Model tests and numerical analysis on the evaluation of long-term stability of existing tunnel

Essais expérimentaux sur modèle réduit et analyse numérique pour l'évaluation de la stabilité à long-terme des tunnels

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ABSTRACT

Two types of tunnel model tests, failure test and constant load creep test, were executed on a manmade soft rock model ground made of a mixture of gypsum and diatom whose mechanical behaviors are very similar to soft sedimentary rock. Meanwhile, finite element analyses based on an elasto-viscoplastic model, which can properly consider the influence of the intermediate principal stress, are conducted to simulate the model tests. The simulated results indicate that the finite element analysis based on a suitable constitutive law can appropriately describe the long-term deformation behavior of tunnels in soft rock.

RÉSUMÉ

Deux types d'essai de comportement de tunnels – à la rupture et de fluage sous charge constante – ont été menés sur un sol modèle constitué d'un mélange de gypse et de diatomées et présentant un comportement mécanique très similaire à une roche tendre sédimentaire. Parallèlement, des modélisations numériques par éléments finis de ces essais expérimentaux ont été réalisées en utilisant un modèle élasto-viscoplatique, modèle qui permet notamment de tenir compte de l'influence de la contrainte principale intermédiaire. Les résultats des simulations indiquent que l'analyse numérique, lorsqu'elle est assortie d'une loi constitutive appropriée, conduit à une description satisfaisante du comportement à long terme en déformations des tunnels en roches tendres.

Keywords : elasto-viscoplastic model, FEM, model test, tunnel, manmade soft rock

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. Sometimes, it may also show time-dependent behavior. The breakdown of microstructure of soft rock is usually caused by various processes, such as a large shearing, slaking, and weathering. Progressive failure in an excavation problem, which may threaten the long-term stability of an excavated earth structure, is usually caused by the following two factors, namely, (a) the deterioration of the microstructure of the geologic materials during and/or after the excavation, and (b) the time-dependent behavior of the geologic materials.

The purpose of this study is to propose an effective evaluating method for the long-term stability of existed tunnel in soft rock ground. Firstly, the effectiveness of finite element analysis (FEM) based on an elasto-viscoplastic model (Zhang et al, 2003) with strain softening in analyzing long-term deformation behavior of tunnel excavated in soft rock due to creep behavior of a soft rock ground, is verified. In the constitutive model on which the finite element analysis is based, tij concept that can consider properly the influence of the intermediate principal stress is introduced into a model proposed by Oka and Adachi (1985). Secondly, two types of tunnel model tests, failure test and constant load creep test, were executed on a manmade soft rock model ground made of a mixture of gypsum and diatom whose mechanical behaviors are very similar to soft sedimentary rock. By comparing the results of model tests with the corresponding finite element analysis, the effectiveness of the proposed numerical method is verified. The material parameters in the model were determined by triaxial compression tests and triaxial creep tests on the manmade soft rock..

2 CONSTITUTIVE MODEL AND ITS VERIFICATION WITH TRIAXIAL TESTS

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. Sometimes, it may also show time-dependent behavior. The breakdown of microstructure of soft rock is usually caused by various processes, such as a large shearing, slaking, and weathering. Progressive failure in an excavation problem, which may threaten the long-term stability of an excavated earth structure, is usually caused by the following two factors, namely, (a) the deterioration of the microstructure of the geologic materials during and/or after the excavation, and (b) the time-dependent behavior of the geologic materials.

Zhang et al (2003) proposed an elasto-viscoplastic model considering the influence of the intermediate principal stress on the mechanical behaviors of soft rock by introducing the tij concept (Nakai and Mihara, 1984) to a model proposed by Oka and Adachi (1985). The original characteristics of the model, such as the ability to describe not only the strain softening behavior of soft rock but also the stress-dilatancy relation, the ability to obtain a unique solution for initial value and boundary value problems (BVP) in a finite element analysis, remain valid. In the model, however, the values of some parameters are confining-stress dependent. For this reason, these parameters are re-defined by some equations as the functions of confining-stress in which some new stress-independent parameters are use so that all parameters involved in the model are uniquely determined. Detailed description about the modification of the model can be found in the reference (Tasaka et al, 2007).

The validity of the modification is checked by conventional triaxial compression and creep tests on a manmade soft rock under drained condition. The manmade soft rock is made from gypsum and diatom and its composition and material properties are listed in Tables 1 and 2. Conventional triaxial compression

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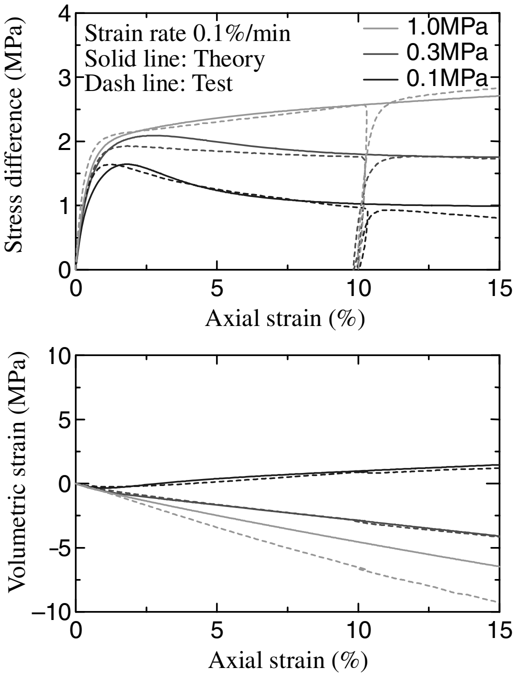
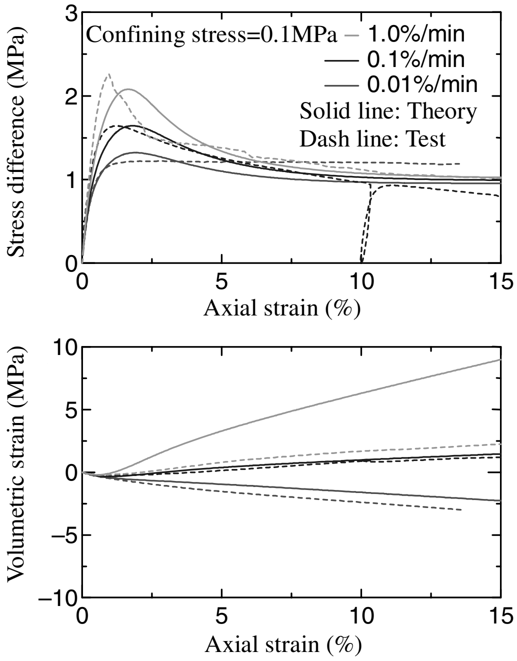
tests were conducted under different confining stresses and shear strain rates with constant strain rate loading condition. The confining stresses used in the tests are σ_3=0.1, 0.3 and 1.0MPa and the loading rate are 1.0, 0.1 and 0.01%/min respectively. The creep stresses used in the creep tests are 80% of the peak stresses of the specimen at the same confining stress in triaxial compression test. It is confirmed that the strength and dilatancy behavior of the specimens under drained and undrained condition are almost the same and that there is no water observed along the shear band after the loading reached residual state, which means pore water has little influence on the mechanical behavior of the manmade soft rock. Figures 1 and 2 show the comparison between test results and theoretical results, which indicate a high accuracy of the theoretical prediction of the modified model not only in triaxial compression tests but also in triaxial creep tests.



(a) Confining stress dependency



(b) Strain rate dependency

Figure 1. Theoretical and test results of stress-strain-dilatancy relation of manmade soft rock in conventional triaxial compression tests

Table 1. Material weight ratio of manmade rock

gypsum	diatom	Water	Retardation
1.0	0.3	1.0	0.4 %

Table 2. Physical properties of manmade rock

Wet unit weight (g/cm^3)	Water content (%)	Uniaxial strength (MPa)
1.45～1.51	67.9～73.5	1.68～1.83

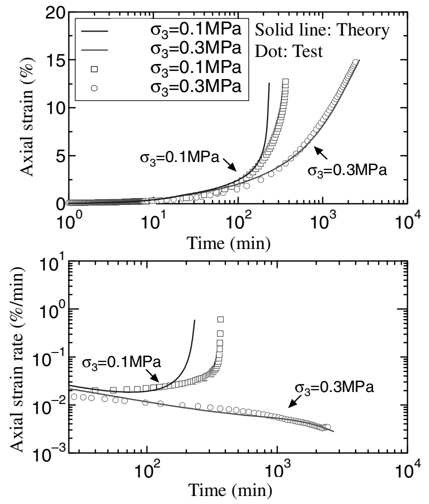


Figure 2. Theoretical and test results of time history of strain and strain rate of manmade soft rock in conventional triaxial compression tests

3 TUNNEL MODEL TESTS AND THEIR NUMERICAL SIMULATION

Model tests of existing tunnel whose ground is made of manmade soft rock were also conducted to investigate the mechanical behaviors of the BVP of tunnel, especially the long-term behavior. The main advantage of using the manmade soft rock is that the mechanical behavior of the material is quite the same for all specimens if compared with natural soft sedimentary rock whose mechanical behavior is often scattering.

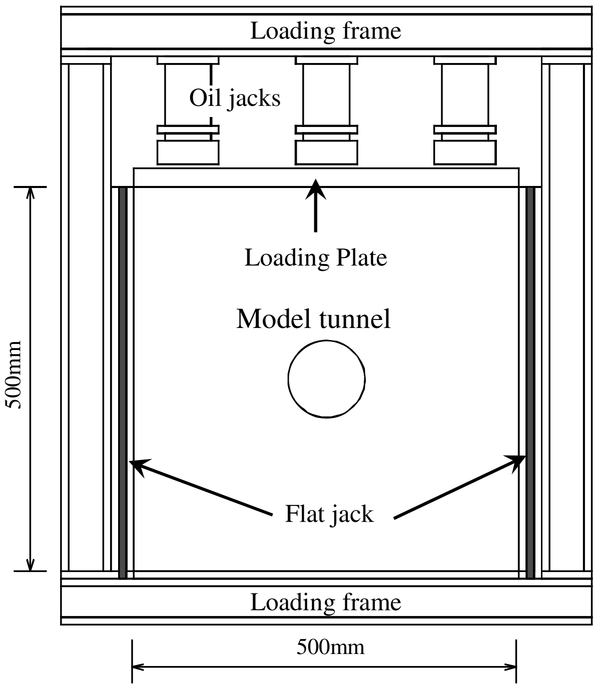


Figure 3. Loading device of model test of tunnel

Figure 3 shows the model test device used in this research. The size of the model ground is 500mm in high, 500mm in width and 145mm in thickness with a circle tunnel diameter of 106mm located at the center of the model. The loads are applied with three vertical jacks and two flat jacks in side surfaces to apply vertical and horizontal stresses. During the tests, strain gauges along three directions are coated on the surface of tunnel and vertical planes. Displacement meters and photography are also use to measure the displacement of the tunnel in three directions.

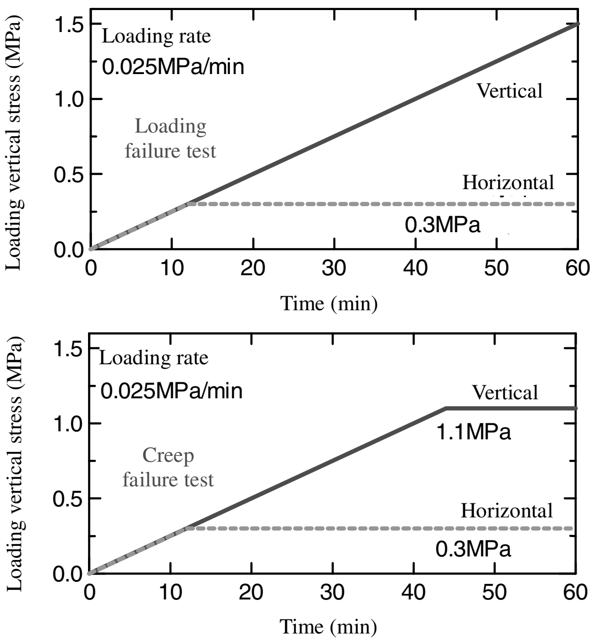


Figure 4. Loading processes of model test of tunnel

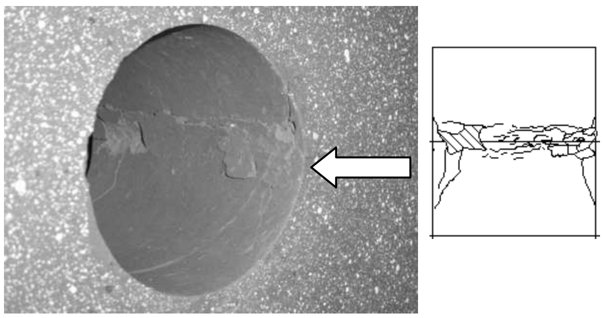


Photo 1. Failure pattern of tunnel surface in loading failure test

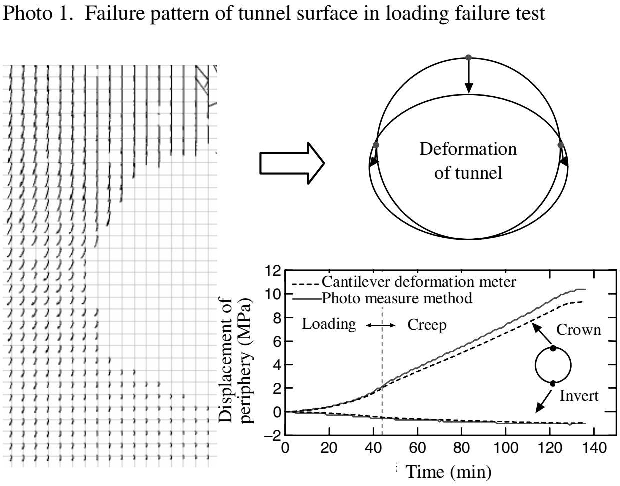


Figure 5. Displacements of tunnel periphery measured by cantilever deformation meter and photo measuring method

Two types of loading tests on the model tunnel were conducted. One is the straight loading test at constant loading rate of 0.025MPa/min, in which the loads were increased until the model failed (σ_v=1.4MPa) and is called as loading failure test. Another test is creep test in which the vertical load is applied to a prescribed value (σ_v =1.1MPa and σ_h =0.3MPa) and is called as creep failure test, as shown in Figure 4. It is known from the tests that the failure of the model tunnel always firstly happened along the tunnel surface evenly both in loading failure test and creep failure test, as shown in Photo 1, which means that geometry and loading condition are in plane-strain condition. Figure 5 shows the displacements of tunnel periphery measured by cantilever deformation meter and photo measuring method. Two methods gave the same result which implies that the measuring accuracy of the methods is verified.

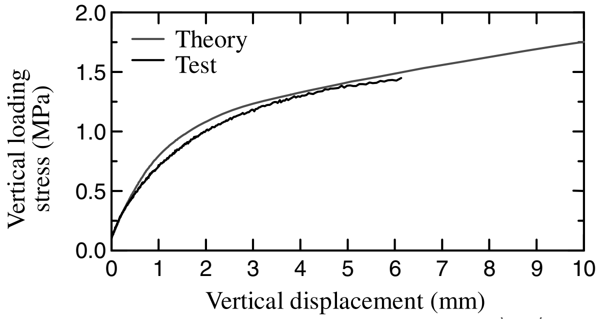


Figure 6. Vertical load-displacement relation in loading failure test

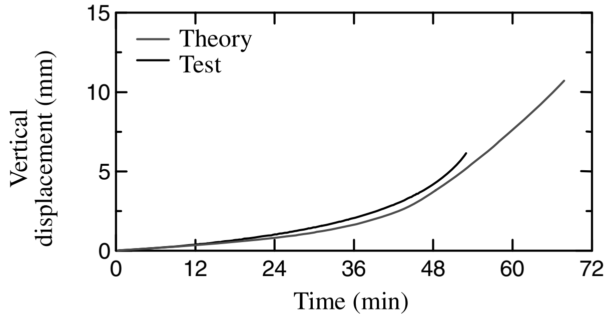


Figure 7. Time history of vertical displacement in loading failure test

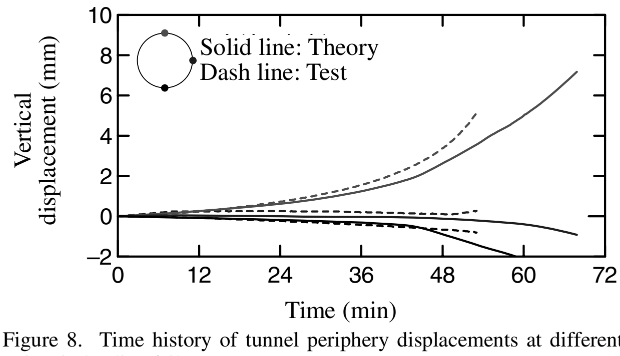


Figure 8. Time history of tunnel periphery displacements at different points in loading failure test

In the simulation of the model tests of tunnel, a FEM code cold 'SOFT' was used, in which the ground behavior is described by the modified model described in previous section. In the calculation, due to symmetric condition both in geometry and loading conditions, only half of the model ground was considered. Strictly speaking, the BVP of model test of tunnel is a three-dimensional (3D) problem. Nevertheless, the mechanical behavior of the model tunnel is found to be mainly in plane-strain condition as aforementioned, the analyses were conducted in two-dimensional (2D) condition.

Figure 6 shows the comparison between calculated and test results of vertical load-displacement relation in loading failure test. Figure 7 shows the comparison between calculated and test results of time history of vertical displacement in loading failure test. Figure 8 shows the comparison between calculated and test results of time history of tunnel periphery displacements at different points in loading failure test. It is known from these figures that the numerical results fit well with the test results, indicating that the finite element analysis based on a suitable constitutive law can appropriately describe the mechanical behavior of tunnels in soft rock subjected to a load up to failure with satisfactory accuracy.

Figure 9 shows the comparison between calculated and test results of principal strain distribution on outer-vertical-plane at the failure load (about 1.4MPa) in loading failure test. Different from the tendency shown in Figures 6, 7, and 8, there exists a big difference between the test and the calculated results, especially in the area near tunnel periphery. This is thought to be the reason that, in model test, outer vertical surface is free while in numerical calculation, it is assumed as plane-strain condition, which means the outer vertical surface is restrained. This difference leads to the discrepancy between the test and the calculated results, indicating that three-dimensional analysis is preferred to increase the accuracy. The main results shown in Figures 6, 7, and 8, however, indicate that 2D analysis remains valid in major aspects.

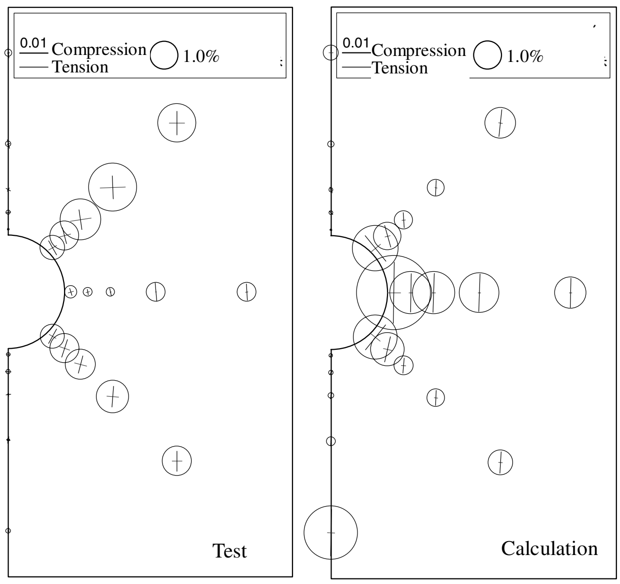


Figure 9. Principal strain distribution on outer-vertical-plane at the failure load (about 1.4MPa) in loading failure test

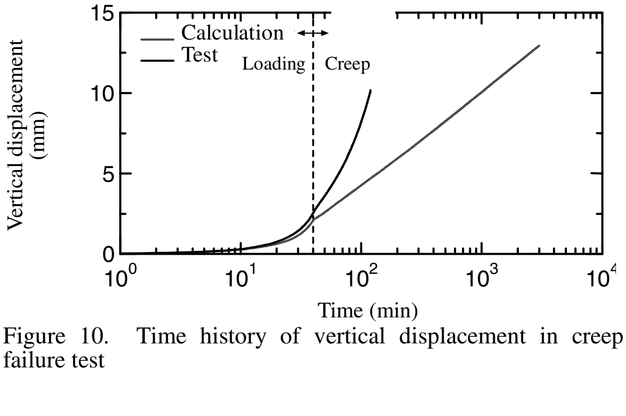


Figure 10. Time history of vertical displacement in creep failure test

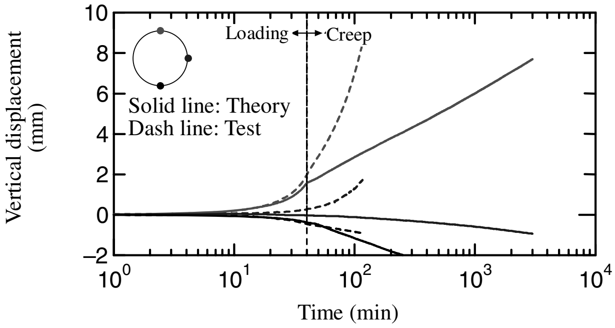


Figure 11. Time history of tunnel periphery displacements at different points in creep failure test

As to the creep failure test, the loading process is clearly shown in Figure 4, in which the vertical stress was firstly loaded to 1.1MPa and then kept constant in creep stage. The horizontal stress was kept at 0.3MPa during creep stage. Figure 10 shows the comparison between calculated and test results of time history of vertical displacement at loading plate during loading and creep stages. It is found that during the loading stage (from 0.1MPa to 1.1MPa), the results are coincident with each other very well while in the creep stage, big discrepancy occurred. The same tendency can be seen in the time history of vertical displacements around tunnel periphery, as shown in Figure 11. Therefore, it is easy to reason that the influence of assuming a plane-strain condition on the prediction of mechanical behavior of the model tunnel used in this paper is much larger in creep stage than in loading stage, which should be checked with 3D analysis.

4 CONCLUSIONS

In this study, two types of tunnel model tests, loading failure test and creep failure test, were executed on a manmade-soft rock model ground made of a mixture of gypsum and diatom. Meanwhile, the model test results are also simulated by a 2D finite element analysis based on an elasto-viscoplastic model with strain softening. The simulated results obtained in this study indicate that the finite element analysis based on a suitable constitutive law can appropriately describe the mechanical behavior of model tunnel subjected to uniform vertical loading. As to the creep failure test in which a constant uniform vertical loading is applied on the surface of model ground, the long-term deformation behavior of tunnel can be simulated qualitatively by 2D analysis. In order to get more accurate numerical results, 3D analysis is preferred, which should be done in the near future.

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