Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division VII

Improvement of Fault Displacement PRA Methodology and Example of its Application to an Assumed NPP

(2) Control Point and its Relevant Uncertainties of PFDHA

Ayumi Yuyama[1], **Hideaki Tsutsumi**[2], **Katsumi Ebisawa**[2], **Yoshinori Mihara**[3],
and Ryusuke Haraguchi[4]

[1] Nuclear Risk Research Center, Central Research Institute of Electric Power Industry, Abiko, Japan (yuyama@criepi.denken.or.jp)
[2] Nuclear Risk Research Center, Central Research Institute of Electric Power Industry, Abiko, Japan
[3] Kajima Corporation, Tokyo, Japan
[4] Mitsubishi Heavy Industries, Ltd, Kobe, Japan

ABSTRACT

The objectives of a series of these studies are to improve the methodology of fault displacement Probabilistic Risk Assessment (PRA) and also to present application cases to an assumed nuclear power plant. In this paper, from the viewpoints of control point of Probabilistic Fault Displacement Hazard Analysis (PFDHA), various theoretical and numerical methods are shown to evaluate the relationship between fault displacement on ground surface given in conventional PFDHA and that on free bed-rock surface defined in general Probabilistic Seismic Hazard Analysis (PSHA). Furthermore, from the viewpoints of input conditions for fault displacement SSC fragility analysis, the relevant uncertainties regarding fault displacement propagation from its control point to ground surface are also presented using numerical model with an assumed dip-slip fault.

INTRODUCTION

Empirical methods for PFDHA are proposed by Youngs et al. (2003), Peterson et al. (2011) and Takao et al. (2015). Their fault displacements are conventionally given on ground surface. On the other hand, control point of PSHA in Japan is generally defined at free bed-rock surface. Considering multi-hazard PRA combined PFDHA with PSHA, control point of PFDHA should be identically defined at free bed-rock surface and thus fault displacement at the point has to be evaluated with individual geography and soil conditions around the site using theoretical or numerical methods based on surface fault displacement.

In this paper, focusing on distributed faults in Japan, various theoretical and numerical methods are comprehensively studied to evaluate the relationship between fault displacement on free bed-rock surface and that on ground surface based on empirical PFDHA methods proposed by Takao et al. (2015). The schematic image is shown in Figure 1.

From the viewpoints of input boundary conditions for fault displacement SSC fragility analysis, the relevant uncertainties regarding fault displacement propagation from its control point defined in this study such as free bed-rock surface to ground surface including the location beneath structure foundations are also presented using numerical model with an assumed dip-slip fault. Parameters of numerical study using finite element analysis consider soil layer, soil stiffness, soil pressure, structure weight and slip condition between distributed fault surfaces.

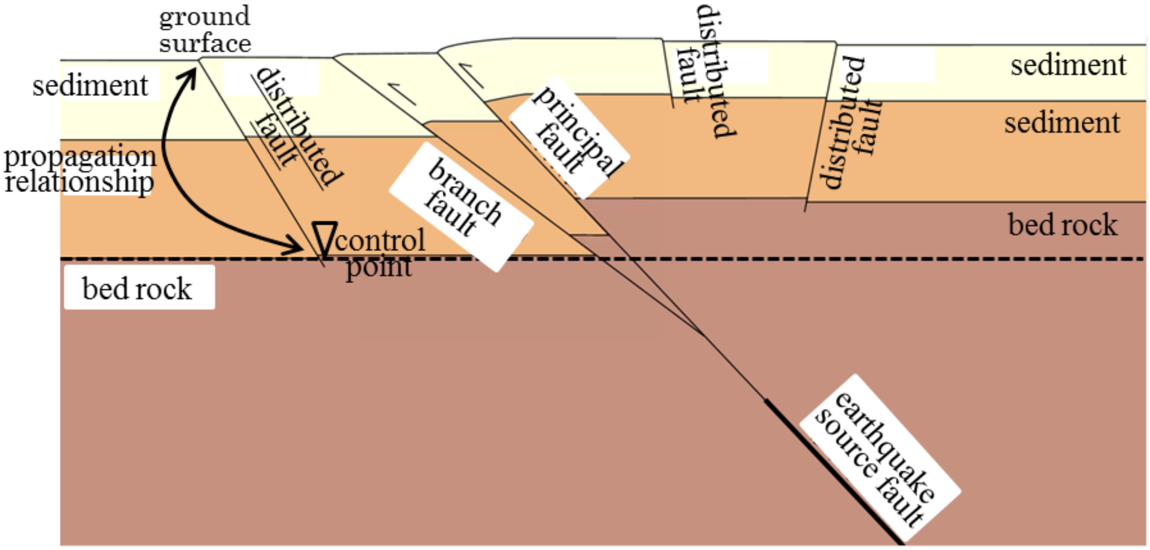


Figure 1. Relationship between distributed fault displacement at control point and ground surface.

ANALYTICAL FRAMEWORK

To quantitatively evaluate the relationship between fault displacement caused by not only principal fault but also distributed fault on free bed-rock surface and that on ground surface, various theoretical and numerical methods are comprehensively discussed from the viewpoints of advantages and disadvantages of the following selected key issues to be evaluated.

(a) Modelling of relatively complicated layered soil structures and material property from seismic basement of bedrock through subsurface layer of sedimentary stratum
(b) Consideration of individual surrounding geography
(c) Evaluation procedure at control point based on PFDHA and also PSHA
(d) Numerical capability to consider a lot of uncertainties
(e) Multi hazard implementation between seismic motion and fault displacement

Based on the comparing investigation above, 2-D static nonlinear elastic finite element analysis is selected to quantitatively evaluate the relevant uncertainties regarding fault displacement on ground surface in the case of input fault displacement is given at control point. The following model parameters are considered to perform variability numerical analyses with 2-D static nonlinear elastic finite element method. Although, structure weight effect is considered only in the limited numerical cases. Schematic image with the following model parameters is shown in Figure 2.

*Model dimensions of soil with fault: 200m width and 100m depth
*Assumed reverse dip-slip fault
*Fault dip angle: 60 degree
*Soil material property: shear wave velocity (Vs) 200m/s and also 2,000m/s assumed to be elastic
*Soil structures: uniform soil and also two layered stratified soil composed of 50m-depth upper layer and 50m-depth lower layer
*Coefficient of friction along assumed fault (Cf): Cf=0.0 to 2.0
*Ratio of horizontal confined soil pressure to vertical soil pressure (Kv): Kv=0.5 and also 1.0
*With or without structure weight effect assumed actual reactor building

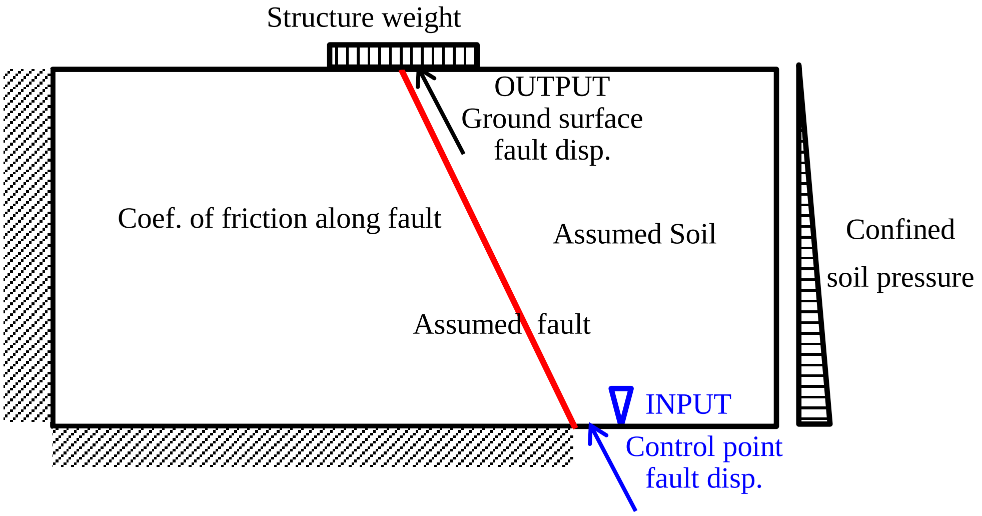


Figure 2. Schematic image with varied model parameters.

DATA AND METHODOLOGY

Following the analytical framework described previously, actual 2-D finite element model is shown in Figure 3. Static nonlinear elastic finite element analyses are carried out in the sequence of three steps. The 1st step is imposing soil pressure on side and surface of the model. The 2nd step is releasing internal stress along the fault line and the 3rd and final step is giving fault displacement 2m at control point. In addition, various numerical cases with the above model are shown in Table 1. Commercial code Abaqus 3DEXPERIENCE R2017x is used for static nonlinear elastic analyses.

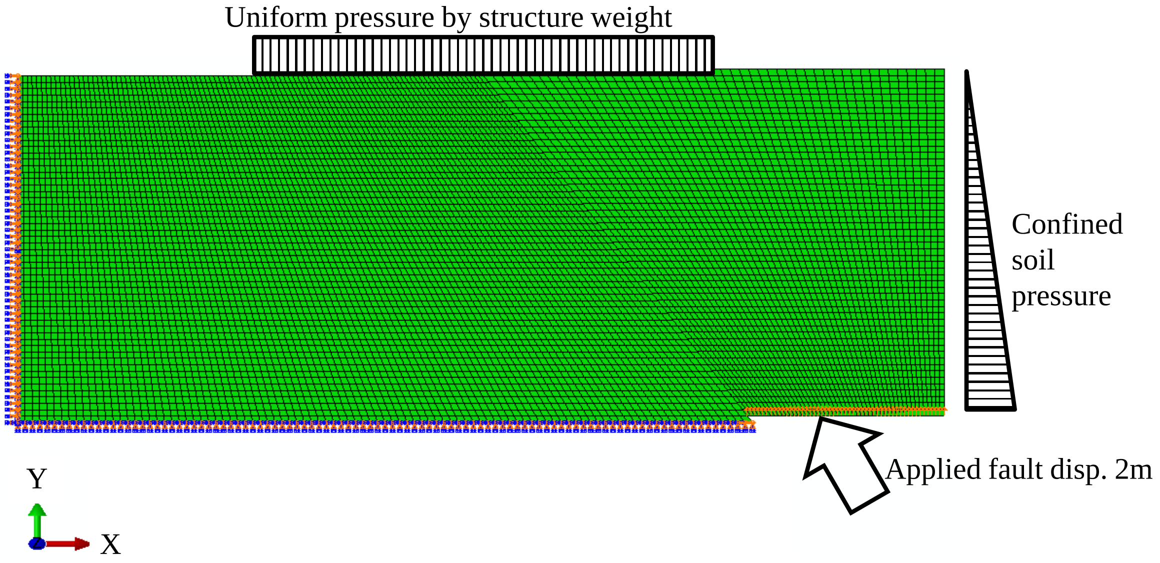


Figure 3. Numerical model with 2-D finite element.

Table 1: Various numerical cases.

Case #	Shear wave velocity Vs		Structure weight	Kv	Cf
	Upper layer	Lower layer			
1a	2,000m/s	2,000m/s	W/O	0.5	0.1, 0.5, 1.0, 2.0
1b	2,000m/s	2,000m/s	W/O	1.0	0.1, 0.5, 1.0, 2.0
2a	200m/s	200m/s	W/O	0.5	0.1, 0.5, 1.0, 2.0
2b	200m/s	200m/s	W/O	1.0	0.1, 0.5, 1.0, 2.0
3a	200m/s	2,000m/s	W/O	0.5	0.1, 0.5, 1.0, 2.0
3b	200m/s	2,000m/s	W/O	1.0	0.1, 0.5, 1.0, 2.0
4	2,000m/s	2,000m/s	W/	0.5	0.1, 0.5, 1.0

Note:
Based on actual conditions of structure foundations of nuclear power plants, case #4 is presumed as hard rock and also realistic values for Kv and Cf.

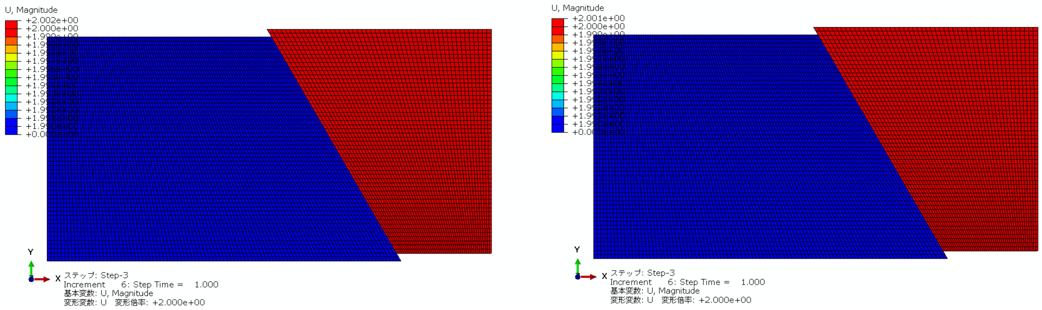
RESULTS AND DISCUSSION

To obtain fault displacement propagation from control point to ground surface, absolute displacement contour plots for all cases computed from 2-D static nonlinear elastic finite element analyses are shown in Figure 4 to Figure 10. Absolute displacement means the mathematically composed displacement by the square root of sum of square of each component. Red color represents the displacement larger than 2m whereas blue color shows the displacement smaller than the prescribed value such as 1.99m, 1.98m, 1.90m, 1.40m and so on that is appropriately adjusted in each numerical case.

Regarding fault displacement propagation from control point to ground surface considering soil layer, soil stiffness, soil pressure, structure weight and slip condition between distributed fault surfaces, numerical findings are shown below.

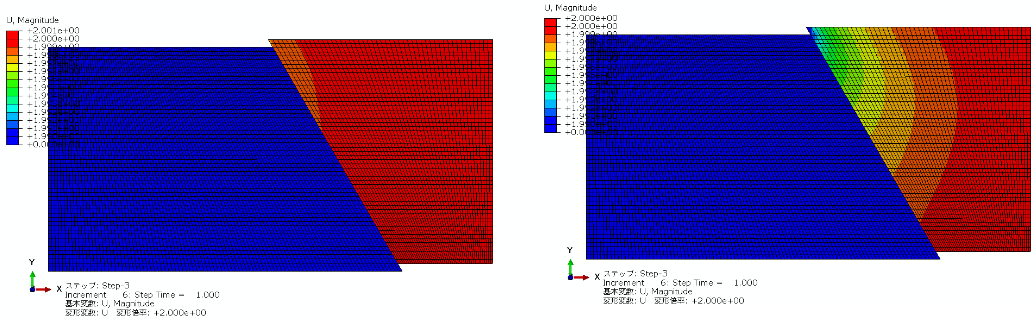
(a) In the case of coefficient of friction along fault smaller than 0.5, there is no significant difference between fault displacement on ground surface and that at control point irrespective of soil stiffness, horizontal confined soil pressure and other parameters except structure weight effect.
(b) In the case of soil shear wave velocity 2,000m/s, there is no significant difference between fault displacement on ground surface and that at control point irrespective of coefficient of friction along fault, horizontal confined soil pressure and other parameters except structure weight effect.
(c) In the case of soil shear wave velocity 200m/s and coefficient of friction along fault larger than 1.0, there is a significant difference between fault displacement on ground surface and that at control point. The discrepancy by coefficient of friction along fault is about 5 to 10 percent for Cf = 1.0, 30 to 35 percent for Cf = 2.0. The discrepancy by horizontal confined soil pressure is about 5 percent in this study.
(d) If the upper layer soil becomes softer even if the lower layer soil is hard, there is a significant difference between fault displacement on ground surface and that at control point in the case of coefficient of friction along fault larger than 1.0. The discrepancy depends on the thickness of upper layer soil.
(e) In the case of consideration of structure weight assumed in an actual reactor building, there is a significant difference between fault displacement on ground surface and that at control point even if

the coefficient of friction along fault is small and soil shear wave velocity is 2,000m/s. In addition, ground surface deformation distribution within the loading area of structure weight becomes more complicated. Therefore, from the viewpoints of fault displacement SSC fragility analysis, it is very important to evaluate its value and area imposing structure weight.



Cf = 0.1 (Ground surface disp. > 1.99m)

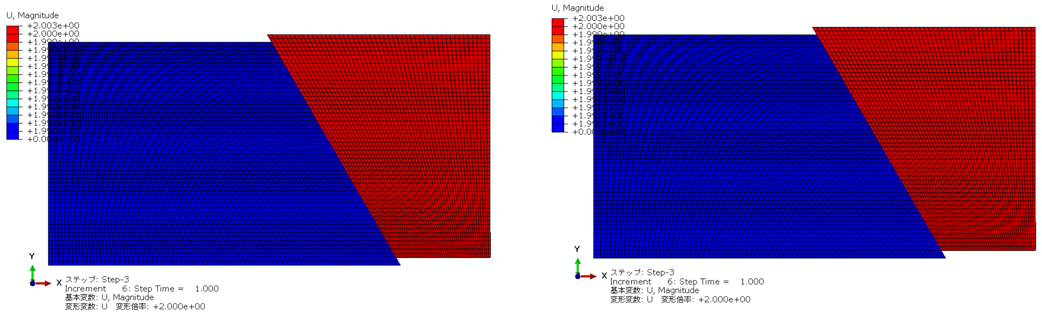
Cf = 0.5 (Ground surface disp. > 1.99m)



Cf = 1.0 (Ground surface disp. > 1.99m)

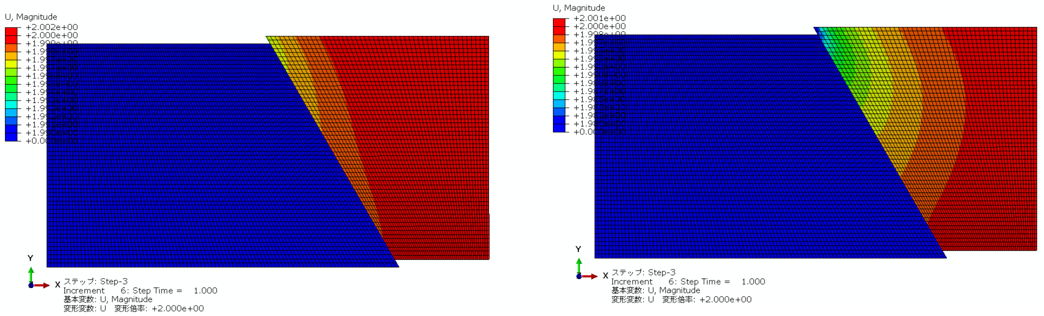
Cf = 2.0 (Ground surface disp. > 1.99m)

Figure 4. Absolute displacement contour plots for Case #1a.



Cf = 0.1 (Ground surface disp. > 1.99m)

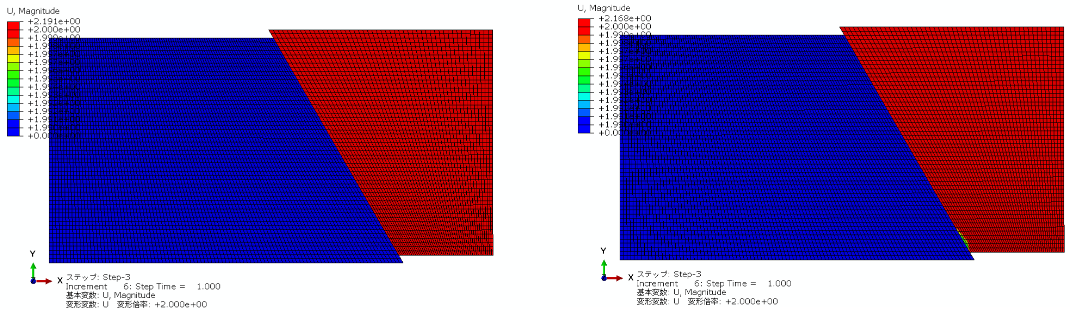
Cf = 0.5 (Ground surface disp. > 1.99m)



Cf = 1.0 (Ground surface disp. > 1.99m)

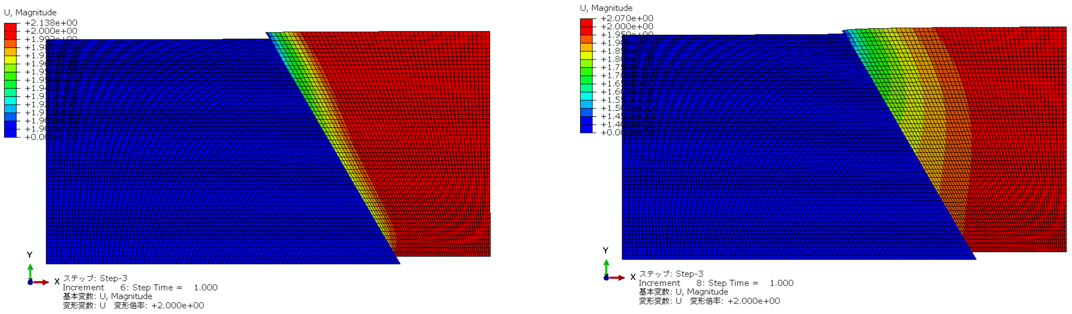
Cf = 2.0 (Ground surface disp. > 1.98m)

Figure 5. Absolute displacement contour plots for Case #1b.



Cf = 0.1 (Ground surface disp. > 1.99m)

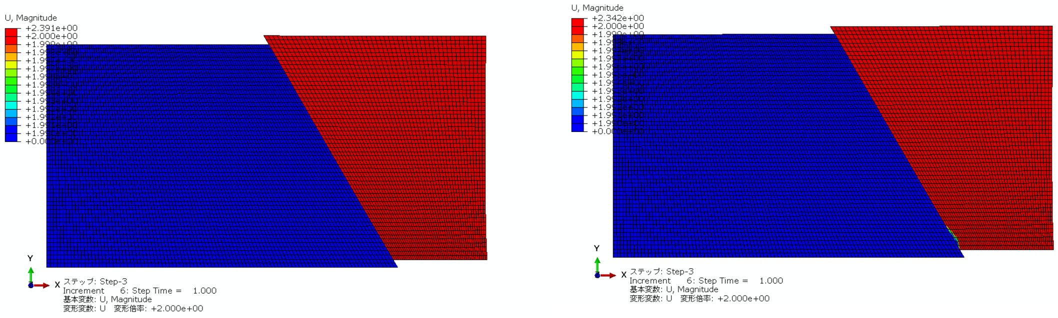
Cf = 0.5 (Ground surface disp. > 1.99m)



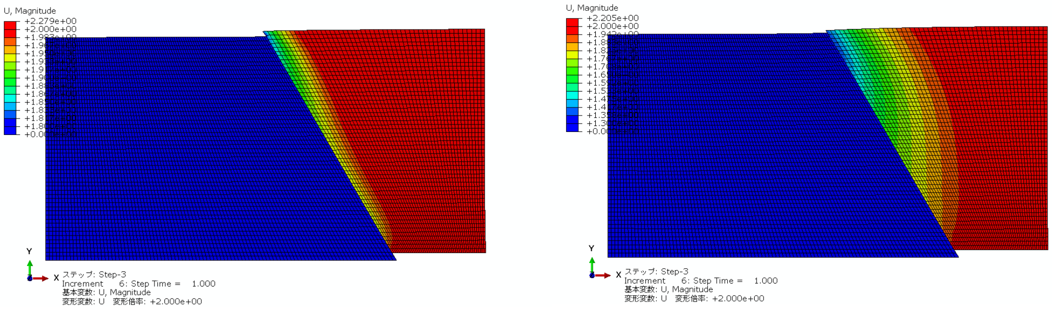
Cf = 1.0 (Ground surface disp. > 1.90m)

Cf = 2.0 (Ground surface disp. > 1.40m)

Figure 6. Absolute displacement contour plots for Case #2a.

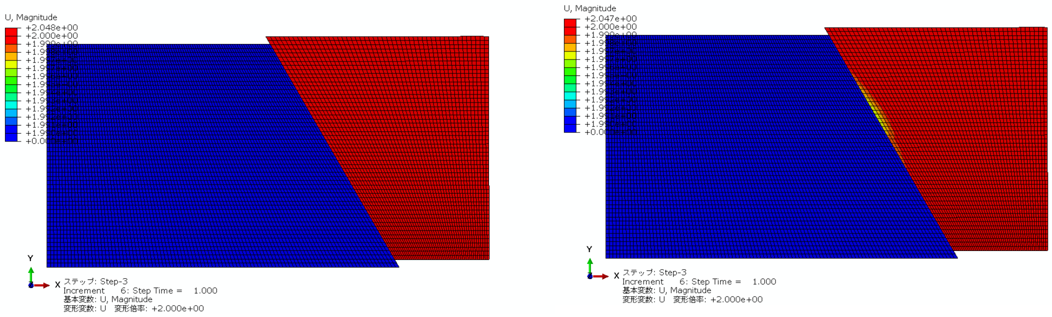


Cf = 0.1 (Ground surface disp. > 1.99m) Cf = 0.5 (Ground surface disp. > 1.99m)

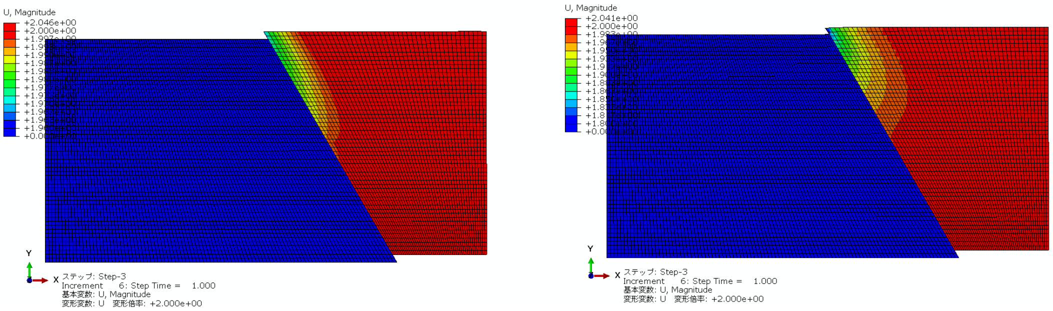


Cf = 1.0 (Ground surface disp. > 1.80m) Cf = 2.0 (Ground surface disp. > 1.30m)

Figure 7. Absolute displacement contour plots for Case #2b.

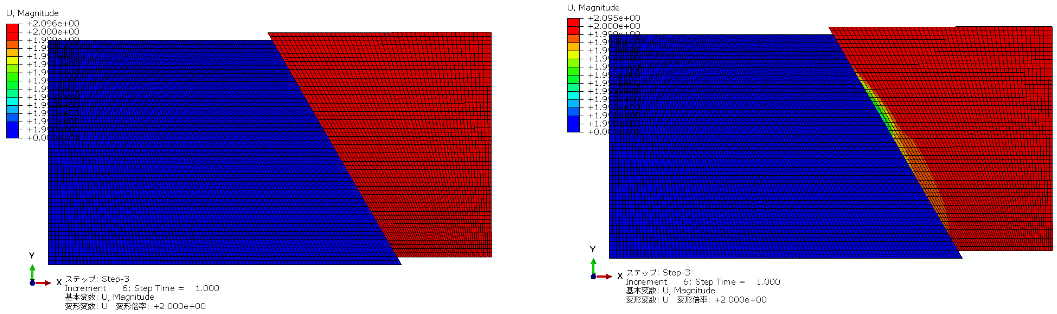


Cf = 0.1 (Ground surface disp. > 1.99m) Cf = 0.5 (Ground surface disp. > 1.99m)

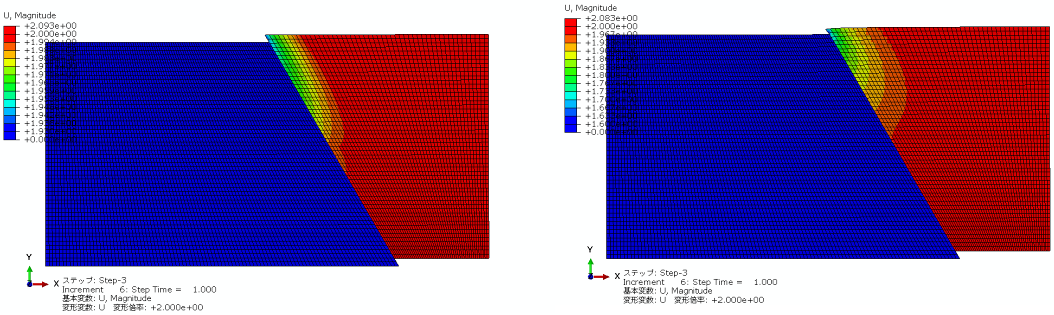


Cf = 1.0 (Ground surface disp. > 1.96m) Cf = 2.0 (Ground surface disp. > 1.80m)

Figure 8. Absolute displacement contour plots for Case #3a.

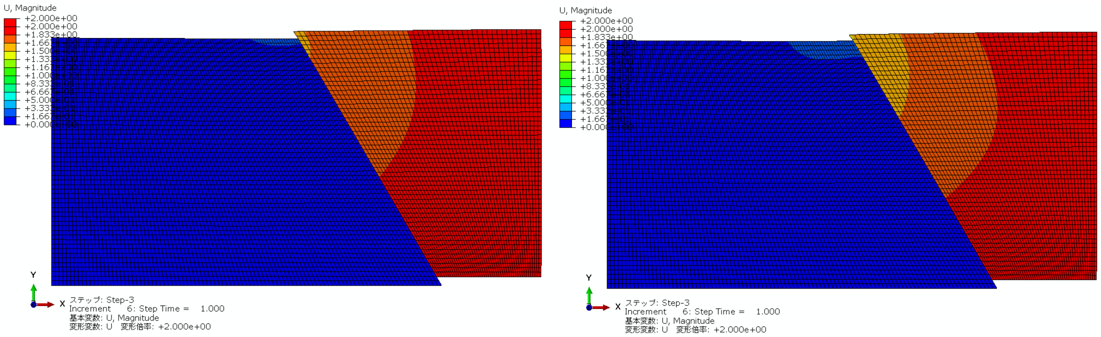


Cf = 0.1 (Ground surface disp. > 1.99m) Cf = 0.5 (Ground surface disp. > 1.99m)

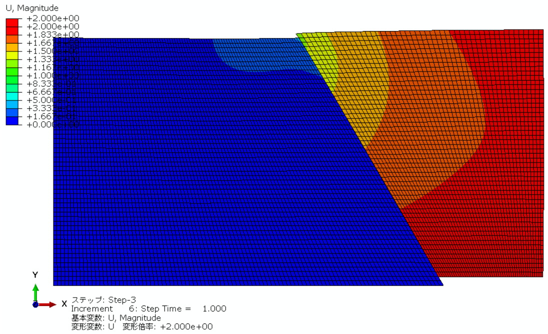


Cf = 1.0 (Ground surface disp. > 1.93m) Cf = 2.0 (Ground surface disp. > 1.60m)

Figure 9. Absolute displacement contour plots for Case #3b.



Cf = 0.1 (Ground surface disp. > 1.62m) Cf = 0.5 (Ground surface disp. > 1.48m)



Cf = 1.0 (Ground surface disp. > 1.27m)

Figure 10. Absolute displacement contour plots for Case #4.

CONCLUSION

In this paper, focusing on distributed faults in Japan, various theoretical and numerical methods are comprehensively studied to evaluate the relationship between fault displacement on free bed-rock surface and that on ground surface based on empirical PFDHA methods proposed by Takao et al. (2015).

From the viewpoints of input boundary conditions for fault displacement SSC fragility analysis, the relevant uncertainties regarding fault displacement propagation from its control point defined in this study such as free bed-rock surface to ground surface including the location beneath structure foundations are also presented using numerical model with an assumed dip-slip fault. Parameters of numerical study using finite element analysis consider soil layer, soil stiffness, soil pressure, structure weight and slip condition between distributed fault surfaces.

As the result of 2-D static nonlinear elastic finite element analyses, the amplitude ratio of fault displacement at control point to that on ground surface is around 1 to 1.5 in this study. In addition, in the case of consideration of structure weight assumed in an actual reactor building, the ratio becomes larger and the ground surface deformation distribution within the loading area of structure weight becomes more complicated. Therefore, from the viewpoints of fault displacement SSC fragility analysis, it is very important to evaluate its value and area imposing structure weight.

Finally, numerical model and parameters are limited in this study in order to quantitatively evaluate sensitivity of key parameters. Thus, its applicability to actual observed fault records remains a further issue.

ACKNOWLEDGEMENTS

This study was conducted as a preparation project regarding nuclear power plant risk assessment and study under the Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry. The authors hereby express gratitude to the organizations and all who supported the project.

REFERENCES

Youngs, R.R., et al. (2003), A methodology for probabilistic fault displacement hazard analysis (PFDHA), *Earthquake Spectra*, Vol.19, No.1, pp.191-219.

Petersen, M.D., et al. (2011), Fault displacement hazard for strike-slip faults, *Bull. Seismol. Soc. Am.* 101, pp.805-8257.

Takao, M. et al. (2015), Establishment of evaluation formulae for Probabilistic fault displacement hazard analysis (PFDHA) in Japan, Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations, Vienna, Austria, November 18-20, 2015.