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## **Prediction of long-term crustal movement for geological disposal of radioactive waste**

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### **Abstract**

Long-term stability of the geological environment is essential for the safe geological disposal of radioactive waste, for which it is necessary to predict the crustal movement during an assessment period. As a case study, a numerical analysis method for the prediction of crustal movement in Japan is proposed. A three-dimensional elastic analysis by FEM for the geological block structure of the Kinki region and the Awaji-Rokko area is presented. Stability analysis for a disposal cavern is also investigated.

### **1 Introduction**

Recently, the necessity of predicting long-term crustal movements in order to evaluate the stability of geological repositories of radioactive waste and neighboring rock mass has been recognized. There are various methods of predicting crustal movement, such as research and model testing of crustal movement patterns in the past. In these methods, the establishment of a computer-based model is indispensable for quantitative prediction. In this paper, computational techniques of simulating the crustal movement for about 10,000 years are proposed and the numerical results are compared with the features of surveyed crustal movement.

### **2 Types of crustal movement prediction method [1]**

Geological prediction methods are generally classified as follows.

- (a) Prediction by extrapolation: The fundamental method for geological prediction is not only effective especially in steady slow phenomena, but also applicable to periodic and cyclic ones. The prediction should be made based on detailed observations over a sufficiently longer time span than the prediction period, and the possibility of changes in tendency should be checked by other prediction methods.
- (b) Prediction by analogy: The future prediction is carried out by identifying similar phenomena in the past. This method is an effective approach for crustal movement phenomena, and is called natural analogue, which is the only reliable method of validating conceptual and numerical models for long-term prediction for radioactive waste disposal.
- (c) Prediction by experiment: The phenomena are artificially modeled, then the prediction is carried out by using the experimental model. The method is necessary for understanding the mechanism of geological phenomena because the conditions can be precisely controlled. Long-term quantitative prediction by using this method is difficult, however.
- (d) Prediction by probability: Statistical research is indispensable for assessing the risk of some catastrophic events, but statistically fine data of geological phenomena are difficult to obtain.
- (e) Prediction by conceptual model: The plate tectonic model is useful for predicting tectonic movements in a plate boundary region such as the Japanese archipelago.
- (f) Prediction by numerical simulation model: Past phenomena are not perfectly the same as present ones, so a complicated underground environment cannot be simulated even by experiment. Numerical calculations by computer are necessary in order to predict changes of crustal movement phenomena quantitatively, in which various factors interact. Mechanical stability analyses and seepage analyses are carried out to evaluate the performance of geological disposal at present.
- (g) Prediction by safety assessment model: Simplified safety assessment models are useful to analyze the overall performance of a complex disposal system. The safety assessment requires the development of synthetic models, scenario analyses and consequence analyses. Long-term geological prediction should be performed and crosschecked by the different methods.

A systematic approach with several prediction methods as mentioned above for the prediction of long-term tectonic stability is more practical. In this study, a numerical simulation model that combines extrapolation is adopted.

### **3 Crustal movement prediction**

#### *3.1 Outline of crustal movement of Japan [1]*

The disposal of radioactive waste in deep geological formations is a safer, viable technology at present. However, since the Japanese archipelago is close to the plate boundary, crustal movements and associated active faults are more intense than in continental areas. Therefore, volcanoes are not evenly distributed, with few located between the volcanic front and the oceanic trench where the plate sinks, but many concentrated in the volcanic front zone. Uneven distribution by region is also remarkable on the active faults. There are regions characterized with few active faults between the volcanic front and the oceanic trench (Figure 1).

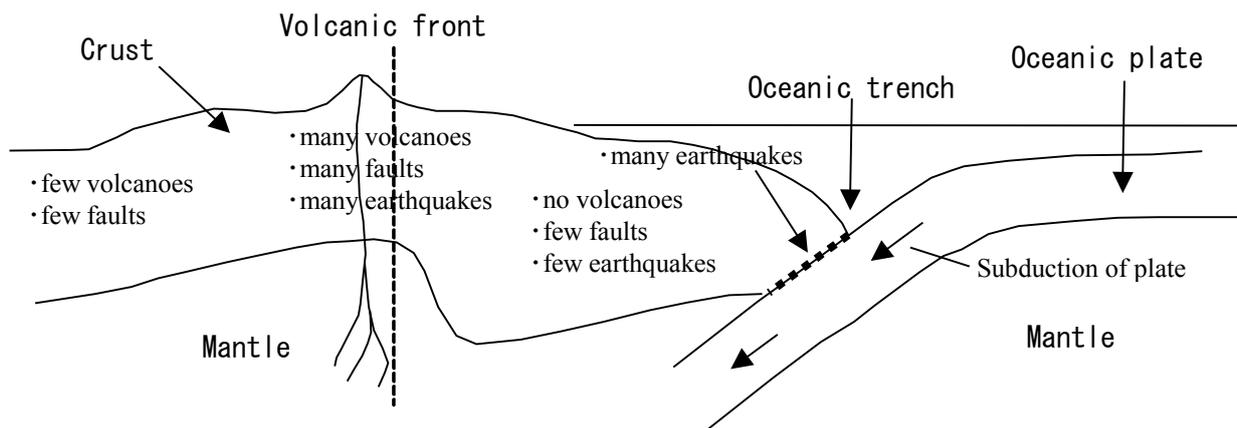


Figure 1. Schematic distribution of crustal movement features in an island archipelago (modified [2])

Underground, earth pressure and temperature increase with depth and the strength of rock also increases with depth to about 10 km. However, the strength of rock deeper underground than 10 km drastically decreases as the rock becomes fluidic due to geothermy. Near the volcanic front, the temperature is high due to the magma rising from deep underground. Hence, the crust with high rigidity is very thin in the region. On the other hand, in the region between the oceanic plate and the volcanic front, the crust with high rigidity is thin due to the effects of subduction of plates. As a result, crust deformation is concentrated near the volcanic front with the thin crust. Therefore, the crust with high rigidity between the volcanic front and oceanic trench is stable (Figure 1).

The upheaval region of the crust is concentrated near the plate boundary and volcanic front. However, the rate in the region of maximum upheaval is about several mm/year on average. In most regions, crustal upheaval or subsidence rates are within 1 mm/year. The average displacement rate is about several mm/year even in an active fault. Such active faults are distributed near the plate boundary, volcanic front and near the Median Tectonic Line. The average slip rate of major active faults in other regions is less than 1 mm/year.

For the evaluation of long-term stability of disposal sites, it is essential to estimate the magnitude of future geological events.

### 3.2 Outline of crustal movement prediction method

For assessment of the long-term mechanical stability of the disposal site, it is necessary to estimate the change in the long-term physical properties of the rock mass and the stress change caused by crustal movement. Especially, examination not only in the vicinity of the disposal site but also over a wider region, which could be a source of variability of plate motion, is required. In order to evaluate the stability of the vicinity of the disposal site (vicinity model), it is necessary to determine the boundary conditions including plate movement. Therefore, an area extending several tens of kilometers (medium-scale model) is examined, and to determine the boundary of the medium-scale model, an even wider region (large-scale model) is examined. In general, the accuracy of the model becomes rough as the region enlarges. However, this is useful for estimating the stress change caused by crustal movement in a complicated geological environment. The examination of long-term geological stability is carried out roughly with the large-scale model and the result thus obtained can be used for the boundary condition of the medium-scale model to determine the technical reasons on which to select the disposal site.

### 3.3 Crustal movement prediction analysis of large-scale model

Japan is located in a particularly complicated region, being close to four plate boundaries unlike continental regions. Eastern Japan is primarily affected by two compressed plates, in which reverse faults develop. On the other hand, Western Japan is affected by four complex sunk plates, in which lateral slip faults develop. Therefore, the examination is carried out separately for the regions of Eastern Japan and Western Japan as a case study. This paper presents the model for Western Japan. In Western Japan, the Kinki district is treated as a large-scale model region. The Kinki district is divided geologically into several blocks by active faults (Figure 2). Many active faults seem to derive from the geological block boundary. A qualitative evaluation by lateral slip, upheaval and subsidence behavior around the Osaka block is carried out by three-dimensional linear elastic FEM. In the depth direction, it is modeled to the lower-limit plane depth (estimated from the hypocentral depth distribution) of the upper crust. The lower crust is treated as a distribution spring. The inclination of the block boundary is also considered.

Compressive strain in the east-west direction is considered by giving an enforcement displacement (30 m/1,000 years) referring to the horizontal strain of the Kinki district of the past 100 years measured by the Geographical Survey Institute. Details of the other analysis conditions are given in reference 4. Figure 3 shows the relative lateral slip rate vectors around the Osaka block. This result simulates the lateral slip behavior of the fault, which was generated over the past 10,000 years. Figure 4 shows the upheaval and subsidence distribution of the ground level. In comparison with the present landform, the phenomenon in which the Osaka block settles has qualitatively been simulated.

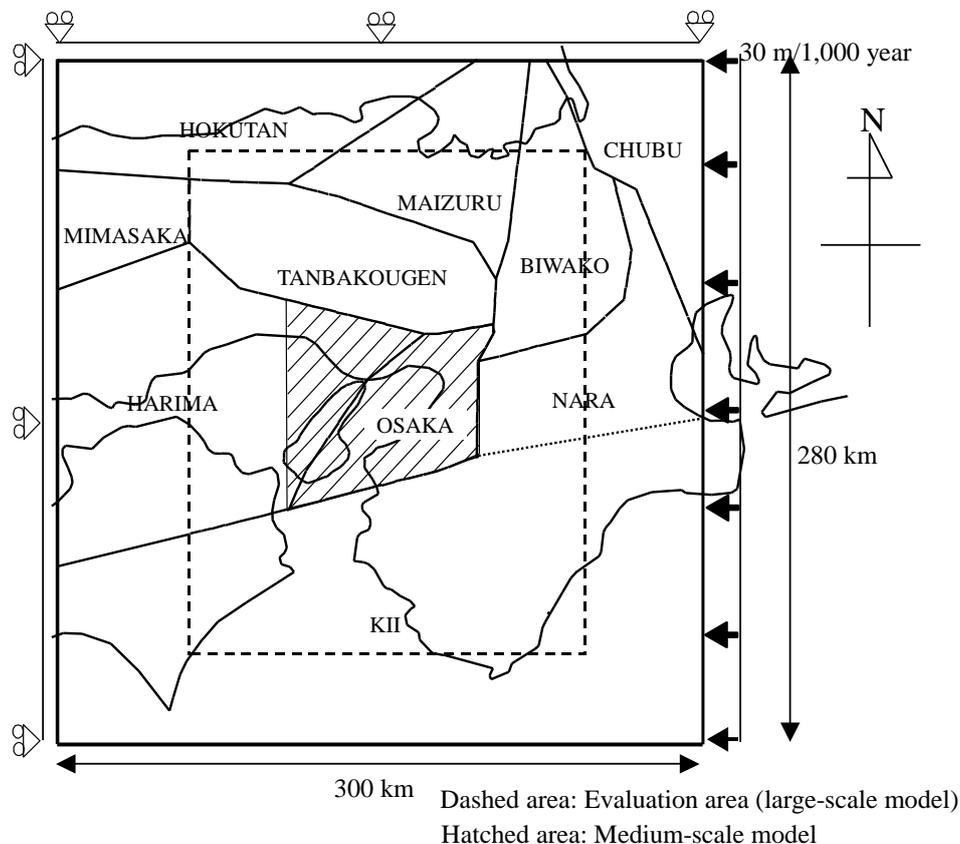
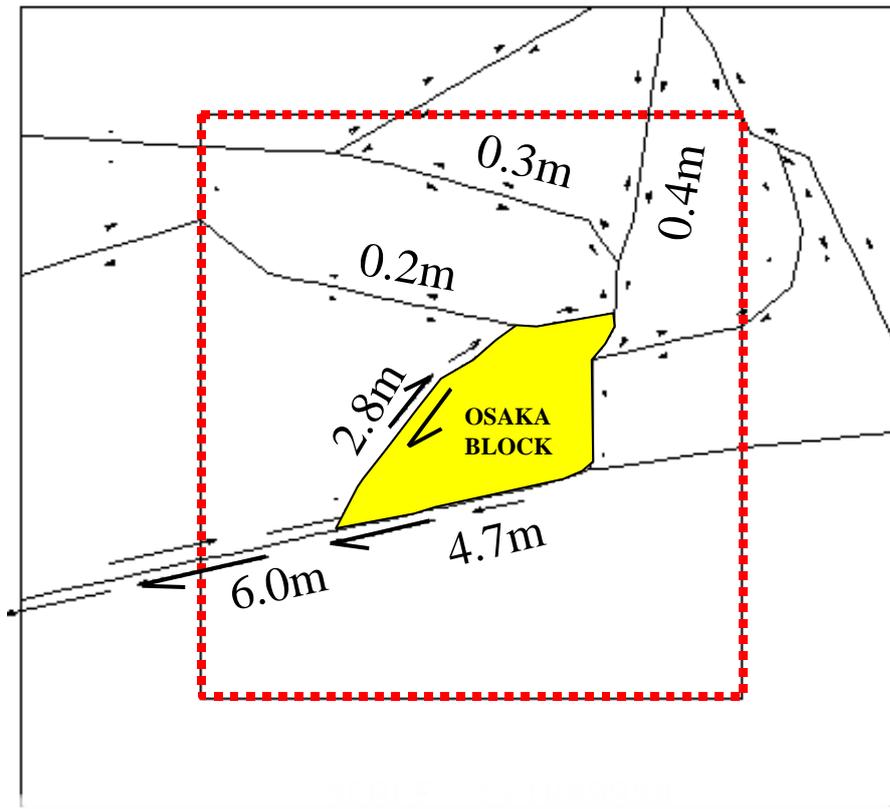
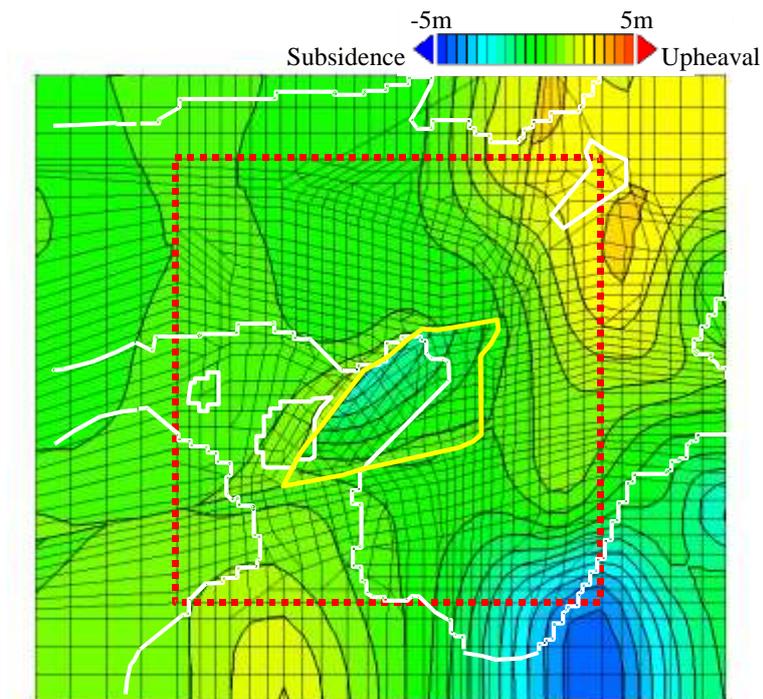


Figure 2. Analytical model and boundary conditions (large-scale model)



Dashed area: Evaluation area (large-scale model)

Figure 3. Relative lateral slip rate vectors



Dashed area: Evaluation area (large-scale model)

Figure 4. Upheaval and subsidence distribution of the ground level

### 3.4 Crustal movement prediction analysis of medium-scale model

The medium-scale model region shown by the hatched area in Figure 2 is examined, because there are many additional geological data of this region which was investigated after the 1995 Hyogo-ken Nambu Earthquake. The purpose of this model is to set the analytical conditions of the vicinity model, and to examine the behavior of the Awaji island north fault system over the long term. Figures 5 and 6 show three-dimensional FEM analytical models of the Awaji and Rokko region. In the medium-scale model, minor active faults that are not considered in the large-scale model have been modeled. The boundary conditions are given on the enforcement displacement and the value of displacement is obtained from large-scale model analysis. The mechanical properties of the rock mass and faults are assumed to be linear elastic like the large-scale model. Figure 7 compares the analytical results for the relative slip rate vector with the surveyed ones. It seems that the analytical results qualitatively match the survey results. Figure 8 shows the distribution of maximum shear strain. This result shows how the strain is concentrated around the Awaji and Rokko faults. The analytical results provide useful suggestions on the relation between distance from the faults and stability.

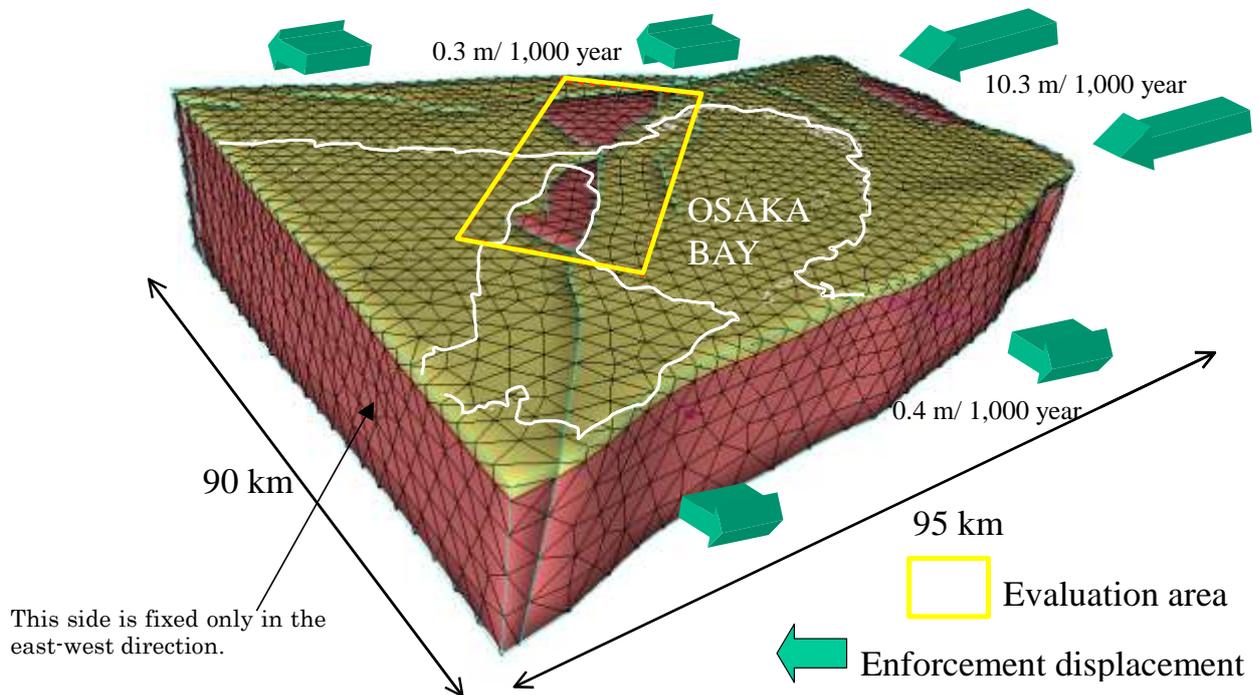


Figure 5. Analytical model of the Awaji and Rokko region (medium-scale model)

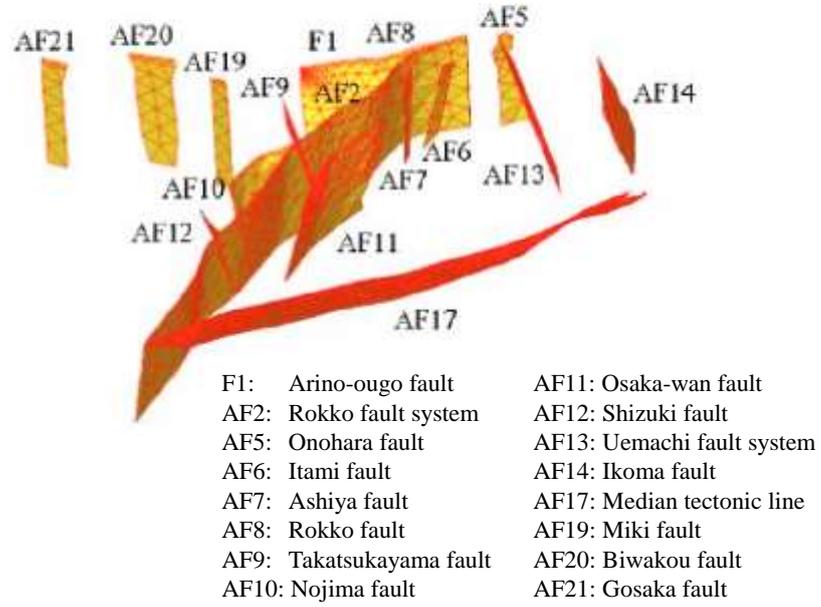


Figure 6. Modeled active faults of the Awaji and Rokko region

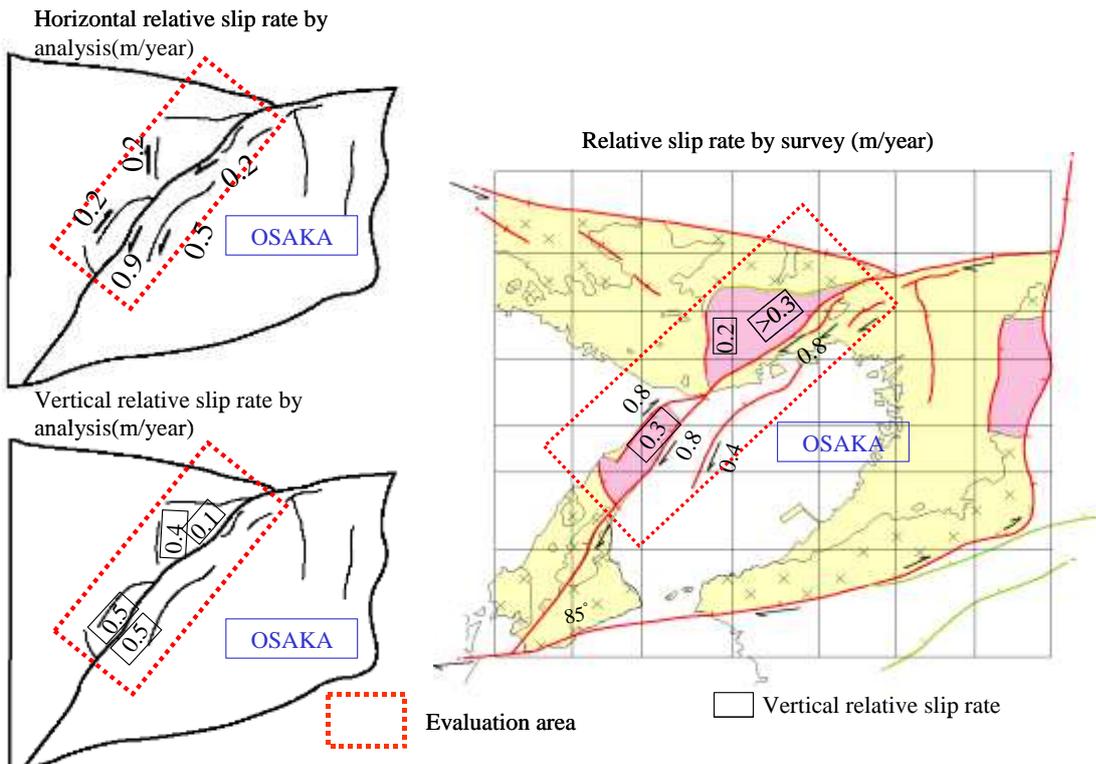


Figure 7. Comparison of analytical results on the relative slip rate vectors of the medium-scale model and survey results

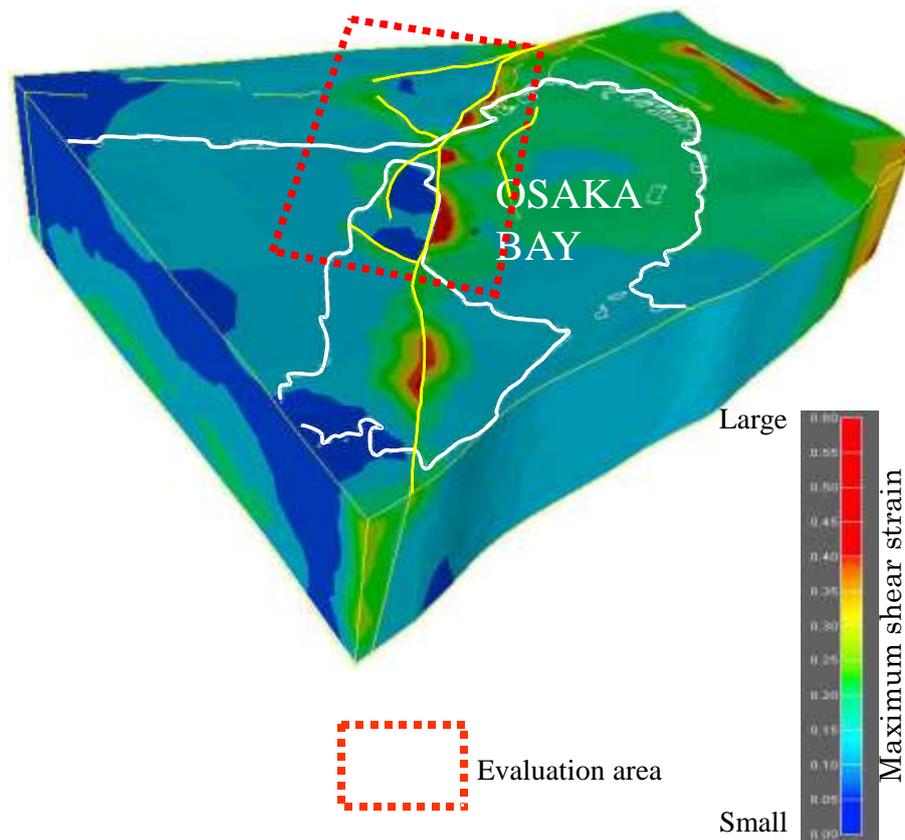


Figure 8. Distribution of maximum shear strain

### 3.5 Crustal movement prediction analysis of the vicinity model

The vicinity model (shown in Figure 9) is analyzed in order to predict the long-term mechanical stability of the disposal cavern. In this examination, the long-term earth pressure increment that accompanies crustal movement is assumed by extrapolation based on the analytical results for the medium-scale model. The nonlinear visco-elastic constitutive model proposed by Okubo [5] is used to take the long-term creep behavior of the rock mass into account. It is assumed that a seam (mechanically weakened plane) exists in the vicinity model.

Figure 10 shows the compliance (reciprocal of the elastic modulus) of the rock mass 10,000 years later after the closure of the disposal cavern. The plastic zone (the region above peak strength) expands from the surface of the cavern to a distance that is roughly equal to the radius of the cavern symmetrically. This result shows the seam does not affect the plastic zone.

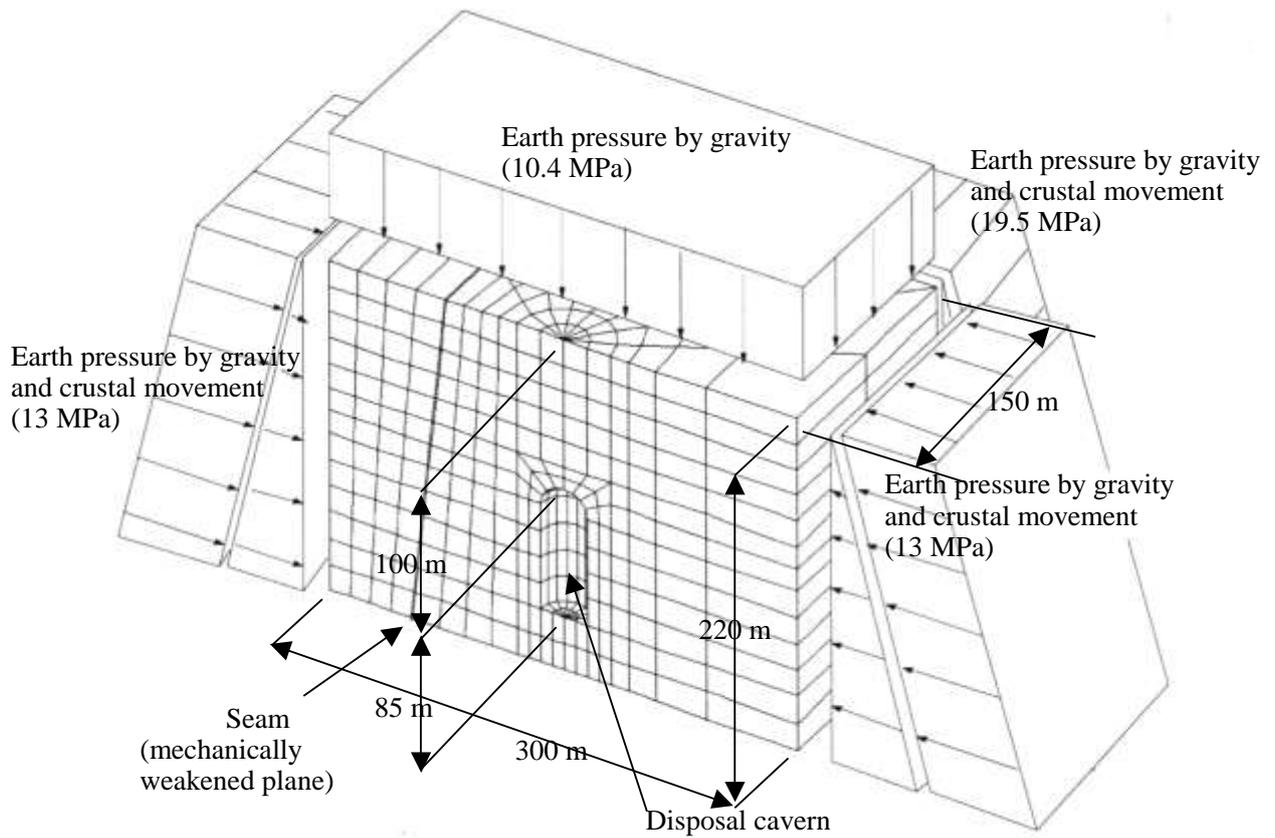


Figure 9. Vicinity model

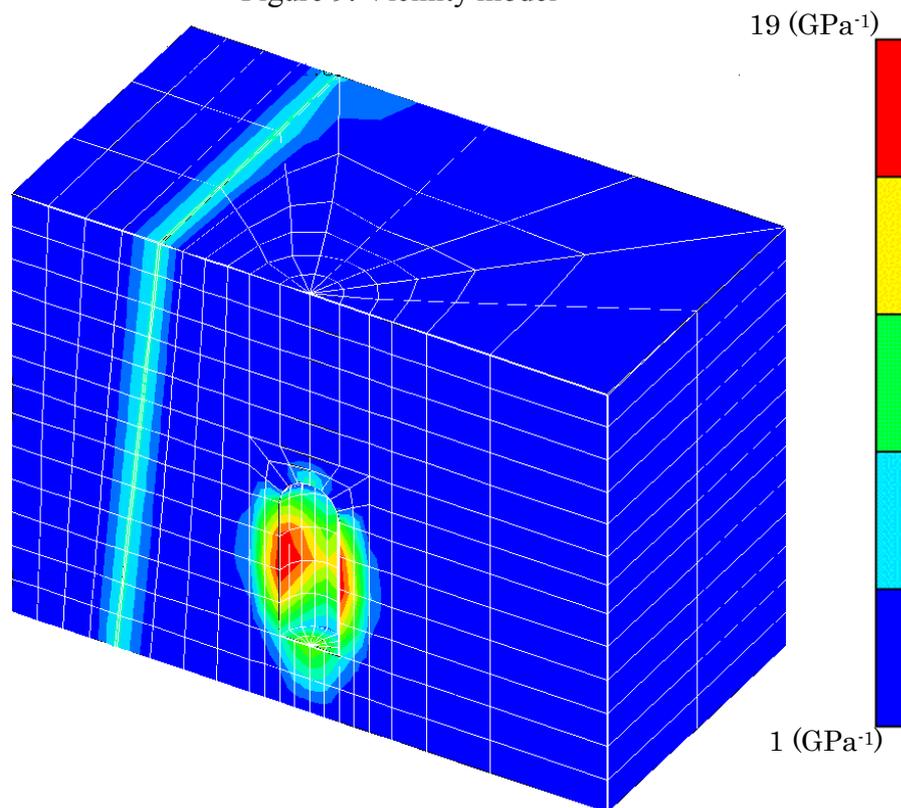


Figure 10. Compliance distribution at 10,000 years after closure of disposal cavern

## 4 Conclusions

Research on crustal movement prediction techniques for underground disposal sites for radioactive waste for long periods exceeding 1,000 years is required. Though there are various methods of such prediction, computational simulation techniques are necessary in order to predict the crustal movement quantitatively. One of the problems in crustal movement prediction is that there is little information of the deep underground. In this paper, the long-term prediction of crustal movement for geological disposal sites within about 10,000 years was examined, and an example of the procedure and modeling technique using the finite element method were proposed. To improve the accuracy of crustal movement prediction, more precise modeling of the fault is required. It is also important to judge synthetically the result of the numerical analysis by geology and rock engineering because crustal movement prediction involves many uncertain and complicated factors. The validity of the model must be verified by comparison with crustal movements in the past.

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