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Numerical analysis to evaluate repair work of swelling-rock damaged tunnels in the mountains using *FLAC*

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1 INTRODUCTION

1.1 *Overview of the tunnel*

This tunnel was constructed through a mountain with an altitude of about 2000 meters to improve the convenience of local transportation in Fukushima Prefecture. It is 4 km long and serves some of the local arterial roads.

1.2 *Tunnel deformation*

In this tunnel, uplift of the pavement surface was confirmed after service was started. After that, field surveys, onsite monitoring and laboratory tests were carried out, and one of the causes of the deformation was pointed out: in addition to progressive deterioration of the ground due to tunnel drilling, the influence of groundwater infiltration from the around tunnel and absorption swelling due to groundwater supply.

1.3 *Consideration on tunnel deformation*

Based on such tunnel deformation and geological condition around the tunnel, we made a model to simulate the damage mechanism of the tunnel to help us consider the method of repair and the reconstruction design. We also developed a numerical simulation model by using *FLAC* (Itasca 2016) that considered the absorption swelling of the ground, calculated the assumed external force by swelling, and examined repair and reconstruction design based on the *FLAC* result.

2 SETTING SWELLING MODEL

2.1 *Overview of swelling model*

There are several existing swelling models for tunnels. One model that requires setting of multiple model parameters (Yashiro et al. 2009), and other models that require assumption of the swelling range before modeling (Okui et al. 2009). For practical use, it is desirable that the model is easy to handle and does not require assumptions in advance. When using this model, the user can easily set parameters by onsite monitoring data and laboratory test data. Also, in this model, setting of the swelling range is unnecessary.

2.2 *Feature of swelling model*

The mechanism of this model is that the elastic module of the ground decreases with increasing in the swelling strain caused by the swell of the ground.

In this model, the relationship between the stress after swelling, the elastic module, and the swelling strain is shown in Equation 1.

$$\{\sigma\}=[D_0 \exp(-a\varepsilon_v)(\{\varepsilon\}-\{\varepsilon_0\}) \quad (1)$$

where, $\{\sigma\}$:swelling stress after swelling, $[D_0]$:elastic module, a:any value, ε_v: volumetric swelling strain ($\varepsilon_v=\varepsilon_x+\varepsilon_y$) ,$\{\varepsilon\}$:actual strain, $\{\varepsilon_0\}$:swelling strain that given value.

As shown in Equation 2, $[D_0]\exp(-a\varepsilon_v)$ which is the part of the elastic module corresponding to the volumetric swelling strain of Equation 1, can be obtained from the results by using the curve of swelling test results. Therefore, the elastic module decreases exponentially in accordance with the volumetric swelling strain, and the ratio of the reduction is in accordance with parameter a.

$$[E]=[D_0]\exp(-a\varepsilon_v) \quad (2)$$

Substituting Equation 2 into Equation 1 yields Equation 3.

$$\{\sigma\}=[E](\{\varepsilon\}-\{\varepsilon_0\}) \quad (3)$$

According to Equation 3, the elastic module corresponding to the swelling strain commensurate with the actual strain is set by the curve shown in Figure 1, and as a result, the swelling stress considering swelling strain is calculated.

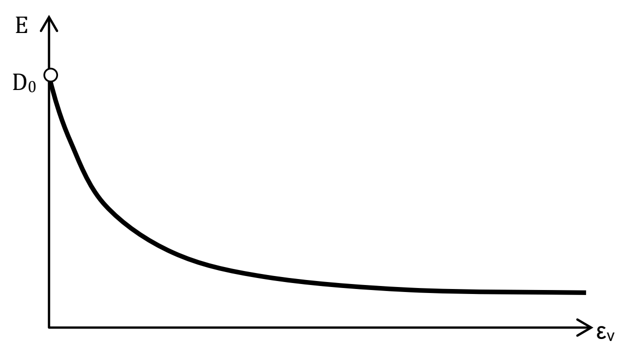


Figure 1. Relationship between the volumetric swelling strain and the elastic module.

3 APPLICATION TO TUNNEL

This section covers the result of applying to the actual tunnel using the created swelling model.

3.1 *Parametric analysis due to differences in swelling range and supportive work*

Three cases were set for parametric analysis as shown in Table 1.

Table 1. Case setting in parametric analysis.

Case number	Model conditions
Case1	The swelling area was set around the tunnel.
Case2	The swelling area was set a part of the tunnel periphery. Each case does not have tunnel structure.
Case3	A support structure and invert concrete were set in the tunnel and a part of invert concrete was set with a scratch*, so the inverted concrete was deformable to the inner side.

* Removed one invert element in the *FLAC* model to represent a partial loss of invert.

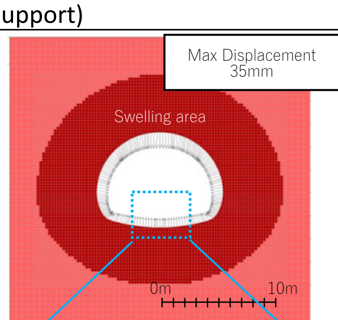
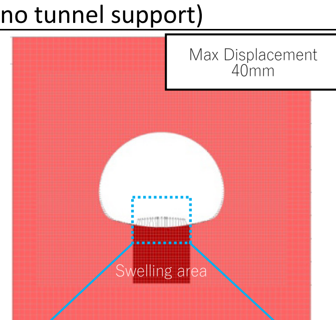
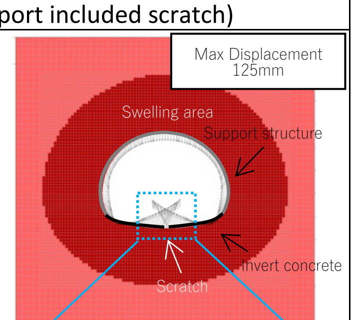
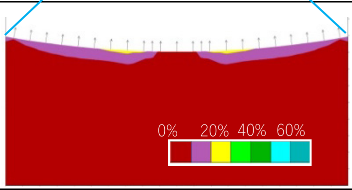
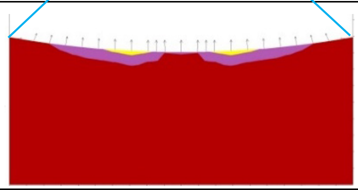
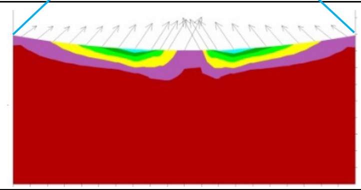
The upper part of Table 2 shows the amount of displacement after swelling and the lower part shows the ratio of volumetric swelling.

As a result of the analysis, Case 1 shows a substantially uniform displacement distribution around the entire circumference of the tunnel. Case 2 has a displacement distribution centered on the swelling range. There is no difference in the volume swelling ratio in each case, but the maximum displacement is larger in Case 2 than in Case 1. As a reason of the difference between the two cases, the uniform displacement distribution occurs in the whole circumference of the tunnel in Case 1; on the other hand, since the swelling range of Case 2 is smaller than Case 1 and localized, as a result, maximum displacement in Case 2 is larger than Case1. Also, in Case 3, maximum displacement at the scratch point is larger than Case 1 with the same swelling range and distribution of the volume swelling ratio is larger than Case 1 around the scratch point.

In this way, even if the swelling range is the same, when it has a tunnel support and local scratches, both the maximum displacement and the ratio of volumetric swelling are larger than when there is no tunnel support.

This is one of the important features of this model. The behavior of this model is consistent with the general mechanism where the stress concentrates on the weak part of the tunnel and is considered to be a feature indicating the validity of the developed model.

Table 2. The results of parametric analysis.

	Case1 the swelling area was set around the tunnel (no tunnel support)	Case2 the swelling area was set a part of the tunnel periphery (no tunnel support)	Case3 the swelling area was set around the tunnel (tunnel support included scratch)
Displacement			
The ratio of volumetric swelling			

3.2 *Application to remodeling repair design*

Using the swelling model, we examined the swelling pressure and set the external force condition of the tunnel's design

In this tunnel, there was a deformation at the roadbed and the tunnel lining due to the swelling rock. Also, several measuring devices were installed to get rock deformation data around the tunnel. By using this monitoring data, the relationship between the swelling ratio and the elastic module was set.

We modeled the tunnel shape and applied the swelling pressure to the tunnel using the relationship between the swelling ratio and the elastic module. As a result, the distribution of the section force generated in the tunnel was obtained as shown in Figure 2, and this section force was used to decide the repair design. The dotted line shown in Figure 2 indicates the reconstruction tunnel specification.

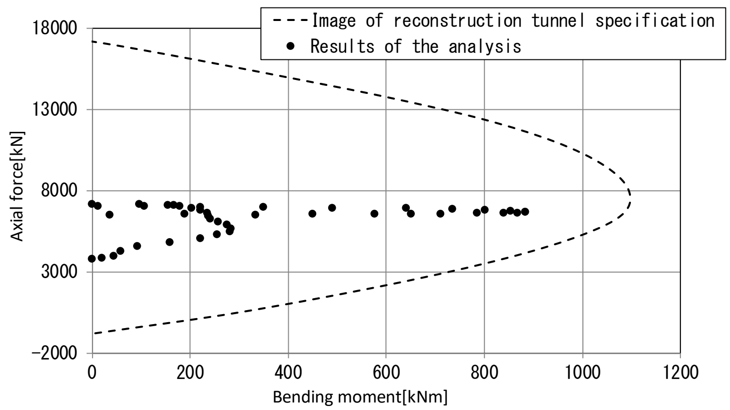


Figure 2. The distribution of the section force and the reconstruction tunnel specification.

4 SUMMARY OF RESULTS

From the examination using the created swelling model, the following conclusions were drawn:

- We developed a numerical simulation model, which considered the interaction between the swelling pressure of the rock and the tunnel structure using the rock deformation due to swelling characteristic of the rock. It was confirmed that this model showed the basic behavior as observed in the laboratory test.
- By applying the model to the actual tunnel and examining the characteristics of the model, it was shown that this model was consistent with the general mechanism that the swelling pressure concentrated on the weak part of the tunnel due to the influence of the swelling pressure.
- In addition, we examined the reconstruction design of the mountain tunnel under service. We investigated swelling pressure by using the model. As a result, we decided on the repair design that included the distribution of section force obtained by analysis

5 FUTURE DIRECTIONS

In this study, the adequacy of the swelling mechanism assumed from the field survey results was verified by using the developed swelling model and simulation model.

Since the developed model was able to reflect the site situation, we plan to improve the model using monitoring data and to proceed with the reconstruction tunnel design using the model in the future.

REFERENCES

Itasca Consulting Group, Inc. 2016. *FLAC – Fast Lagrangian Analysis of Continua, Ver. 8.0*. Minneapolis: Itasca.

Okui, Y., Tsuruhara, T., Ohta, H., Sakuma, S. & Nakata, T. 2009. Analysis of heaving behavior in Sakazukiyama road tunnel under use. *Tunnel Engineering Journal*, Vol.19. (In Japanese)

Yashiro, K., Shimamoto, K., Kojima, Y., Takahashi, K., Matsunaga, T. & Asakura, T. 2009. Study on simulation analyses of deformed tunnels due to earth pressure by ground strength deduction model and it's applicability to long term prediction. *Journal of Japan Society of Civil Engineering*, Vol.65, No.1. (In Japanese)