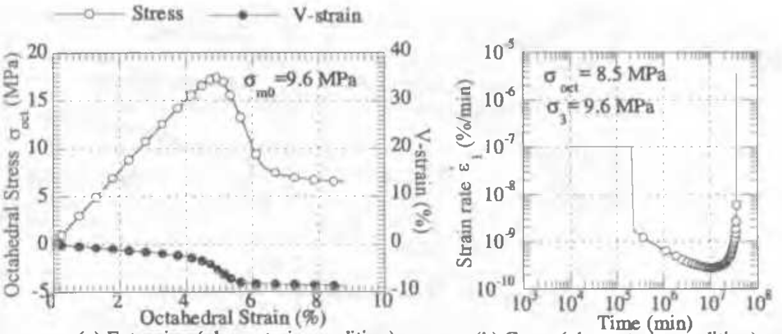
Table 1. Parameters of the constitutive model for the ground (G_4).

E (MPa)	500	*a*	0.959
ν	0.20	*C*	0.265
b (MPa)	0.87	M^*_f	1.15
σ_{mb} *(MPa)*	18.0	*G'*	454
$\bar{M}_m$	1.25	*τ*	90000

In the numerical analysis, the parameters involved in the constitutive model are determined through the laboratory tests such as multi-stage triaxial compression tests and uniaxial creep tests. In order to investigate the influence of the cavity on the sectional force of lining, two cases, that is, tunnel excavation with the existence of a cavity and one without a cavity, are considered. The calculations were carried out under fully drained conditions. The tunnel excavation, long-term stability, and the remedial work were simulated in three steps, that is, the excavation of the tunnel, the installation of the lining, and the injection of mortar into the existing cavity by adding some elements in cave area.

Table 1 lists the material parameters of the ground. These parameters usually should be determined with triaxial compression tests and triaxial creep tests for at least two different confining pressures. In the present case, however, they are determined with triaxial compression tests and uniaxial creep tests. Young's modulus is evaluated with supersonic wave propagation tests. In the succeeding analyses, including an element simulation and a finite element analysis, the parameters are the same as those listed in Table 1.

Figure 2 shows the simulated stress-strain relations for different confining pressures and the strain rate-time relations in the triaxial tests. Images of the creep behavior of the geologic materials at different creep stress levels are also plotted in the figure.



(a) Extension (plane-strain condition) (b) Creep (plane-strain condition)

Figure 3. Theoretical stress-strain and strain rate-time relations under a plane-strain condition.

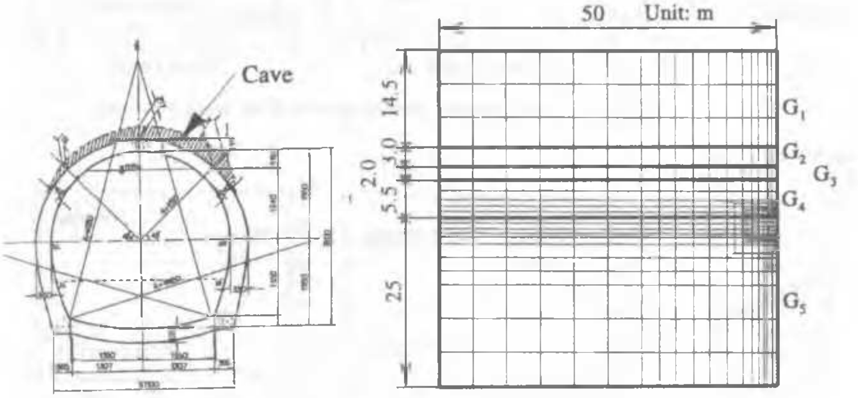


Figure 4. Section of the tunnel and the geologic profile of the surrounding ground.

It is found from Figures 1 and 2 that the theoretical peak strength in the stress-strain relations is almost the same as that from the triaxial tests under a confining pressure of 1.0 MPa. For a case in which the confining pressure is less than 1.0 MPa, the theoretical strength is less than that in the test results, while for a case in which the confining pressure is larger than 1.0 MPa, the theoretical strength is larger than that in the test results. It can be said, therefore, that the theoretical simulation was able to predict the test results to some extent.

Meanwhile, parameter C in Table 1 is determined in such a way that α, the gradient of the strain rate-time relations in the logarithm axis, should coincide with the tested one, as shown in Figure 1b. It is obvious from Figure 2c that because α is the same for different shear stress levels, it is possible to determine the C value with uniaxial creep tests.

Figure 3 shows the simulated stress-strain and creep relations under a plane-strain extension. In the simulation, the initial mean stress is taken as 9.6 MPa which corresponds to the initial stress state at the center of the tunnel. Furthermore, the creep stress σ_{oct}=8.5 MPa is correspondent to the octahedral stress immediately after the tunnel excavation. It is estimated from Figure 3b that since the stress state at the excavated surface is the same as the plane-strain extension, a creep failure of the ground at the stress state will occur 57 years after the excavation.

Figure 4 shows the geometry of the tunnel, the geologic profile and the mesh used in the finite element analysis. The overburden of the tunnel is 400 m. The initial stress field is supposed to be homogeneous within the calculated area of 50 × 50 m, and it takes the value of 9.6 MPa. Due to the tunnel's symmetrical condition, only half of the domain is considered in the calculations.

Except for the G_4 layer, where the elasto-viscoplastic behavior is prominent, the other layers mainly consist of relatively fresh rock and can be regarded as elastic. The material properties of the ground in these layers are listed in Table 2.

Table 2. Material parameters of the ground.

	G_1	G_2	G_3	G_4	G_5
E (MPa)	4000	1500	1500	500	1900
ν	0.20	0.20	0.20	0.20	0.20

In simulating the long-term stability of the tunnel, the calculations are divided into three stages, namely, the excavation of the tunnel, the installation of the lining, and the injection of mortar into the cavity.

Figure 5 shows the distribution of the bending moment in the lining due to the creep of the ground and the cavity. It was found that the moment exceeded the cracking moment when a cavity existed. Due to the eccentric earth pressure cause by the cavity, the moment of the lining in the case of a tunnel cavity is much larger than that without a cavity. The location where much cracking was found in the tunnel examination coincides with the calculated one.

Figure 6 shows changes in the bending moment of the lining with time. It was found that at the shoulder of the tunnel (Node 304), the bending moment exceeded the cracking moment 7.6 years after the excavation of the tunnel, proving that a cavity truly leads to the development of cracks.

On the other hand, it is found from Figures 7 and 8 that the surrounding ground remains at a steady state of creep and that creep failure does not occur.

Figure 9 shows changes in the bending moment of the lining with time at Node 304. It is found that the bending moment tends to decrease after the injection of mortar, implying that the injection of mortar into the cavity between the tunnel and the lining is very effective.

4 CONCLUSION

It was found that due to the time dependent behavior of the ground, the earth pressure acting on the lining of tunnels changes constantly. It was also found that the existence of a

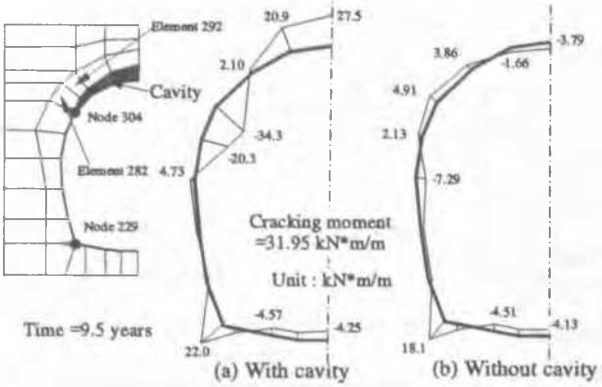


Figure 5. Distribution of the bending moment in the lining due to the creep of the surrounding ground.

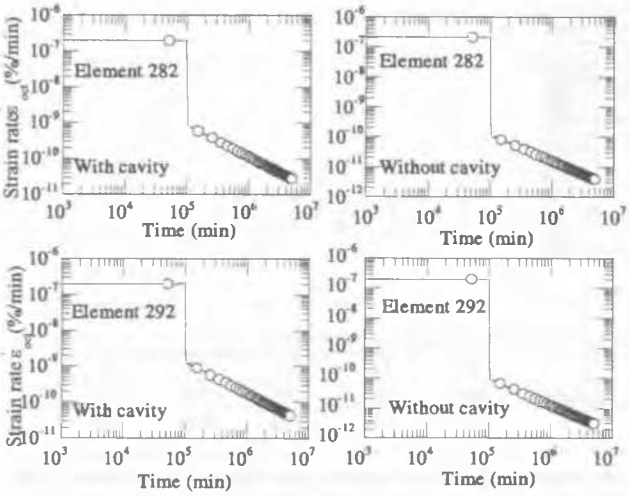


Figure 7. Time history of the strain rate within the surrounding ground

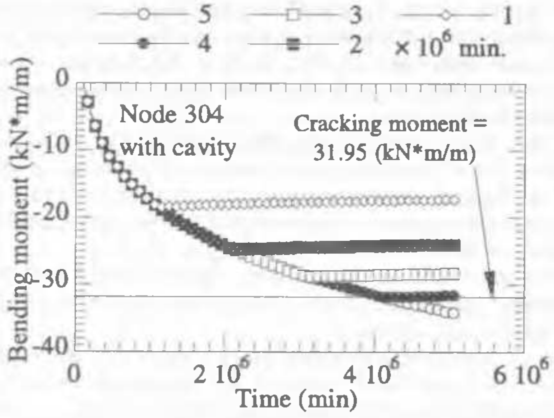


Figure 9. Effect of the mortar injection into the cavity between the tunnel and the lining.

cavity may greatly change the distribution of the bending moment and may lead to the cracking of the concrete.

Remedial work, that is, the injection of mortar into existing cavity is found to be very effective in reducing the section force on the lining.

The calculated results were compared and checked with the

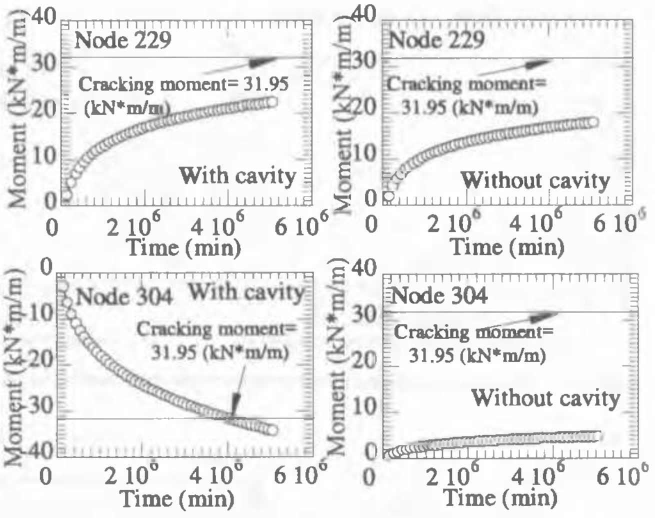


Figure 6. Changes in the bending moment of the lining with time.

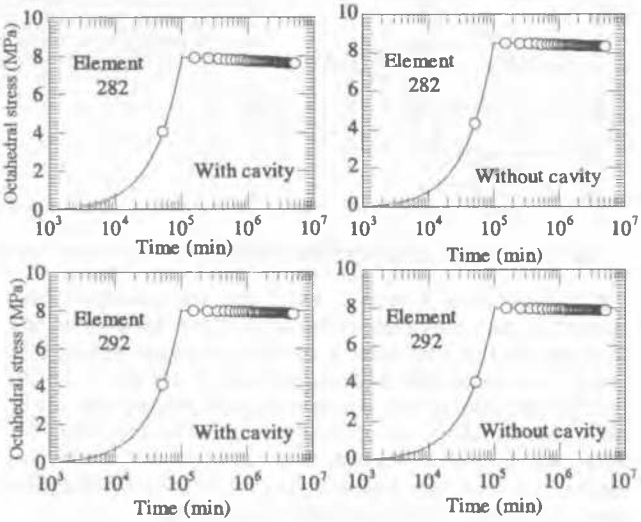


Figure 8. Time history of the stress within the surrounding ground

results obtained from field measurements accumulated over a long period. It was found from the numerical analysis that if the mechanical behavior of the ground is simulated with a suitable elasto-viscoplastic model with strain softening, the long-term stability of a tunnel can be simulated to a reasonable accuracy with the finite element analysis conducted in this paper.

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