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Long-term Stability Evaluation for Foundation Material using Creep Analysis

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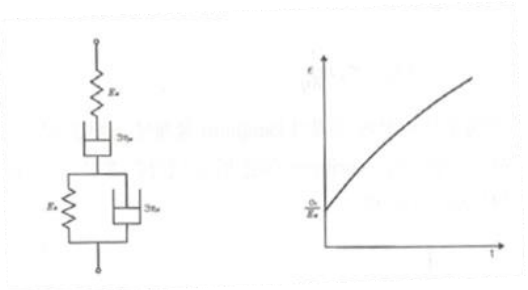
1. Introduction

The rock specimen under constant maintained load for a long time shows the time dependent deformation characteristics, creep. Time dependent deformation can be thought as the results from viscous characteristics such as viscoelastic and viscoplastic behavior. According to these behavioral characteristics, creep is divided into Maxwell model and Kelvin model. In view of these two models, long-term behavioral characteristic of the foundation under constant maintained load is analyzed and applied for the evaluation of heavy building foundation’s long-term stability.

2. Methods

Creep strain model used in common rock mass generally follows the Burger body model. In Burger model, the Maxwell model and the Kelvin model are connected in series as shown in Fig. 1.



a. Mechanical model b. when the load is applied

Fig. 1. Burgers body

2.1 Maxwell Model

The concept of Maxwell model is that if the stress is applied to a body, the stress is distributed to each component equally and the total strain is equal to the sum of the strain to each component. In case that the stress is maintained constantly, strain can be expressed as Eq. 1 below

$$\epsilon = \frac{\sigma_0}{E} + \frac{\sigma_0}{3\eta} t \qquad \text{Eq. (1)}$$

And $\frac{\sigma_0}{E}$ of Eq. 1 is integral constant which means elastic strain occurred at t=0.

When the stress is applied to Maxwell body under constant maintained load, elastic strain will occur after that, the strain rate is continuously increased with time by a dashpot action. When the stress is eliminated the elastic strain rate will be recovered right after but the viscous strain rate will remain as a permanent strain.

2.2 Kelvin Model

The concept of Kelvin body is that the total stress subjected to the body is equal to the sum of each stress acting on each component. The strain occurs at Kelvin body and that occurs at each component are equal. Therefore, if the stress is applied constantly, Eq. (2) can be obtained.

$$\epsilon = \frac{\sigma_0}{E_K}\left(1 - exp\left(-\frac{E_K}{3\eta_K} t\right)\right) \qquad \text{Eq. (2)}$$

According to Eq. (2), spring-caused elastic strain will not occur at the moment that the stress is applied but it exponentially approaches to the ultimate elastic strain by dashpot. When the stress is eliminated, the strain will not be recovered promptly owing to dashpot instead, it will decrease exponentially with unlimited time.

2.3 Burgers Model

The Burgers model connecting two rheological models in series can be expressed as shown in Eq. (3)

$$\epsilon = \frac{\sigma_0}{E_M} + \frac{\sigma_0}{3\eta_M} t + \frac{\sigma_0}{E_K}\left(1 - exp\left(-\frac{E_K}{3\eta_K} t\right)\right) \text{ Eq. (3)}$$

According to Eq. (3), when the stress is subjected to the Burgers body, the strain occurs instantly by the spring comprising the Maxwell body and the stress is acting on continuously, the strain by the dashpot of Maxwell body is added to the strain of Kelvin body, finally the total strain will increase non-lineally.

When the stress is eliminated, elastic strain caused by the spring of Maxwell body will be recovered instantly, and the strain caused by Kelvin body will be recovered exponentially with unlimited time. But the strain caused by dashpot of Maxwell body will be left as permanent strain [1, 2].

2.4 Strain Curve

Fig. 2 shows the time-dependent strain curve when 80% of the uniaxial strength is loaded continuously to the body. The strain curve has three stages with time.

Primary creep, the strain diminishes with time (transient creep). Secondary creep, the strain is constant (steady state creep). Tertiary creep, the strain increases with time (accelerating creep) and eventually rupture occurs.

When 70~80% of the ultimate uniaxial compressive strength is applied to the body for long time, generally the unstable tertiary creep could not be avoided. However, in most cases under less than 60% of uniaxial strength, secondary creep where strain rate change will not occur is maintained continuously [3].

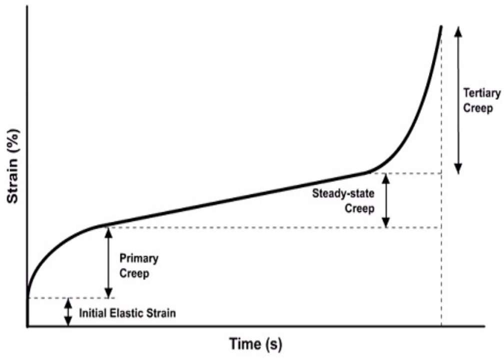


Fig. 2. Typical strain vs. time curve for the uniaxial creep test

3. Strain Curve Analysis

Fig. 3 and Fig. 4 show the settlement amount and strain-time curve for Wolsung-1 reactor containment building for about 36 years. Using these long-term settlement data, we analyzed the creep strain for the containment building foundation material under constant load. The resulting strain curve shows two types, one is primary creep probably caused by plastic deformation of fractures and pores in rock and the other is secondary creep caused by constant loading after primary creep which continues to present.

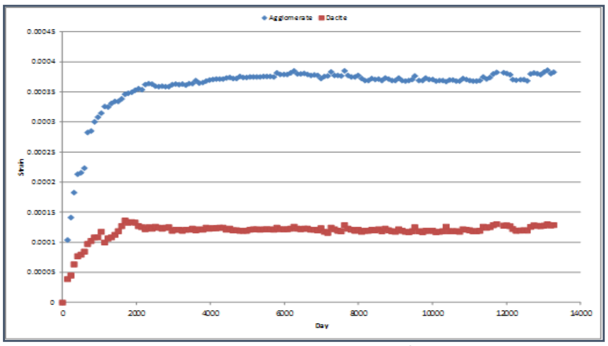


Fig. 3. Settlement variance with time for Wolsung-1 NPP containment building

The settlement amount for dacite area shows far below the allowable limit value and shows stable secondary creep characteristics. For the agglomerate area, the settlement amount is larger than those of dacite but it still within the allowable limit value and shows stable secondary creep characteristics too.

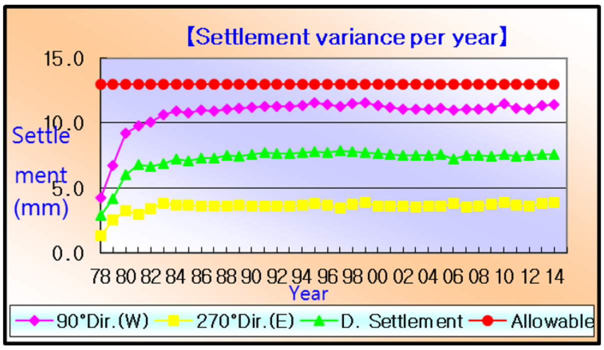


Fig. 4. Strain-time curve for Wolsung-1 NPP containment building foundation rock, agglomerate (blue curve) and dacite (red curve)

The loaded stress calculated at the time when the construction started is 0.36MPa and it is assumed that this stress is loaded to the two types of foundation rock areas, agglomerate and dacite, equally to the present. Under this assumption, creep strain rate can be calculated and rock deformation and coefficient of viscosity can be obtained.

3.1 For agglomerate area:

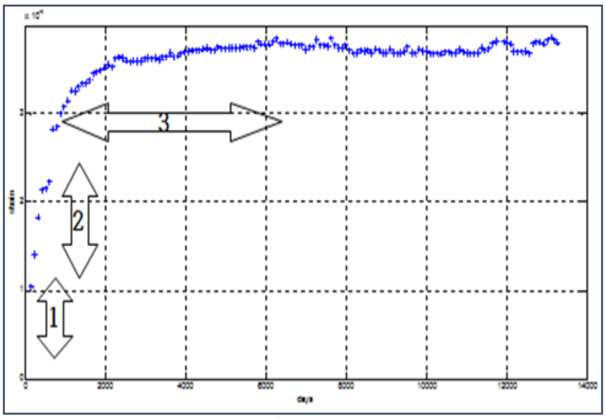


Fig. 5. Strain-time curve for Wolsung-1 NPP containment building foundation agglomerate

As shown in Fig. 5, strain-time creep curve for agglomerate is analyzed for three areas. The linear part corresponding to 1 and 2 is the deformation parts by Maxwell body, which shows the strain caused by fractures and pores in agglomerate by the containment building load. Using the lease-square regression equation, the intercept and the gradient for the creep 1 and 2 area is obtained and then Maxwell deformation modulus EM and the viscosity ηM are calculated as follows;

EM = 7200 MPa, $\eta M = 2.6\times10^{16}$ Pa·sec

The strain of creep 3 area passing after the initial linear area is caused by Kelvin body, and is analyzed by linear regression equation using least-square method (Fig. 6).

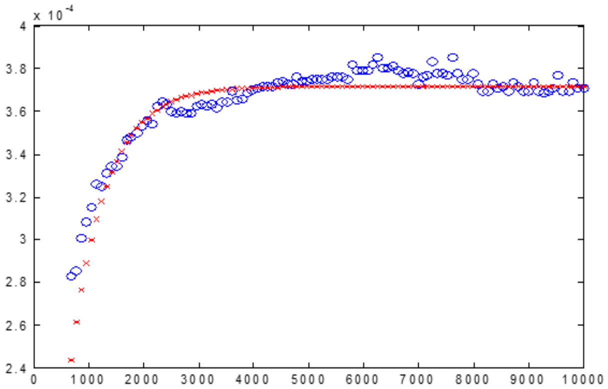


Fig. 6. The non-linear regression analysis result for Kelvin model application area

Using above method, the Kelvin deformation modulus Ek and the viscosity ηK are calculated as below.

Ek = 995 MPa, $\eta K = 1.83\times10^{16}$ Pa·sec

3.2 For dacite area

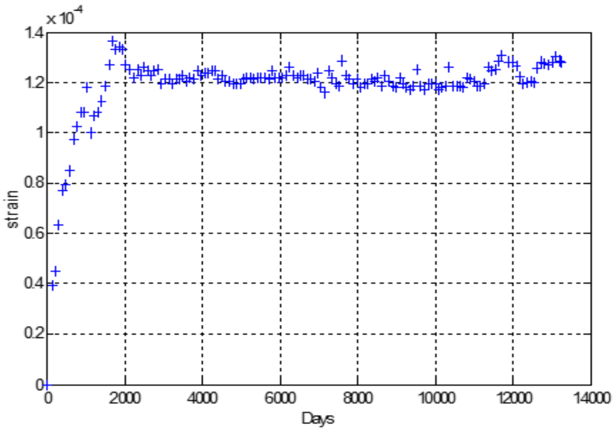


Fig. 7. Strain-time creep curve for dacite area

As same as agglomerate area, initial linear area is controlled by Kelvin body. After calculating the intercept and the gradient in this area using linear regression equation with least-square method, we obtained the Maxwell deformation modulus EM and viscosity ηM as follow;

EM = 12,000 MPa, $\eta M = 1.3\times10^{17}$ Pa·sec

The inflection area passing after the initial linear area of creep curve and the secondary creep area corresponds to the strain by Kelvin body, and the following results shown in Fig. 8 can be obtained using linear regression equation with least-square method. The Kelvin deformation modulus Ek and viscosity ηK is calculated as follows;

Ek = 3062 MPa, $\eta K = 4.8\times10^{16}$ Pa·sec

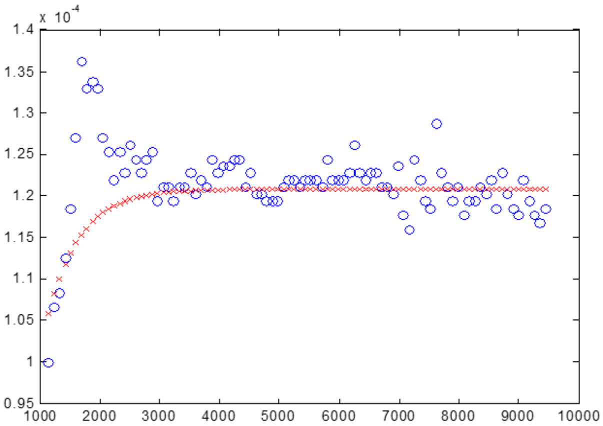


Fig. 8. The non-linear regression analysis result for Kelvin model for dacite area

4. Conclusions

Under the assumption that the building load calculated 0.36MPa is applied constantly after the building was constructed and the settlement has occurred, we analyzed the creep curve with strain-time and then calculated the deformation modulus and the viscosity for dacite and agglomerate. For primary creep area, Maxwell model was applied considering initial strain. For secondary creep area, Kelvin model was applied. We calculate the deformation modulus and viscosity for each model by regression analysis suitable for each model.

For agglomerate, the following were obtained:

EM = 7,200 MPa , $\eta M = 2.6\times10^{16}$ Pa·sec

Ek = 995 MPa, $\eta K = 1.83\times10^{16}$ Pa·sec

For dacite, the following were obtained

EM = 12,000 MPa, $\eta M = 1.3\times10^{17}$ Pa·sec

Ek = 3,062 MPa, $\eta K = 4.8\times10^{16}$ Pa·sec

Maxwell deformation modulus and the viscosity arose from initial strain of Maxwell model, reflecting the fractures and pores of rocks, and the strain by deformation modulus EM shows the elastic deformation but the deformation by viscosity ηM is considered as permanent deformation. The deformation caused by deformation modulus of Kelvin model within secondary creep area is elastic deformation and is considered to show viscoelastic deformation recovered into original state through much long period. In other word, the viscosity for the permanent viscoelastic deformation shows more than 10^{16}, which interpreted that the viscous deformation is very small and most deformation is caused by elastic deformation.

The deformation modulus for agglomerate and dacite supplied by CANATOM Ltd. at the initial stage of construction are as shown below;

-Agglomerate (Estat-long term) = 34,230psi (=240 MPa)

-Dacite (Estat-long term) = 151,053 psi (= 1040 MPa)

The Kelvin deformation modulus of agglomerate and dacite calculated by creep curve analysis is 4 times more and 3 times more than the expected strain at the initial stage of construction for each rock. The difference of deformation modulus between the initially expected and the calculated by creep curve analysis can be approved by the results that the strain occurred to the present shows less value than the initially expected strain. Strain occurred to the present is 24.7% and 36.8% compare to the initially expected strain for agglomerate and dacite, respectively, which are still within the allowable limit and tend to be convergent to the present settlement amount.

Conclusively, we calculated the deformation modulus and viscosity of agglomerate and dacite at Wolsung-1 NPP foundation using the creep curve, on the condition that the relationship between the str ain curve and settlement with constant maintained load shows the creep deformation and the strain occurred to the present, and evaluated that the deformation is elastic deformation.

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