RELIABILITY ANALYSIS OF NUMERICAL SIMULATION IN NEAR FIELD BEHAVIOR

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The uncertainties of the boundary conditions, the elastic modulus and Poisson's ratio on the mechanical behavior at near field of high level radioactive waste repository were examined. The method used to examine the error propagation was the first order second moment method. The reliability of the maximum principal stress, maximum shear stress at crown of the tunnel and the minimum principal stress at spring line was examined for one million years. For elastic model, the reliability of the maximum shear stress gradually decreased while that of the maximum principle stress increased. That of the minimum principal stress was relatively low for one million years. This tendency was similar to that from the damage model.

Key Words : *high level radioactive waste disposal, uncertainty analysis, near field, mechanical behavior*

1. INTRODUCTION

To safely dispose of the high level radioactive waste (HLW), the repository is composed by multi-barrier system. In Japan, the waste is planed to be surrounded by the highly compacted bentonite as a buffer material. The repository is planned to be set at the deep geology under 300 m from the ground level¹⁾. The waste will be isolated from the human activity for very long time. The safety of the repository has to be ensured for a long period.

The geological environment may change for a long period. The average displacement velocity of active faults in Japan is considered to be in a range of about 0.01-10 meters/1000years²⁾. Moreover, the uplift and denudation are the gradual processes that generally extend over an extremely long period. The uplift speed in the Quaternary period is considered to be from 0.5 mm / year to 1.0 mm / year for most regions of Japan³⁾. The cycle of cold and warm period, which affects the sea level change, is about

100,000 years⁴⁾. In addition to these kinds of large and long scale change, Japan has the various types of rocks which are distributed irregularly. Therefore, the change in geological environment may be very specific locally, which will cause the uncertainty in the prediction of the safety of the repository.

While the above discussion is related to the geological condition, the near field of the repository has the other uncertainty related to the repository design. The waste generates a heat for a long period and the groundwater level recovers after closing the repository. The phenomena of the far field have an effect on the boundary conditions of the near field. The stability of the ground around the repository tunnel will be affected by the change in the boundary conditions. To discuss the stability of excavation disturbed zone (EDZ), the international cooperative study, DECOVALEX (DEmonstration of COupled models and their VALidation against EXperiments) - THMC project takes place to support the development of mathematical models of the coupled thermal, hy-

draulic, mechanical and chemical processes in geological media⁵⁾.

In the task of the project, the effect of chemically degraded properties on the stability of rock around the repository tunnel was discussed. Among possible various chemical phenomena, the effect of sea water was focused on. This is because a few repositories in the world are planned to be built at the coastal area at present. In the task, the examination of uncertainty was also one of the subjects. In this paper, the results examined for the subject are presented.

As mentioned earlier, while there are many uncertainties related to the stability of the repository tunnel, the effects of the change in boundary conditions of near field on the behavior of EDZ are focused on in this study. Uncertainties related to the simulation of ground behaviors arise from two sources: the scatter of properties, and the systematic error in properties and problem establishment. The latter contributes to the numerical evaluation differently from the former because the spatial variability of the parameters averages over the regional volume of ground while the systematic error is constant. Therefore, the systematic error propagates almost unchanged through the analysis and can have a greater influence on predictive uncertainty than does spatial variability⁶⁾. The systematic error consists of errors of the sampling process, bias in the measurement, estimation of boundary conditions and so on. However, the study about the propagation of systematic error has not been carried out for HLW project. On the other hand, the uncertainty induced from the scatter of properties has been examined so much. In particular, the effect of heterogeneity of permeability on the safety assessment has been discussed well⁷⁾. Moreover, the upscaling method of the permeability from small to large region has been studied well⁸⁾. This is related to the uncertainty of the model of the distribution of the parameters used in the numerical calculation. In this study, the systematic error of boundary conditions at the near field of HLW repository is examined by using the reliability analysis. This is probably the first approach to examine the systematic error for HLW project.

The boundary conditions of the near field change for a very long period. In this study, the boundary conditions for one million years are estimated from the results of simulation of far field. The variances of the boundary conditions are estimated from variation for one million years. This procedure may give a larger estimation of the variance than the case that only the effect of the different waste composition is considered. In addition to the influence of the boundary conditions on the uncertainty of the mechanical behavior, the effect of the fundamental mechanical properties, the elastic modulus and

Poisson's ratio, is also examined. Moreover, the difference of uncertainties due to the different analysis model is also discussed by comparing the results from the elastic model and the damage expansion model.

2. VARIANCE AND CORRELATION OF VARIABLES

(1) Boundary conditions of near field

The boundary condition of near field was obtained from the results of far field model⁹⁾. The far field model had a vertical depth of 1000 m and horizontal length of 35 m. The repository tunnel was excavated at the depth of 500 m. As a rock, a crystalline rock such as granite is assumed. The initial horizontal stress was given as $\sigma_h = 0.055d + 4.6$ MPa, and the initial vertical stress was $\sigma_v = 26487d$ Pa, where d was the depth from the ground surface with a unit of meter. The vertical thermal gradient was 30°C/km with a fixed temperature of 10 °C at the ground surface. The groundwater table was fixed at the ground level and the fluid pressure at the bottom boundary was set at 9 MPa. Under the above conditions, the repository tunnel was excavated in one-step. After excavation, the waste and the bentonite buffer were installed instantaneously. Post-closure simulation was carried out by considering the heat generation from the waste and the constant swelling pressure of buffer material. Thermal, hydraulic and mechanical behavior of surrounding rock mass was calculated for one million years. **Fig. 1** shows the obtained boundary conditions of near field from the analysis of far field. In this study, the variation of boundary conditions for one million years is considered.

(2) Variance and correlation

The boundary conditions are considered as a variable for the examination of uncertainties of the behavior of near field. **Fig.2** shows the model of near field. The size of vertical boundary is the same as that of the horizontal one. The vertical, the horizontal and the radial stresses obtained from the far field examination are used as the boundary conditions, and the temperature and the fluid pressure are applied to the entire region of near field model as an interior condition, meaning that the transfer of heat and fluid pressure is not considered in the near field model. The effect of these variables on the behavior of near field is examined in this study.

The correlation coefficients of five variables: the inner conditions of temperature T and fluid pressure P , and the boundary conditions of vertical stress σ_v ,

(a) Stress evolution

(b) Fluid pressure and temperature evolution

Fig. 1 Conditions of near field model **Fig.2** Model of near field analysis

σ_h : Horizontal stress, σ_v : Vertical stress, σ_r : Radial stress, P : Fluid pressure, T : Temperature.

Table 1 Correlation coefficient of boundary conditions

	σ_v	σ_r	P	T
σ_h	0.829	0.629	-0.590	-0.870
σ_v	-	0.347	-0.280	-0.930
σ_r	-	-	-0.996	-0.21
P	-	-	-	0.15

Table 2 Standard deviation and increment of each variable

	σ_h (MPa)	σ_v (MPa)	σ_r (MPa)	P (MPa)
SD	5.2	1.7	4.8	2.0
Δx	1	1	0.02	0.01

	T (°C)	E (GPa)	ν
SD	16	21	0.03
Δx	3	0.1	0.001

SD: Standard deviation, Δx : increment

Table 3 Elastic parameters used for examination

Parameter	Value
Elastic Modulus	70 GPa
Poisson's ratio	0.3
Thermal expansion coefficient	$1 \cdot 10^{-5} \text{ } ^\circ\text{C}^{-1}$

horizontal stress σ_h and radial stress σ_r , are calculated from the temporal change shown in **Fig.1**. The result is shown in **Table 1**. It is found that temperature has a high correlation with the horizontal and the vertical stresses, and the fluid pressure has high correlation with the radial stress.

While the variance of the stress boundary conditions has to be evaluated from the past measured results of in-situ stress, the measurement giving the information on the variance of in-situ stress have not been obtained. However, since the boundary condition will vary with time during the evaluation period as shown in **Fig.1**, the variance of the boundary conditions is estimated from the temporal variation for simplicity. **Table 2** shows the standard deviation of each variable. As shown in the table, the standard deviation of each variable is relatively high and there is a wide variation among variables. Even if the case that the different wastes are stored in the repository is examined, the relation among the variables from temporal change would be appeared similarly. In the table, the standard deviation of elastic modulus and Poisson's ratio is also indicated. For the examination of the uncertainty of the mechanical behavior of near field, the effect of two parameters is evaluated. The standard deviation of elastic modulus is estimated to be 30 % of the average by referring the result of Lee, *et al.*¹⁰⁾. While that of Poisson's ratio has not been known well, the standard deviation is assumed to be 10% of the average. **Table 3** shows the mean elastic parameters used for examination. Since the effect of thermal expansion coefficient is the same as that of elastic modulus in this problem, the effect of the thermal expansion coefficient is not examined in this study.

In **Table 2**, the increment of each variable is also indicated. The increment is used to evaluate the partial derivatives by numerical differentiation. The increment of radial stress and fluid pressure is small

in comparison with that of horizontal and vertical stresses. This is because the fluid pressure and the radial stress are very small at the beginning as shown in **Fig. 1**. The increment of elastic modulus and Poisson's ratio is set at a small value to reduce the error of partial derivatives.

Although the comparison with the damage expansion model is carried out in this study, the effect of damage parameters on the results is not examined. This is because the resultant variance increases with increase of the number of variables. The damage parameters are assumed to be correct. The effect of seven variables, vertical, horizontal and radial stresses on the boundary, temperature and fluid pressure in the region, elastic modulus and Poisson's ratio, is examined to evaluate the uncertainty of the mechanical behavior at the near field for one million years.

3. FIRST ORDER SECOND MOMENT METHOD

There are some methods to examine the reliability index and the probability of event such as the point estimate method¹¹⁾, Hasofer-Lind method¹²⁾ and Monte Carlo simulation. In this paper, the first order second moment method is applied. This is because this method can examine the effect of each variable. Christian, *et al.*¹³⁾ applied this method to examine the stability of the dikes.

Examination of uncertainty is to evaluate the error propagation of each variable. The error of the variables propagates through the calculation and affects the final result. The result of the calculations can be considered to be a function g of the several variables. The variables $(X_1, X_2, \dots, X_n)$ are evaluated at some values $(x_1, x_2, \dots, x_n)$. Thus,

$$g = g(x_1, x_2, \dots, x_n) \quad (1)$$

The first order of Taylor's series for multiple variables gives

$$g(x_1, x_2, \dots, x_n) \approx g(\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn}) + \frac{1}{1!} \sum_{i=1}^n (x_i - \mu_{Xi}) \frac{\partial g}{\partial x_i} \quad (2)$$

The partial derivatives are taken at $\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn}$. μ_{Xi} is the mean value of X_i . The expected value of g is assumed to be given by the value of the function calculated with the mean values of all the variables.

$$\mu_g \approx g(\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn}) \quad (3)$$

The variance of a function g is given from Equations (2) and (3) by

$$\begin{aligned} \sigma_g^2 &= E[(g - \mu_g)^2] \approx E\left[\left(\sum_{i=1}^n (x_i - \mu_{Xi}) \frac{\partial g}{\partial x_i}\right)^2\right] \\ &= \sum_{i=1}^n \sum_{j=1}^n \rho_{Xi Xj} \sigma_{Xi} \sigma_{Xj} \frac{\partial g}{\partial x_i} \frac{\partial g}{\partial x_j} \\ &= \sum_{i=1}^n \sigma_{Xi}^2 \left(\frac{\partial g}{\partial x_i}\right)^2 + \sum_{i=1}^n \sum_{j \neq i}^n Cov(X_i, X_j) \frac{\partial g}{\partial x_i} \frac{\partial g}{\partial x_j} \end{aligned} \quad (4)$$

The approximation sign replaces the equal sign because the higher order terms of Taylor's series are assumed to be small. The partial derivative in Equation (4) is calculated numerically by

$$\frac{\partial g}{\partial x_i} \approx \frac{\Delta g}{\Delta x_i} \quad (5)$$

While the central difference needs to increase and decrease the variable by a small amount, the differentiation is carried out by increasing the variable from the mean value. This is because the numerical efficiency is not good since each numerical calculation has to be carried out for one million years. The increment Δx used for each variable is shown in **Table 2**. The correlation coefficient among each variable is indicated in **Table 1** and the variance is obtained from the standard deviation in **Table 2**. **Fig. 3** shows the incremented horizontal stress. In this case, 1MPa is added to the value obtained from the far field analysis for one million years. The evolution of boundary conditions from far field analysis is considered as a mean value of boundary conditions. In similar way, the vertical and radial stresses, temperature and fluid pressure are incremented. While the increment of each variable has been suggested to be equal to the standard deviation, the value is set to be smaller than the standard deviation to reduce the error of the numerical differentiation. While the confirmation of the estimation error of the partial derivative is not carried out for the low numerical efficiency, the estimation error is expected to be small for the relatively small increment. In particular, since the increments of the elastic properties are set to be very small, the estimation error will be small. For the boundary conditions, while the increments of the horizontal and vertical stresses are relatively large, the effect of the increment of 1 MPa on the behavior of crystalline rock having the elastic properties shown in **Table 3** is expected to be very small. Even if the behavior is nonlinear, the difference of the occurrence of the nonlinearity by the increment of 1

Fig. 3 Incremented boundary condition of horizontal stress

MPa can be considered to be negligible. Contribution of variable X_i to the variance σ_g^2 is given by

$$\sigma_{X_i}^2 \left(\frac{\partial g}{\partial x_i} \right)^2 + \sum_{j \neq i}^n \text{Cov}(X_i, X_j) \frac{\partial g}{\partial x_i} \frac{\partial g}{\partial x_j} \quad (6)$$

If this contribution is large, it can be understood that the variable X_i has a large uncertainty for the result g . The reliability index of function g is given by

$$\beta = \mu_g / \sigma_g \quad (7)$$

When the reliability index is high, it can be understood that the uncertainty of the function g is low.

In this study, the behavior of near field of HLW repository is examined. Although the function g is usually the safety factor in the geotechnical problem, the safety factor of the ground around the repository tunnel is not a problem after closing the repository. It is more worried that the mechanical behavior of the ground causes a bad effect on the function to prevent the contaminant transport. As a function g , the maximum principal stress at the crown of the tunnel, the minimum principal stress at the spring line and the maximum shear stress at the crown are examined. This is because each stress has the highest value at the location in the elastic model. Moreover, the damage variable and the permeability at the crown, which are estimated from the damage analysis, are also examined. The difference from the result obtained by using the mean boundary conditions and mechanical properties is considered as Δg , which value is divided by the Δx shown in **Table 2** to obtain the partial derivative. In the examination of HLW disposal project, the examination period is very long. The boundary and interior conditions also change through a long period as shown in **Fig.1**. Therefore,

the contribution of each variable to the mechanical behavior may change temporally. To investigate the temporal change of contribution of each variable, the function g at 100, 1,000, 10,000, 100,000, 1,000,000 years after closing the repository is examined. Although the error of numerical differentiation may change through an evaluation period, that is assumed not to affect the examination so much.

4. NEAR FIELD MODEL

(1) Elastic model

To examine the fundamental effect of the uncertainty of each variable, the elastic model is applied. As mentioned earlier, the vertical, horizontal and radial stresses are used as a boundary condition, and the temperature and fluid pressure are applied to the entire region of near field model as an interior condition. In the calculation, the linear thermal expansion and effective stress are incorporated. While the result of model shown in **Fig.2** is difficult to compare with the theoretical one, the numerical approach was validated for the quadrilateral model by comparing with the theoretical displacement¹⁴⁾.

(2) Damage expansion model

In damage mechanics, the change in mechanical behavior due to the growth of damage (cracks) in material is considered¹⁵⁾. This behavior is expressed by means of damage variable D . The damage expansion model is based on the damage mechanics theory¹⁶⁾. For the isotropic damage evolution, the total stress, σ_{ij} - strain, ε_{ij} relation of damage expansion model is expressed by

$$\sigma_{ij} = (1 - D) \left\{ \left(\lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij} \right) - \frac{1}{3} \varepsilon_{kk}^v (3\lambda + 2\mu) \delta_{ij} \right\} - \delta_{ij} P - (3\lambda + 2\mu) \delta_{ij} \alpha \Delta T \quad (8)$$

where D is the damage variable, λ and μ are Lamé's constants. ε_{kk}^v is the volumetric strain induced by damage development. P is the fluid pressure, α is the linear thermal expansion coefficient, δ_{ij} is the Kronecker's delta, and ΔT is the increment of temperature. The damage potential Y_{eq} in relation to D is described as

$$Y_{eq} = K_d D^{n_d} + B_0 \quad (9)$$

where K_d and n_d are damage parameters, B_0 is the initial damage potential. Y_{eq} in relation to ε_{kk}^v is also assumed to be

$$Y_{eq} = K_v \left(\frac{1}{3} \varepsilon_{kk}^v \right)^{n_v} \quad (10)$$

K_d , n_d , B_0 , K_v and n_v are called the damage parameters. The damage potential Y_{eq} is equivalent to the elastic work. When Y_{eq} is larger than B_0 , the damage variable increases¹⁷⁾. Then, B_0 is updated to Y_{eq} . B_0 becomes the previous maximum damage potential. Therefore, the damage progresses when the elastic work is larger than the past maximum elastic work. It was confirmed that the relation of stress and axial strain and that of stress and volumetric strain at the uniaxial compression test were realized well by the damage expansion model with the identified damage parameters¹⁸⁾. In this study, the damage parameters are assumed to be correct. The uncertainty of elastic work induced from the error of elastic properties and boundary conditions will affect the damage development.

By using the volumetric strain due to damage development ε_{kk}^v , the change in permeability can be modeled. Now, let Δe_f be the average aperture increment of a single fracture due to damage development. This can be estimated by using the fracture density f and average fracture length L as

$$\Delta e_f = \frac{4\varepsilon_{kk}^v}{f \cdot L^2 \pi} \quad (11)$$

in which the shape of fracture is assumed to be a circle. Using the increment of the aperture of a single fracture, the equivalent permeability K_{eq} is written as following with the cubic law:

$$K_{eq} = \frac{\rho g_a (e_0 + \Delta e_f)^3}{12\mu_d} \cdot f \quad (12)$$

where μ_d is the dynamic viscosity, ρ is the density of water, g is the gravitational acceleration and e_0 is the initial aperture. The change in permeability due to damage development is estimated by the above equivalent permeability.

The damage parameters were obtained from the degraded rock sample submerged in saline water for 90 days¹⁹⁾. The tests were conducted on Ävrö granite from the Äspö Hard Rock Laboratory in Sweden. The damage parameters were quite objectively determined by the test results²⁰⁾. Y_{eq} was obtained by incorporating the unconfined compression condition. The damage variable D was estimated by the difference of stress from the stress- elastic axial strain relation. The expansive strain due to damage progress was also estimated by the difference of volu-

metric strain from the elastic volumetric strain. Then, by using the Equations (9) and (10), K_d , n_d , K_v and n_v were determined by the fitting process. The obtained values were $K_d=1.7\text{MPa}$, $K_v = 106\text{MPa}$, $n_d=0.8$ and $n_v=0.95$. The fracture density and length used for the examination are given in **Table 4**.

5. EXAMINATION RESULTS

(1) Elastic model

Table 5 shows the maximum principal stress at crown of the elastic case. In the table, 'Mean' is the case using the mean values for all variables. The column of variable indicates the incremented variable. When one variable is incremented, the other variables are set at the mean value. Similarly, **Tables 6** and **7** indicate the minimum principal stress at spring line and maximum shear stress at crown, respectively. As shown in the tables, the method using in this examination does not have an efficiency to examine the effect of temperature. The results are the same as the ones from mean variables. This is because the increment of temperature between time steps is the same as the mean case. Moreover, it is found that the effect of elastic modulus and Poisson's ratio appears for the maximum and the minimum principal stresses until 10,000 years so much. This is because the variation of the elastic parameters affects the thermal stress.

By using the results, the contribution of each variable to the variance is calculated by Equation (6). **Figs. 4-6** show the contribution of each variable to variance of the maximum principal stress at crown, the minimum principal stress at spring line and the maximum shear stress at crown, respectively. For the maximum principal stress at crown and the minimum principal stress at spring line, the elastic modulus has a quite large effect until 10,000 years and Poisson's ratio also has an effect. This is because the change in the results for the increment of the variables is relatively large as shown in **Tables 5** and **6** and the standard deviation is also large in comparison with the increment. The results mean that the variation of elastic properties gives the large difference in the maximum and the minimum principal stresses during the occurrence of thermal stress. On the other hand, for the maximum shear stress at crown, the radial and horizontal stresses have a large effect. The elastic modulus becomes influential after 100,000 years. Since the shear stress is not related to the volumetric change, the thermal stress does not have an effect on the shear behavior. It is, however, noticeable that the contribution to the variance of the maximum shear stress is very small in comparison with that to the

maximum and the minimum principal stresses.

Fig. 7 shows the reliability index of each stress. The reliability index of maximum shear stress is large until 1,000 years after closing the repository and then becomes steady value from 1 to 2. That of the maximum principal stress becomes large gradually and the highest reliability is observed after one million years. The reliability index of the minimum

Table 4 Parameters at EDZ used for examination

Distance from tunnel wall (m)	Fracture density (Num./m ²)	Average fracture length L(m)	Initial damage variable D_0	Initial damage potential B_0 (kPa)
0-0.2	35	0.3	0.3	50
0.2-0.3	25	0.3	0.1	60
0.3-0.4	15	0.3	0.1	65
0.4 -	5	0.3	0.0	80

Table 5 Maximum principal stress at crown of elastic case

Years	100	1000	10000	100000	1000000
Variable	Maximum principal stress (MPa)				
Mean	-42.0	-56.7	-69.5	-76.1	-76.4
σ_v	-40.5	-55.1	-67.9	-74.5	-74.9
σ_h	-45.7	-60.4	-73.2	-79.8	-80.1
σ_r	-42.0	-56.6	-69.4	-76.1	-76.4
P	-41.6	-56.4	-69.3	-76.1	-76.4
T	-42.0	-56.7	-69.5	-76.1	-76.4
E	-37.6	-51.8	-66.6	-75.7	-76.4
ν	-35.3	-50.1	-65.9	-75.6	-76.4

Table 6 Minimum principal stress at spring line of elastic case

Years	100	1000	10000	100000	1000000
Variable	Minimum principal stress (MPa)				
Mean	67.3	47.9	9.39	-14.0	-14.9
σ_v	63.6	44.3	5.78	-17.6	-18.5
σ_h	68.8	49.5	11.0	-12.4	-13.3
σ_r	67.3	47.9	9.41	-14.0	-14.8
P	67.6	48.1	9.50	-14.0	-14.9
T	67.3	47.9	9.39	-14.0	-4.9
E	71.6	52.7	12.3	-13.6	-14.8
ν	74.0	54.5	13.0	-13.5	-14.8

Table 7 Maximum shear stress at crown of elastic case

Years	100	1000	10000	100000	1000000
Variable	Maximum shear stress (MPa)				
Mean	43.7	40.6	31.0	24.8	24.7
σ_v	43.0	39.8	30.2	24.1	24.0
σ_h	45.6	42.3	32.8	26.7	26.4
σ_r	43.7	40.5	30.9	24.8	24.7
P	43.7	40.6	31.0	24.8	24.7
T	43.7	40.6	31.0	24.8	24.7
E	43.7	40.6	31.0	24.9	24.7
ν	43.7	40.5	31.0	24.8	24.7

Fig.4 Contribution to variance of each variable for the maximum principal stress in elastic case. The left vertical axis is for the elastic modulus and the right one is for the other variables.

Fig.5 Contribution to variance of each variable for the minimum principal stress in elastic case. The left vertical axis is for the elastic modulus and the right one is for the other variables.

Fig.6 Contribution to variance of each variable for the maximum shear stress in elastic case

Fig.7 Reliability index in elastic case

principal stress is small through one million years.

It is found from the above results that the uncertainty of the predicted maximum shear stress is low through the evaluation period, while that of the minimum principal stress is high through the period and that of maximum principal stress changes. The high uncertainty of the minimum and maximum principal stresses until 10,000 years is related to the occurrence of thermal stress.

(2) Damage model

Tables 8-10 show the maximum principal stress at crown, the minimum principal stress at spring line and the maximum shear stress at crown of damage model case. In comparison with the results of elastic model, the stress becomes small entirely while the tendency of temporal change is similar. This is because the rock becomes soft by damage development. From the results, the contribution to variance of each variable is obtained as shown in Figs. 8-10. For the maximum principal stress, the elastic modulus and Poisson's ratio has a large effect until 10,000 years after closing the repository. The horizontal stress has a mostly constant effect throughout one million years. For the minimum principal stress, Poisson's ratio has a very large influence after 1,000 years. The elastic modulus has a similar contribution to the maximum principal stress. For the maximum shear stress, while the effect of each variable is the mostly same throughout one million years, horizontal stress has a relatively large effect. These tendencies are quite different from those of elastic case. However, the contribution is relatively small in comparison with that of elastic case. The large effect of Poisson's ratio on the minimum principal stress is caused from the expansive strain including the volumetric change due to damage progress. The reason why the horizontal stress has an effect is that the deformation is influenced by the horizontal stress. It is found that the contribution to the uncertainty is quite dependent on

Table 8 Maximum principal stress at crown of damage model case

Years	100	1000	10000	100000	1000000
Variable	Maximum principal stress (MPa)				
Mean	-28.8	-40.8	-51.5	-57.1	-57.4
σ_v	-27.8	-39.8	-50.5	-56.1	-56.4
σ_h	-31.3	-43.3	-54.0	-59.6	-59.9
σ_r	-28.8	-40.8	-51.5	-57.1	-57.4
P	-28.8	-40.8	-51.5	57.1	-57.4
T	-28.8	-40.8	-51.5	-57.1	-57.4
E	-28.7	-40.8	-51.5	-57.1	-57.4
ν	-28.4	-40.6	-51.4	-57.1	-57.4

Table 9 Minimum principal stress at spring line of damage model case

Years	100	1000	10000	100000	1000000
Variable	Minimum principal stress (MPa)				
Mean	52.9	36.9	5.54	-13.5	-14.2
σ_v	52.0	34.4	3.01	-16.1	-16.8
σ_h	52.7	36.3	5.56	-13.5	-14.2
σ_r	52.9	37.0	5.56	-13.5	-14.2
P	52.9	37.0	5.55	-13.5	-14.2
T	52.9	36.9	5.54	-13.5	-14.2
E	53.0	37.0	5.57	-13.5	-14.2
ν	53.0	35.6	4.05	-15.1	-15.8

Table 10 Maximum shear stress at crown of damage model case

Years	100	1000	10000	100000	1000000
Variable	Maximum shear stress (MPa)				
Mean	37.3	32.8	22.2	15.6	15.4
σ_v	36.8	32.4	21.8	15.1	14.9
σ_h	38.6	34.1	23.5	16.9	16.7
σ_r	37.3	32.8	22.2	15.6	15.4
P	37.3	32.8	22.2	15.6	15.4
T	37.3	32.8	22.2	15.6	15.4
E	37.3	32.8	22.2	15.6	15.4
ν	37.3	32.8	22.2	15.6	15.4

Fig.8 Contribution to variance of each variable for the maximum principal stress in damage model case

Fig.9 Contribution to variance of each variable for the minimum principal stress in damage model case

Fig.10 Contribution to variance of each variable for the maximum shear stress in damage model case

Fig.11 Damage variable evolution

Fig.12 Permeability evolution

the mechanical model.

Figs. 11 and 12 show the temporal variation of the damage variable and permeability at crown. The variation occurs after 18 and 26 years at which temperature becomes about peak value. The permeability is more responsive to the damage development than damage variable. When horizontal stress is incremented, the development of damage becomes large and permeability is changed drastically. After that, the damage variable and permeability do not change until the end of calculation. This means that maximum elastic work occurs at the time when temperature becomes peak.

Fig. 13 shows the evolution of reliability index of each stress. The reliability index of maximum principal stress gradually increases while that of the maximum shear stress decreases. That of the minimum principal stress is relatively small throughout a long period. This tendency is similar to that of elastic case while the value of reliability index of each stress is a little large in the damage model.

Table 11 shows the contribution of the variable to

Fig.13 Reliability index of maximum principal stress, minimum principal stress and maximum shear stress of damage model case

the variance of damage variable and permeability, and the reliability indexes at 100 years. These values do not vary after 100 years. In the table, the reliability indexes for both damage variable and permeability are also indicated, which are also the values remained

Table 11 Contribution of each variable to variance and reliability index for damage variable D and permeability K (m/s) at 100 years

	Mean	σ_v	σ_h	σ_r	P
D	0.301	-3.5E-6	2.9E-5	5.7E-6	-1.7E-6
K	8.4E-8	-1.5E-13	6.9E-12	-7.7E-13	1.3E-13
	T	E	ν	β	
D	0	1.8E-5	5.6E-5	29.7	
K	0	1.0E-13	5.5E-13	0.032	

after 100 years. The contribution of horizontal stress is larger than the other variables for both damage variable and permeability. The reliability of the damage variable is high and that of permeability is quite low.

6. CONCLUSIONS

In this paper, the uncertainty analysis of the mechanical behavior of near field of HLW repository was examined. The uncertainty of the maximum principal stress at crown of the repository tunnel, the minimum principal stress at spring line and maximum shear stress at crown were examined for the variables of boundary conditions, elastic modulus and Poisson's ratio. The variance of boundary conditions was obtained from the temporal variation for one million years which were estimated from the far field analysis.

To examine the contribution of the variables to the variance of each stress, the first order second moment method was applied. As a result, the followings were obtained:

- 1) For the maximum principal stress at crown, the elastic modulus and Poisson's ratio had a large effect on the variance in the elastic and the damage expansion models.
- 2) For the minimum principal stress at spring line, the elastic modulus had an effect on the variance in both models. In the damage expansion model, the Poisson's ratio had a large influence.
- 3) For the maximum shear stress at crown, the boundary condition had a larger effect than the elastic properties in both models.
- 4) The reliability index of maximum stress gradually decreased, that of maximum principal stress gradually increased and that of minimum principal stress was small through a long period. This tendency was similar for both models.
- 5) For damage variable and permeability at crown, the horizontal stress on the boundary had a large influence.

For the elastic case, the occurrence of the thermal stress had an effect on the uncertainty of the behavior

around the tunnel. On the other hand, the damage expansion model showed the effect of mechanical-work on the uncertainty. The uncertainty of the prediction is dependent on the mechanical model. It was, however, found from above results that estimation of boundary conditions was relatively important to examine the stability and permeability change around the repository tunnel as well as the examination of uncertainty of mechanical properties. Besides, since the reliability of the minimum principal stress was expected to be low, careful consideration is needed for the prediction of tension failure and expansion of crack aperture at the spring line.

The effect of temperature could not be identified for the near field model from the method used in this paper. For this purpose, the boundary conditions describing temperature condition has to be applied.

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