# Evaluation of Deformational Behaviors during the Large-scale Underground Cavern Excavation in Soft Rock by Creep Analysis

Obayashi Corporation , Civil Eng.Technology Div., Member Pornkasem JONGPRADIST
Obayashi Corporation , Civil Eng.Technology Div., Member Kunifumi TAKEUCHI
Obayashi Corporation , Civil Eng.Technology Div., Member Tomoyuki SHIMURA
The University of Tokyo, Dept. of Civil Engineering, Member Hideyuki HORII

## 1. Introduction

Efficient technologies for constructing underground cavern in soft rock formations have been recently needed because of increasing demands to utilize underground space in urban areas. An appropriate analysis method, which could represent soft rock behaviors, is one of key issues.

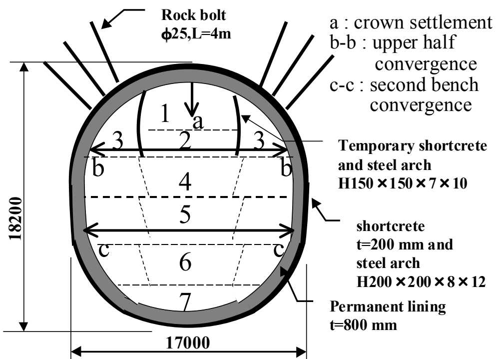



**Fig.1** Typical cross section with construction and measurement details

The large-scale NATM tunnel in soft mudstone was excavated for the purpose of emergency water storage in case of severe rainfall in metropolitan Tokyo[1]. The tunnel cross section, support system, measurement items and their locations and excavation sequences are roughly illustrated in Fig.1. Its cross section area is about 254 $m^2$ in which only a few tunnels with such large-scale area in soft rock have ever existed in Japan. During excavation, rock deformations at both side walls unexpectedly increased and such behaviors could not be predicted by the normal numerical analysis in advance for designing tunnel supports[2),3)]. Fig.2 shows the comparison between measured tunnel convergence at springline and result from conventional analysis.

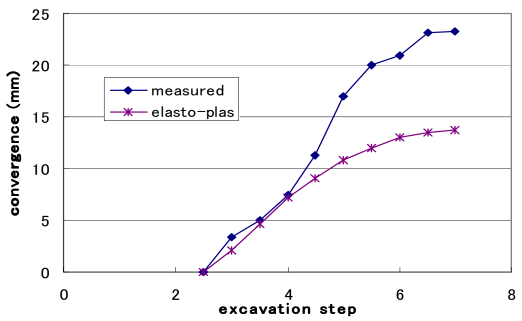



**Fig.2** Comparison between measured tunnel convergence at upper half excavation and analyzed one from conventional analysis

It is well known that soft rocks exhibit the time dependent behavior. Normally, large-scale caverns are excavated in stepwise procedure, which takes time during each excavation step and it is quite often observed the increases of tunnel displacements even in case of no additional excavation. In this study, creep is considered as the mechanism of that tunnel trouble and creep analysis is then carried out.

## 2. Creep constitutive model

In order to reproduce time dependent behavior in soft rock, a creep constitutive model developed for tunnel excavation in soft rock[4)] is adopted in this study. Here, the creep constitutive equations will be briefly summarized.

The dependence of the creep behavior of soft rock on the stress state must be properly modeled. It is treated in the constitutive model with an equivalent stress $\bar{\sigma}$ and in this study we define it as,

$$\bar{\sigma} = \frac{1}{2\cos\phi^*}\left[\sigma_{max}\left(1+\sin\phi^*\right)-\sigma_{min}\left(1-\sin\phi^*\right)\right] \quad (1)$$

where ϕ* is a material parameter which is different from the internal friction angle. The physical meaning of the equivalent stress is shown in Fig.3.

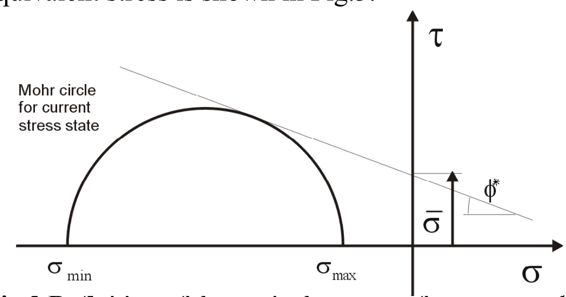



**Fig.3** Definition of the equivalent stress for creep model in this study.

To formulate a creep constitutive equation, an equivalent creep strain is defined as

$$\dot{\bar{\varepsilon}}^c = \sqrt{\frac{2}{3}\dot{\varepsilon}^c_{ij}\dot{\varepsilon}^c_{ij}} \quad (2)$$

---

**Key words** : soft rock, large-scale, underground cavern, creep analysis, deformational behaviors
**Contact address** : 2-15-2 Konan, Minato-ku, Tokyo 108-8502, Tel. (03)5769-1309, Fax. (03)5769-1977

By adopting the flow rule in theory of plasticity, the creep flow rule is given by

$$\dot{\varepsilon}^{c}_{ij} = \lambda \frac{\partial g}{\partial \sigma_{ij}} \qquad (3)$$

where λ is a scalar function which represents the dependence of creep strain rate on the stress, strain and time. The second invariant of deviatoric stress, $J_2$, is selected for the creep potential g.

$$g = J_2 \qquad (4)$$

A power creep law is introduced as a relationship between equivalent creep strain, equivalent stress and time. The following simple relationship is adopted in this study.

$$\bar{\varepsilon}^{c} = A\bar{\sigma}^{m}t^{n} \qquad (5)$$

where t stands for the time passed after the constant load is applied, A, m and n are material parameters. By this simple relationship, the experimental results of creep test using soft rocks from tunnel construction sites can be reproduced[4].

Equation (5) is for constant stress. To derive the constitutive relationship under arbitrary loading history, a hardening rule must be employed. In this study, time hardening is adopted for simplicity as,

$$\dot{\bar{\varepsilon}}^{c} = nA\bar{\sigma}^{m}t^{n-1} \qquad (6)$$

By substituting Eq.(3) with Eq.(4) into Eq.(2), the following can be derived with expressing the equivalent creep strain rate as:

$$\dot{\bar{\varepsilon}}^{c} = \lambda\sqrt{\frac{2}{3}s_{ij}s_{ij}} \qquad (7)$$

where $s_{ij}$ stands for the deviatoric stress tensor. From Eq.(7) and Eq.(6), λ is expressed in terms of current stress, current creep strain and time. Substituting it into the flow rule, the following creep constitutive equation is obtained

$$\dot{\varepsilon}^{c}_{ij} = \sqrt{\frac{3}{2}}\frac{nA\bar{\sigma}^{m}t^{n-1}}{\sqrt{s_{kl}s_{kl}}}s_{ij} \qquad (8)$$

The above equation is easily implemented into finite element codes as an analysis tool for tunnel excavation.

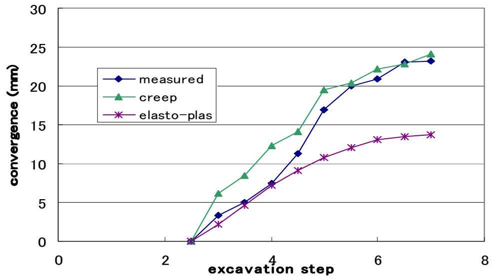
## 3. Creep analysis

Creep analysis of underground cavern excavation is carried out in this section. The material and creep parameters employed in the analyses are listed in Table 1. The stress reduction method is adopted to simulate the real 3D advancing process into 2D analysis and the actual time during each excavation step is also employed in the analyses. The material properties of both concrete lining and rock bolts are assumed to be linear elasticity.

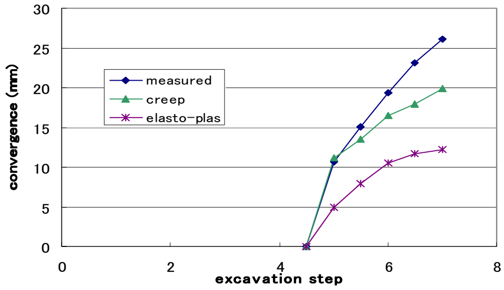
Comparisons of results of the creep analysis and measurement data are illustrated in Fig.4, which also includes the results from elasto-plastic analysis. The analyzed tunnel displacements at any location from creep analysis are reasonably close to the measured ones.

Table 1.Material parameters for soft rock

| notation | | unit |
|---|---|---|
| Elastic Modulus E | 5000 | $kgf/cm^2$ |
| Poisson`s ratio | 0.45 | |
| Density of soft rock | 1.87 | $g/cm^3$ |
| Creep parameters | | |
| A | $7.77*10^{-6}$ | $(kgf/cm^2)^{-1.748}$ $min^{-0.33}$ |
| ϕ | π/15 | |
| m | 1.748 | |
| n | 0.33 | |




(a) Upper half




(b) Second bench

**Fig.4** Comparisons between measured tunnel convergence and analyzed ones from creep analysis

## 4. Conclusions

An analysis method employing a creep constitutive model for soft rock was implemented to analyze the excavation the large-scale underground cavern in soft sedimentary rock. Both the excavation sequence and time during each excavation step are obtained from the actual construction records. The analysis results are then compared with the measured tunnel displacements. It is indicated that the analysis method employing the creep model could improve prediction of tunnel deformational behaviors.

### References

1) The Japanese Technical Association of Tunnel : *Special Committee Report of the Second Meeting on Onmawashi Water Storage Project, December 1999.* (Japanese)
2) Himura, H. et al.: NATM for large-scale urban underground of 254 $m^2$ cavern, *J. Tunnels and Underground Construction*, October 2000, pp.37-48 (Japanese)
3) Himura, H., Goshima, H. and Tsushima, S. : Construction of a large-scale tunnel in sedimentary soft rock near a residential area – Onmawashi-Koen regulating reservoir, *The Proceedings of Rapid Excavation and Tunneling,* 2001, pp. 411-420.
4) Jongpradist, P. et al. : A creep model for soft rock, International Journal forNumerical and Analytical Method in Geomechanics (submitted)