IMPROVEMENT OF FAULT DISPLACEMENT PRA METHODOLOGY AND EXAMPLE OF ITS APPLICATION TO AN ASSUMED NPP (3) THE VALIDATION STRATEGY OF FAULT DISPLACEMENT FRAGILITY EVALUATION METHODOLOGY

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ABSTRACT

The authors have conducted examination of Fault Displacement Probabilistic Risk Assessment (FDPRA) methodology framework and identification of technical issues. As a part of the development, we have confirmed the validity of the Fault Displacement Fragility Evaluation Methodology (FDFEM) based on the actual damaged case. Contrary to the fact that the validation of the Seismic Fragility Evaluation Methodology (SFEM) is based on a number of shaking table test data and damage cases, the development of FDFEM should depend on a few damage cases and unprepared test data. Under the condition, the authors applied composition and procedures of the tentative FDFEM verification framework to damage of Shih-Gang Dam in Chi-Chi Earthquake (Taiwan, 1999) to confirm the feasibility of the proposed framework. Throughout this study, we acquired a prospect of the feasibility of the composition and procedures of the tentative FDFEM validation framework.

INTRODUCTION

Recently in Japan, interests on the risk of principal and secondary FDs beneath nuclear facilities has increased, and it is currently recognized as an urgent issue for investigation for nuclear safety. The current status regarding FD PRA methodology in Japan is as follows:

The Atomic Energy Society of Japan is conducting two activities (AESJ, 2015 etc.). Japan Society of Civil Engineers published research report of FD evaluation that included investigation of FD risks based on numerical analysis and experiment etc. (JSCE, 2015). Also, the international conference related to the trend of FD hazard including nuclear power industry field were held in the United States (FDHAWOC, 2016). Moreover, the authors were conducting analysis and examination for developing fault displacement PRA methodology (Ebisawa et al, 2017). Under this context, the authors have examined and improved FD PRA methodology framework and identified technical issues. (Tsutsumi, 2018)

In this report, the basic policy of development and validation strategy of FDFEM are described firstly and the application of the procedure to the case of Shih-Gang Dam in Chi-Chi Earthquake follows to confirm the feasibility of the composition and procedures of the tentative FDFEM verification framework.
THE COMPOSITION OF TENTATIVE FDFEM VERIFICATION FRAMEWORK

The current status of fault displacement PRA and fragility evaluation methodology

The FDPRA procedure consists of accident scenario identification, hazard evaluation, fragility evaluation and accident sequence evaluation as shown in Figure 1. The evaluation procedure is basically the same as the framework of the earthquake and tsunami PRA procedure.

Figure 1. Procedure of Fault Displacement PRA (Tsutsumi, 2018)

Structure and procedure of tentative FDFEM verification framework

The tentative FDFEM validation framework consists of the five steps and relationship of each steps is shown on the lower side of Figure 2. The framework itself, failure mode/part, a median image model, and the rational range of various influential parameters are set through the iteration process with peer review. Additionally, FDFEM validation framework will be finalized by adjustment for nuclear industry specified fault displacement fragility evaluation methodology described as Step 5 in the Figure.

Figure 2. Structure and Procedure of FDFEM Verification Framework
APPLICATION OF TENTATIVE FDFEM VERIFICATION FRAMEWORK TO DAMAGE CASE

Target case and the progress of application

In order to confirm the feasibility of the composition and procedures of the tentative FDFEM verification framework, the authors applied the procedure mentioned in previous chapters to the actually fault induced damaged structure of the Shih-Gang Dam in Chi-Chi Earthquake. The reasons for choice of the case are that many related information is obtained by field survey after the earthquake and the restoration work. We have collected the information about the fault itself, the surrounding topography, geological structure, the shape and characteristics of the dam structure, the damage situation and so on. As for progress of application, Step 1 through Step 3 (Figure 1.) is being considered including quantitative evaluation, and Step 4-1 through Step 5 is in qualitative examination phase. This paper mainly refers to the former part of the progress.

Step 1 (Collect and analyse the findings of fault displacement damage)
Step 1-1: Collection of Damage Information/Data

Figure 5 shows the topological relationship between the Chelongpu Fault and Shih-Gang Dam. The end of Chelongpu Fault nearby Shih-Gang Dam is branched into three lines stated A, B, and C fault in Figure 3. The dam is located between A and B fault. C fault is observed near the dam right bank.

Figure 3. Topological Relationship of Chelongpu Fault and Shih-Gang Dam (Based on Konagai 2000)

Step 1-2: Structural Damage Status

The length and height of Shih-Gang Dam are about 290 meters and about 27 meters respectively (Figure 4). As shown in Figure 5., the vertical slip fault struck at the point about 20 meters from the right bank of the dam and 8 meters differential occurred at the point. As a result, the embankment body was destroyed, and reservoir function was lost (Ohmachi, 2000) and also, the crack occurred over the 270 meters of left embankment body due to the shortening of dam length of 6 meters in the axial direction and 2 meters in the downstream direction. Additionally, over 3 meters of deformation occurred at the centre of water sluices and 75 thru 200 meters of peeling due to uplift was estimated from the restoration work after the disaster.
Step2: Set tentative parameters to evaluate the capacity
Step2-1: Identification of failure part/mode

Based on the failure situation of collected in Step 1, we focused on both local and global behavior of dam body in the event. As regards local state, 8 meters of vertical slip fault struck at the point about 20 meters from the right side and severely failure (Figure 5.). On the other hand, severe failures of the dam body are mainly absorbed directly above the C fault, and the dam body somewhat away from the C fault remains slightly cracked and deformed. Figure 6. shows the observed micromotion of Shih-Gang dam just after the event. The data or the restoration work report (Ohmachi, 2000) pointed out the uplift stretched the length of remaining dam body. Therefore, the following two cases were set separately for global behavior such as uplift and local behavior in severely failure portion.

Figure 5. Overview of the failure of Shih-Gang Dam (SGRDF,1999)
Step2-2: Identify the failure scenarios based on the failure part/mode

Following the previous steps, we drew the failure scenario as follows:
Firstly, cracks occurred due to several centimetres to 1m deformation in axial compression.
Secondly, vertical movement under compression caused the peeling between all over the supporting soil
and dam body. At the stage, under the influence of the peeling and the eccentricity by non-uniform cross
section, 2m of buckling/bending in the upstream direction occurred. Finally, the foundation and body of
the embankment were collapsed by the of both vertical and axial deformation of fault.

Step2-3: Setting tentative variation range of capacity parameter for each failure part/mode

Considering the general properties for concrete and supporting soil of dam and the effect of nonlinearity
in the large deformation, the tentative variation range of concrete and soil follows as Table 1.
Furthermore, for detailed evaluation, assume that the concrete constitutive law follows the JSCE standard
(JSCE, 2015). At the moment, we conducted only one case with the constitutive law shown in Figure7.
As material properties of the soil, Young's modulus are 100 MPa as soft rock and 8GPa as hard rock.
Poisson's ratio is 0.4, mass density is 2.0 ton/m³, and friction coefficient (Ground) is 0.4 for detailed
calculation.

Table 1: Tentative Variation Range of Strength Parameters

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Young’s Modulus</th>
<th>1.25, 6.33, 20.0, 101, 320 (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poisson Ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Soil</td>
<td>Shear Wave Vel.</td>
<td>50, 100, 200, 316, 1000 (m/s)</td>
</tr>
<tr>
<td>Unit Weight</td>
<td></td>
<td>2.0 (t/m³)</td>
</tr>
</tbody>
</table>
Figure 7. Mechanical Properties of Concrete of Dam Body

Step3: Set tentative parameters to evaluate response

Step3-1: Set response analysis model and variation range of response parameter based on the failure scenarios

For global behavior, FE model shown in Figure 8 was developed to study the relationship between soil-structure interaction and uplift based on the failure scenarios in step2-2.

Forced vertical displacement is given by the blue side of fixed points. Beam elements represent twenty dam bodies each node is connected by soil spring with gap element that judges contact between dam body and supporting soil. Variation range of response parameter is shown in Table 2.

On the other hand, the nonlinear numerical model was developed to study the failure mode using detailed local FE model shown in Figure 9. Since it involves large deformation, destruction and contact-peel, an explicit method that can proceed stably and get solution even with a problem of strong nonlinearity is adopted.

For both global and local analysis, the commercial nonlinear finite element method code Abaqus was used. The tentative input displacement is set based on Step1-3. In this report, the variety of input displacement is not considered at the moment.

Figure 8. Diagrams of Global FE Model
Step3-2: Set median image model

Table 2. shows the list of sensitivity study cases for global behaviour and Figure 10. shows the examples of study results. Index A in Table 2 is defined as the equation below that is the well-known value as the indicator of deformation mode for horizontal load in pile design. Detail of the calculations are reported in the literature (Nikaido et al, 2019).

Table 2: Sensitivity Study Cases for Global Behaviour

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Index A (m)</th>
<th>Young’s Modulus of Concrete (GPa)</th>
<th>Shear Wave Vel. of Soil (m/s)</th>
<th>Weight (MN/m)</th>
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<tr>
<td></td>
<td></td>
<td>1.25 6.33 20.0 101 320 50 100 200 316 1000</td>
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<tr>
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\[
A = \sqrt[4]{\frac{E}{G_{soil}}} \tag{1}
\]

\[
G_{soil} = \frac{Y^2}{g} \tag{2}
\]

Where, \(E\) is Young’s Modulus and \(G_{soil}\) is Shear Modulus of Soil.
Figure 10 shows the example of results. The red colored elements indicate the peeled area. In addition to the closest point to the fault shown at the left side of Figure, the various contact peel behavior appears in the rest of area. Also, the right side of Figure 10. shows the whole results with the relationship of Index A and ratio of peeled area. As can been seen on the figure, the linear relationship and the reasonable range of the stiffness of dam body and supporting soil are assumed.

![Figure 10. Results of Global Analysis](image)

As the condition for the calculation of local failure, the forced fault slip which rate were 7.6 meters for vertical upward, 6 meters toward the dam axial direction (left bank to right bank), the 2 meters toward downstream direction, and the slip speed of 1 m/s were given at the bottom of FE model (Figure 11). We performed iteration by sensitivity analysis so as to approximate the sketch or pictures of the failure shown in Figure 11. Examples of sensitivity analysis are also shown in Figure 12. Compared with the observation, the stiffness of the ground soil largely affects the failure state of FE model. Regarding hard rock case, failure area is spread wider than the observation. Throughout these attempts, a median image model and the rational range of parameters have become clearer.

The progress of collapse of the dam body can also be expressed by the FD-Axial Force relationship shown in the left side on Figure 13. The loss-of-function modes from point (a) through (d) and FE analysis results are shown in the right side on Figure 13. It is clear from the Figure that the compressive failure field generate in thinner and compressive side by bending moment occur by vertical slip at (a) of 60 cm FD, then brittle destruction occurs through (b) of 150 cm FD, after that area of destruction spread on right side of dam body keeping residual axial force from (c) through (d) of 500 cm FD. Since these trends are similar to the general behavior of compressive test for concrete specimen, they are considered as the reasonable image of the tentative median of responses. We also investigate the response range by using this median image making use of the model.

Throughout the process of numerical studies for both global and local analysis, we established the median image model that can simulate the failure scenario.
**Step3-3: Identification of important uncertainty factors of the median image model and setting**

Through the accumulation of interim content by sensitivity analysis in the median model setting, important uncertainty factors are identified and the range of response in global and local behavior been studied.

The followings were identified as important uncertainty parameters. 1) Stiffness and Strength of Supporting Soil 2) Boundary Conditions of Soil-Structure Coupled Analysis Model 3) Stiffness and Strength of Structure 4) Analysis Method

Throughout the application process, the prospect of the feasibility of FDFEM was obtained.
CONCLUSION

The results of this research are as follows;
1) The authors proposed the composition and procedure of the tentative FDFEM verification framework. The configuration/procedure consists of 5 Steps.
2) To confirm the feasibility of the composition and procedures of the tentative framework, the authors applied the procedure to the actually fault induced failure structure of the Shih-Gang Dam in Chi-Chi Earthquake. The scope of its application in this paper is in the middle of Step3.
3) As important data of the Shih-Gang Dam, the surrounding topography / geological structure, the shape and characteristics of the structure, and the failure situation were published. Thus, we could conduct various and valuable studies on the tentative FDFEM verification framework using these pieces of information.
4) Through this application, the prospect of the feasibility of FDFEM was obtained.

In future, we will improve the framework and carry out the final Step5 and improve the composition and procedures of the tentative FDFEM verification framework. Improvement configuration procedure will be applied to conduct FDFEM for nuclear facility and promoted for practical application.

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