The Concept of Validation Strategy about Fault Displacement Fragility Evaluation Methodology and its Application to Actual Damaged Structure

Hideaki TSUTSUMI [a], Yuji NIKAIDO [b], Yoshinori MIHARA [b], Ryusuke HARAGUCHI [c], Katsumi EBISAWA [a]

[a] Central Research Institute of Electric Power Industry, Tokyo, Japan
[b] Kajima Corporation, Tokyo, Japan
[c] Mitsubishi Heavy Industries, Ltd, Kobe, Japan

Abstract: The authors have conducted examination of fault displacement (FD) PRA methodology framework and identification of technical issues. As a part of the development, the authors are confirming the validity of the Fault Displacement Fragility Evaluation Methodology (FDFEM) based on the actual damaged case because the uncertainty to evaluate realistic response have alternatively been determined with reference to the values in seismic fragility evaluation methodology (SFEM) and have not been validated so far. Contrary to the fact that validation of 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. In order to confirm the feasibility of the composition and procedures of the tentative FDFEM verification framework, the authors applied them to damage of Shin-Kang Dam in Chi-Chi Earthquake (Taiwan, 1999). Throughout this study, we got a prospect of the feasibility of the composition and procedures of the tentative FDFEM validation framework.

Keywords: Fault displacement PRA methodology, Fault displacement fragility evaluation methodology, Verification of evaluation methodology, Tentative verification procedure, Damage of hydroelectric power dam by Taiwan Chi-Chi earthquake.

1. Introduction

The Chi-Chi Earthquake, a magnitude of 7.6, occurred in Taiwan in Sept.1999. During the event, dam and buildings have collapsed by fault displacement (FD), and the influence of FD on structures has attracted attention. Recently in Japan, interest on the impact of principal and secondary FDs on nuclear facilities has increased, and it is currently recognized as an urgent issue for investigation. The current status regarding FD PRA methodology in Japan is as follows. The Atomic Energy Society of Japan (AESJ) is conducting two activities [1], [2]. Japan Society of Civil Engineers published research report of FD evaluation that included investigation of Fault and FD, FD evaluation based on numerical analysis and experiment etc. [3]. Also, the international conference related to the trend of FD hazard including nuclear power industry field were held in the United States[4]. The authors were conducting analysis and examination for developing fault displacement PRA methodology [5]. Under this context, the authors have conducted examination of FD PRA methodology framework and identified technical issues. As a part of the development, the authors are confirming the validity of the Fault Displacement Fragility Evaluation Methodology (FDFEM) based on the actual damaged case because the uncertainty to evaluate realistic response have alternatively been determined with reference to the values in seismic fragility evaluation methodology (SFEM) and have not been validated so far. Contrary to the fact that validation of 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. In order to confirm the feasibility of the composition and procedures of the tentative FDFEM verification framework, the authors applied them to damage of Shin-Kang Dam in Chi-Chi Earthquake (Taiwan, 1999). Throughout this study, we got a prospect of the feasibility of the composition and procedures of the tentative FDFEM validation framework.
In this report, the basic policy of development and validation strategy of FDFEM is described firstly and the application of the procedure to the case of Shin-Kang Dam in Chi-Chi Earthquake (Taiwan, 1999)

2. The basic concept of validation strategy of fault displacement fragility evaluation methodology (FDFEM) in FD PRA and composition and procedure of tentative FDFEM verification framework

2.1 The current status of fault displacement PRA and fragility evaluation methodology

Since the effect extent on the risk of nuclear facilities (e.g. Core Damage Frequency) has not been obvious, priority is given to the development of reasonable framework. Once the effect to the risk is significant, it will be refined. The FD PRA procedure consists of accident scenario identification, hazard evaluation, fragility evaluation and accident sequence evaluation as shown in Fig. 1. The evaluation procedure is basically the same as the framework of the earthquake and tsunami PRA procedure. Contrary to the fact that validation of 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. Therefore, validation of FDFEM is conducted using actual damage cases of general industries around the world.

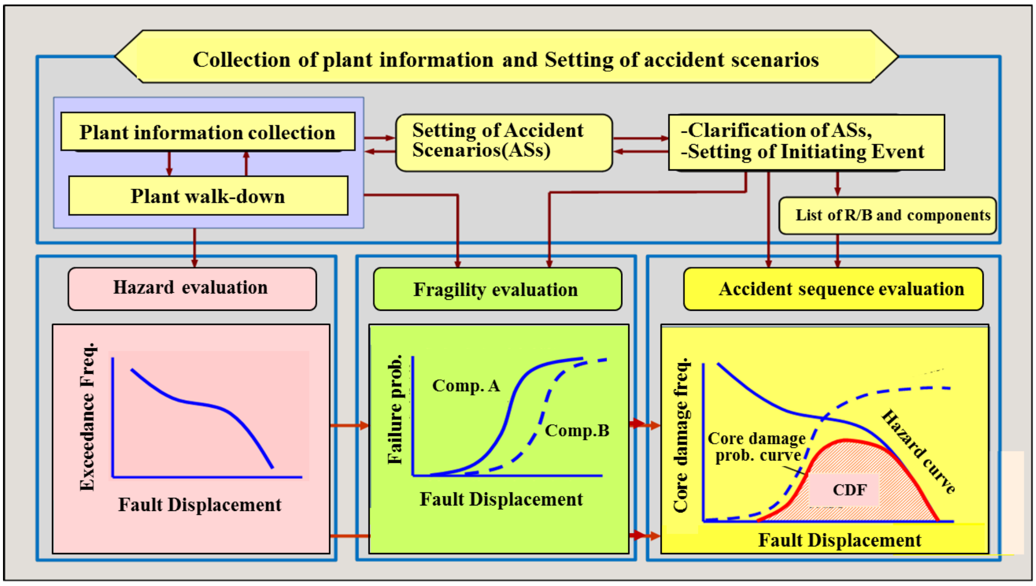


Fig. 1 Procedure of Fault Displacement PRA

2.2 Basic concept of the validation strategy of fault displacement fragility evaluation methodology

The authors propose the following basic concept of the validation strategy of FDFEM;

(1) Since the effect extent on the risk of nuclear facilities (e.g. Core Damage Frequency) has not been obvious, priority is given to the development of reasonable framework. Once the effect to the risk is significant, it will be refined

(2) Validation of FDFEM is conducted using actual damage cases of general industries around the world.

(3) Since the design standards of nuclear facilities and general industrial facilities may be different, the difference is considered as one of the epistemic uncertainty factors.

(4) Quantitative handling of epistemic uncertainty factors in (3) is as follows. First, rough variation band is given as an initial value, and then repeats iteration several times based on the judgment of expert engineers, finally find the rational variation band.

(5) The development of the FDFEM validation framework consists of the following three stages.

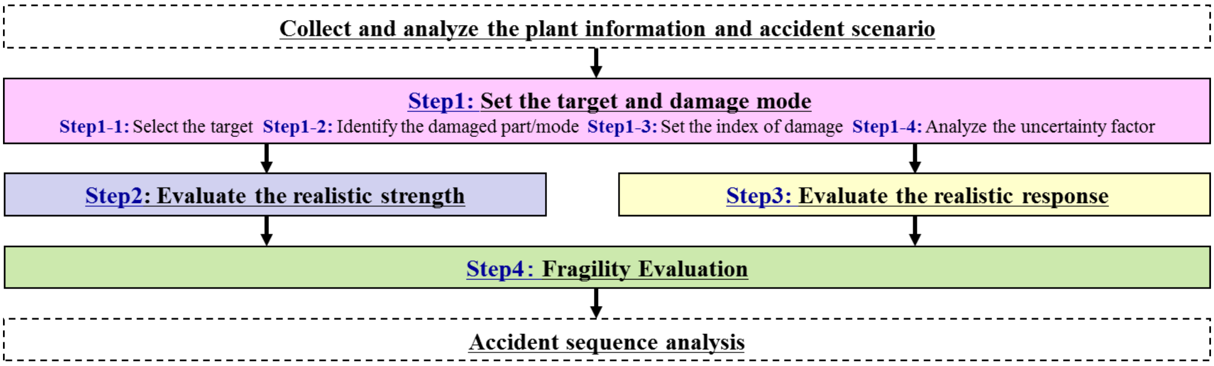
Stage1: Develop the tentative FDFEM validation framework

Stage2: Apply the tentative framework to the actual damage case and improve the framework

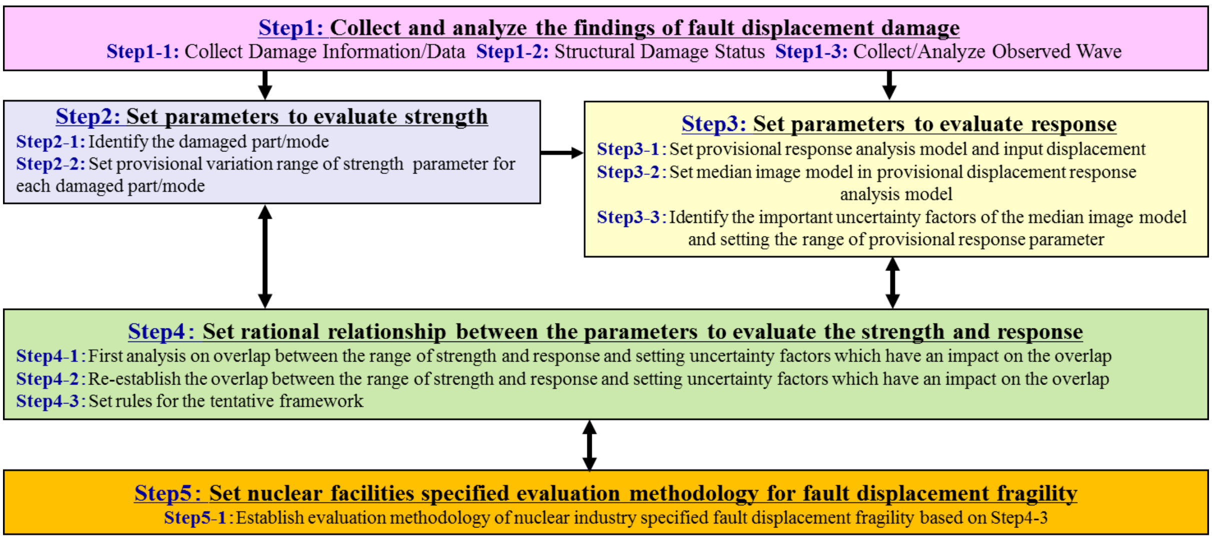
Stage3: Apply the improved framework to the actual damage case again and develop the final FDFEM validation framework

2.3 Structure and procedure of tentative FDFEM verification framework

The tentative FDFEM validation framework is established based on the building fragility evaluation in the earthquake/tsunami PRA procedure briefly shown in the upper side of Fig.2 and the development of the validation framework consists of the five steps and relationship of each steps is shown on the lower side of Fig.2. Contrary to the flow down of the procedure of the SFEM, the framework itself, damage 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 Step5 in the Figure.



(Procedure of Seismic/Tsunami Fragility Evaluation Methodology)



(Structure and Procedure of FDFEM Verification Framework)

Fig.2 Structure and Procedure of FDFEM Verification Framework compared with Seismic/Tsunami Fragility Evaluation

The components of the steps as follows and details are described in the next chapter with the application example.

Step1: Collect and analyze the findings of fault displacement damage

Step1 consists of following 3 items;

Step1-1: Collect Damage Information/Data

Step1-2: Structural Damage Status

Step1-3: Collect and Analyze of Observed Wave

Step2: Set parameters to evaluate strength

Step2 consists of following 2 items;

Step2-1: Identification of damaged part/mode

Step2-2: Set tentative variation range of strength parameter for each damaged part/mode

Step3: Set parameters to evaluate response

Step3 consists of following 3 items;

Step3-1: Set tentative response analysis model and input displacement

1) Set tentative response analysis model based on damaged part/mode identified in Step2-1
2) Set tentative input displacement based on Step1-3
3) Set variation of displacement considering uncertainty of input displacement of 2)

Step3-2: Set median image model in tentative displacement response analysis model

1) Set variation range of damage parameter based on damage mode identified in Step2-1 (from sketch data in survey report on damage case etc.)
2) Repeat iteration by sensitivity analysis so as to approximate the variety range set in 1) using the Step 3-1 tentative response analysis model
3) Set the median image model from the approximation result of 2),

Step3-3: Identify important uncertainty factors of the median image model and setting the range of tentative response parameter

1) Set the tentative range of response parameter for each damaged part/mode after identifying important uncertainty factors through the procedure in Step3-2

Step4: Set rational relationship between the parameters to evaluate the strength and response

Step4 consists of following 3 items;

Step4-1: First analysis on overlap between the range of strength and response and setting uncertainty factors which have an impact on the overlap

1) As shown in Fig.3, the indicator of damage in structure is overlap of load strength capacity range and response range for each damage mode. In other words, it is considered to be damaged when the response exceeds the strength.
2) Analyze the separation between the upper limit of the tentative range of response parameter for each damage mode in Step3-3 and the lower limit of the tentative range of strength parameter for each damage mode in Step2-2 (Fig.3)
3) Set the overlapping coefficient. from the analysis of the uncertainty factor concerning the separation in 2), the ratio of the upper limit value of the range of response and the lower limit value of the range of strength is set as

Step4-2: Reestablish the overlap between the range of strength and response and setting uncertainty factors which have an impact on the overlap

1) Review Step2 and Step3-1 and re-execute Step4-1as the overlapping coefficient set in Step4-1-3) is not logical

Step4-3: Set rules for the tentative framework

1) Set the method of finding the parameters necessary for evaluating the fragility of the structure. Assume that both the tentative range of response parameter for each damage mode in Step3-3 and the lower limit of the tentative range of strength parameter for each damage mode in Step2-2 follow a lognormal distribution.
2) The median and logarithm standard deviation of each strength and response are obtained as follows. Each median and logarithm standard deviation is obtained by two point estimation method using upper and lower limit values of the range of yield strength and response respectively. Divide Each logarithm standard deviation into aleatory and epistemological uncertainty by SRSS method. Assume the overlapping coefficient set in Step4-1-3)

correspond to the stress/response coefficients in the fragility assessment.

3) In order to make the rules of Step4-3-1) and Step4-3-2) specified for nuclear industry, consider the epistemological uncertainty factor in basic policy (3).

Step5: Set nuclear facilities specified evaluation methodology for fault displacement fragility

Establish evaluation methodology of nuclear industry specified fault displacement fragility based on Step4-3. Firstly in this establishment, roughly divide into the difference between the nuclear power industry specified one and others in the contents relating strength term and response term. Then, identify the important uncertainty factors of each term, clarify whichever have an impact, and consider the epistemological uncertainty factor.

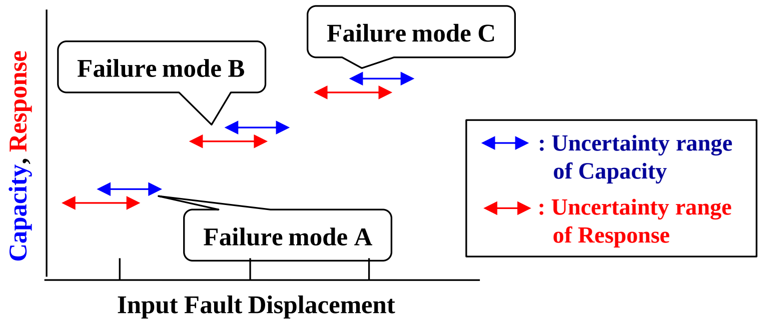


Fig.3 Concept of Overlap between the Range of Strength and Response Uncertainty

3. Application of tentative FDFEM verification framework to the damage case

3.1 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 damage structure of the Shin-Kang Dam in Chi-Chi Earthquake (Taiwan, 1999). Chelongpu Fault which is the low angle reverse fault shown in Fig.4 The reasons for choice of the case are that many related information is maintained. For instance, the fault itself, the surrounding topography / geological structure, the shape and characteristics of the structure, the damage situation, and so on, by field survey after the earthquake, and the restoration work, etc.As for progress of application, Step1 through Step 4-1 in chapter2.3 is being considered including quantitative evaluation, and Step4-2 through STEP 5 is in qualitative examination phase. This paper mainly refer to the former part of the progress.

.3.2 Step1 (Collect and analyze the findings of fault displacement damage)

(1) Step1-1: Collection of Damage Information/Data

Fig.5 (a) shows the topological relationship between the Chelongpu Fault and Shin-Kang Dam. The end of Chelongpu Fault nearby Shin-Kang Dam is branched into three lines stated A, B, and C fault in Fig.5. The dam is located between A and B fault. C fault is observed near the dam right bank.

(2) Step1-2: Structural Damage Status

The length and height of Shin-Kang Dam are about 290 meters and about 27 meters respectively (Fig. 5 (b)). As shown in Fig. 5 (c), the vertical slip fault struck at the point about 20 meters from the right side of the dam and 8 meters differential occurred at the point. As a result, the embankment body was destroyed and reservoir function was lost[6] 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., The port of the intake tunnel (height 4 m, width 4 m) peeled off the tunnel main body and shifted about 30 cm[7]

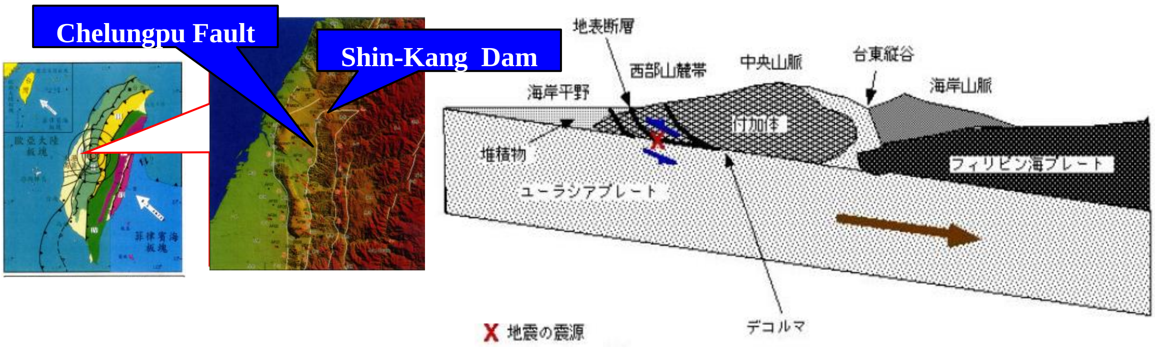
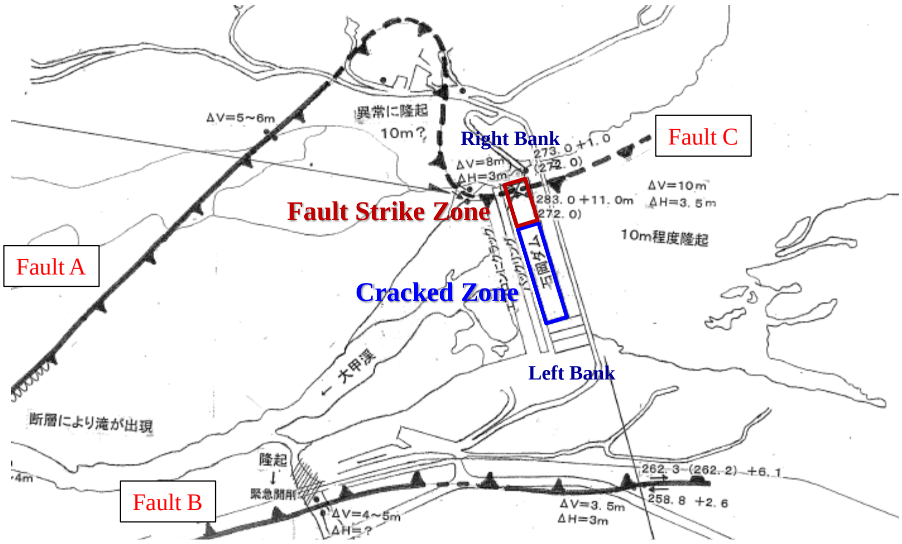
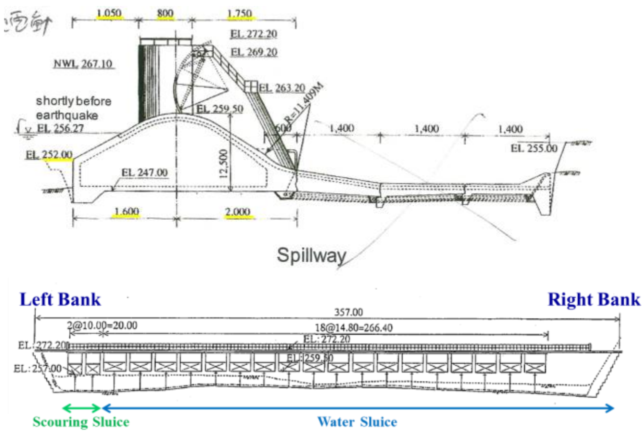
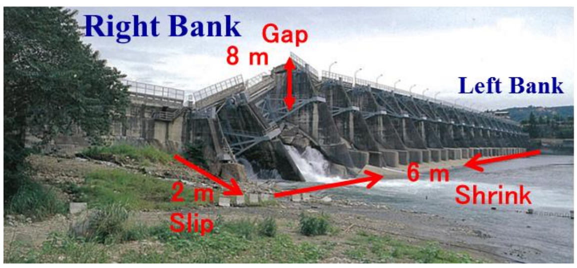


Fig.4 Location of Chelongpu Fault and Shin-Kang Dam in Chi-Chi Earthquake.



(a) Topological Relationship of Chelongpu Fault and Shin-Kang Dam





(b) Structural Overview of Shin-Kang Dam (c) Damage Overview of Shin-Kang Dam
Fig.5 Topological Relationship of Chelongpu Fault and Shin-Kang Dam and Structural and Damage Overview of Shin-Kang Dam

(3) Step1-3: Collection and Analysis of Observed Wave

As shown in Fig. 6 velocity and displacement waveforms are observed near Shin-Kang Dam.

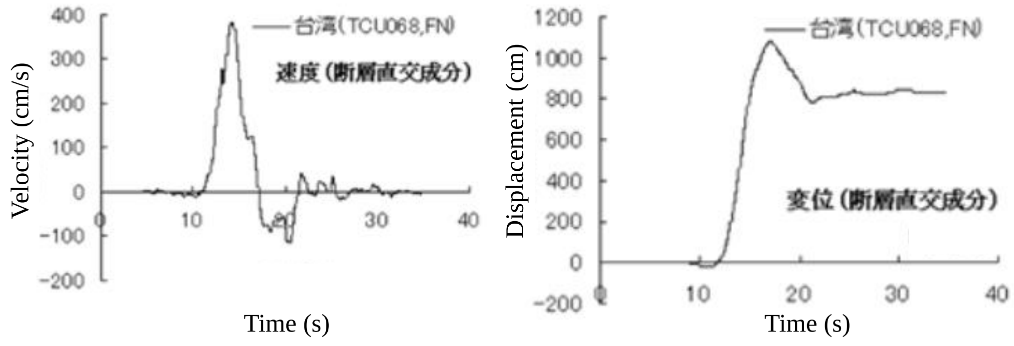


Fig.6 Observation Velocity and Displacement Waveforms

3.3 Step2: Set parameters to evaluate the strength

(1) Step2-1: Identification of damaged part/mode

Based on the damage situation of collected Step1-2, severe damages of the dam body are mainly absorbed by the deformation of the ground and the dam body directly above the C fault, and the dam body somewhat away from the C fault remains slightly cracked and deformed. Therefore, as the damaged part/mode shown in Fig. 7, the following two cases were set separately for damage of the right bank cut-off dam body and crack of the left bank dam body.

- Case A: Cracking mode of the dam wall body with minor damage (deformation of about 1 m)
- Case B: Functional loss mode of the dam body and directly above the fault

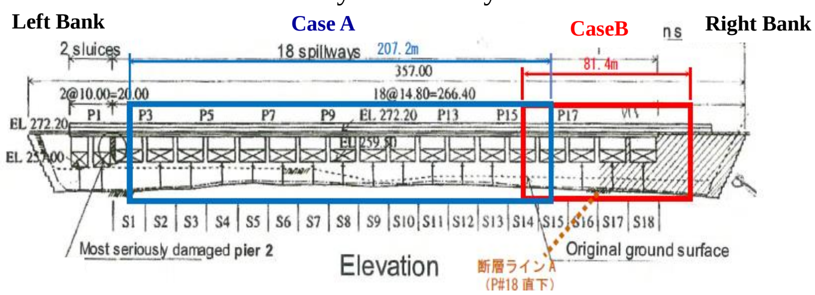


Fig.7 Identification of Damaged Part/Mode

(2) Step2-2: Setting tentative variation range of strength parameter for each damaged part/mode

Assume that the concrete constitutive law follows equation (1-1) to (1-4). In this report, we describe only the average image of the median according to the constitutive law, the analysis of the range of parameters regarding strength is underway and will be reported next time.

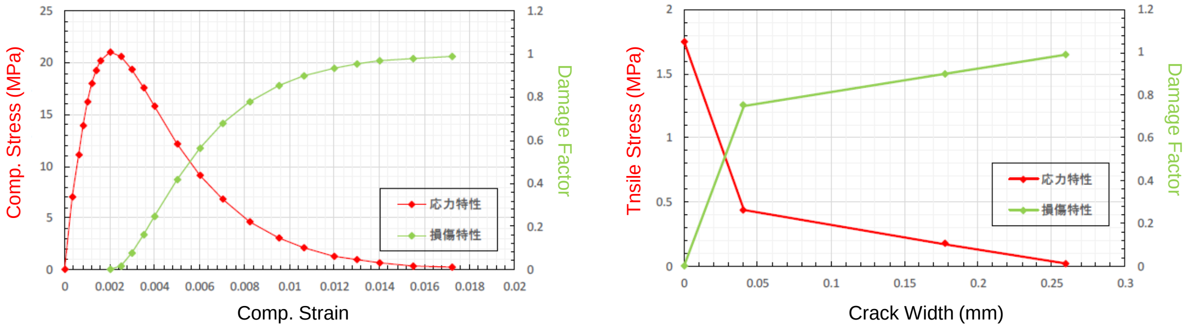
$$\sigma_c = E_0 K(\varepsilon_c - \varepsilon_p) \quad \cdots\cdots\cdots (1\text{-}1)$$

$$E_0 = \frac{2 \cdot f_c}{\varepsilon_{peak}} \quad \cdots\cdots\cdots (1\text{-}2)$$

$$K = \exp\left\{-0.73\frac{\varepsilon_c}{\varepsilon_{peak}}\left(1-\exp\left(-1.25\frac{\varepsilon_c}{\varepsilon_{peak}}\right)\right)\right\} \quad \cdots\cdots\cdots (1\text{-}3)$$

$$\varepsilon_p = \varepsilon_c - 2.86 \cdot \varepsilon_{peak}\left\{1-\exp\left(-0.35\frac{\varepsilon_c}{\varepsilon_{peak}}\right)\right\} \quad \cdots\cdots\cdots (1\text{-}4)$$

Where, σ_c is compressive stress (N/mm^2), $\varepsilon_c$is compressive strain (mm/mm), ε_{peak} is strain at compressive strength(assumed to be 0.002), ε_p is compressive plastic strain (mm/mm), and K is the elastic stiffness residual rate. Fig. 8 (a) shows the compressive stress - compressive strain relationship, and Fig. 8 (b) shows the tensile - crack displacement relationship. As material properties of the ground, Young's modulus is 100 MPa at soft rock (shear wave velocity *Vs* 134 m/s), 8 GPa at hard rock (*Vs* 1200 m/s), Poisson's ratio 0.4, mass density is 2.0 ton / m 3, friction coefficient Ground) is 0.4.



(a) Compressive Stress-Strain Curve (body) **(b) Tensile Stress-Crack Width Curve (body)**

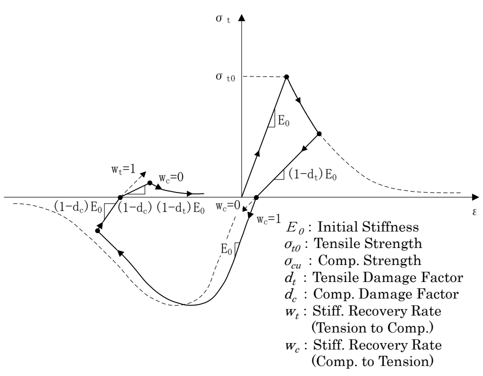
Fig.8 Mechanical properties of concrete of dam body

3.4 Step3: Set parameters to evaluate response

(1) Step3-1: Set tentative response analysis model and input displacement

The response of the concrete structure is assumed to follow the concrete isotropic plasticity damage constitutive law of Fig. 9. In this report, only the average image of the median according to the constitutive law is described and the analysis of the range of parameters regarding response is underway and will be reported next time.

The numerical model is made by finite element method using isotropic plastic damage model shown in Fig. 10. Damage of concrete is captured as a whole state by tensile, shear, and compressive failure, and expressed as a direction independent scalar value. Decrease in slope of unloading response is treated as reduction rate of elastic rigidity (= damage value) of material and decrease in elastic stiffness is expressed by two damage variables *dt* and *dc* (0 to 1) on the tensile side and compression side. These variables can be are functions of plastic strain, strain speed and field variables. As an analysis method, time history response analysis method is chosen. 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 the numerical analysis, the commercial nonlinear finite element method code Abaqus was used. The tentative input displacement was set based on STEP13. In this report, the variety of input displacement is not considered. Table 1 shows the details of the cut-off wall FEM model and the analysis code.



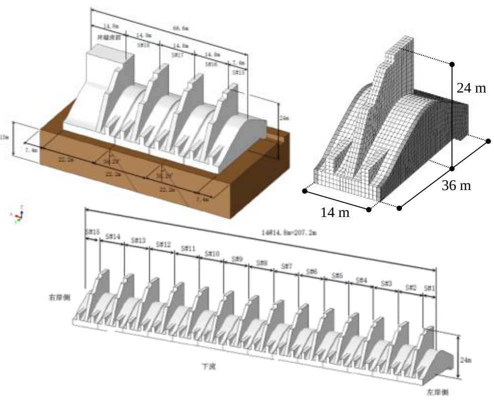


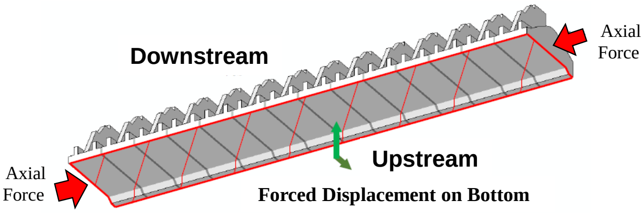
Fig.9 Cyclic Constitutive Law of Concrete Fig.10 Outline of Dam Body FE Model

Table 1 Specifications of FE model and method

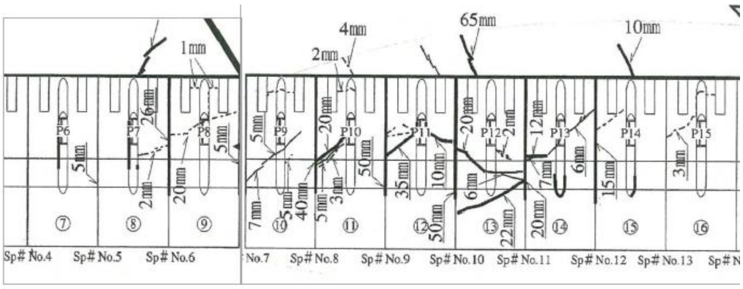
Model	Case A	Case B
Element	107372	87277
Node	90965	73640
Element Type	C3D8R (Reduced Integration)	
Constitutive Low	Concrete Isotropic Plasticity Damage Model	
Method	Stress Deformation Analysis (Explicit/Large Deformation)	
Code Ver.	Abaqus/Explicit 3DEXPERIENCE R2017x	

(2) Step3-2: Set median image model in tentative displacement response analysis model

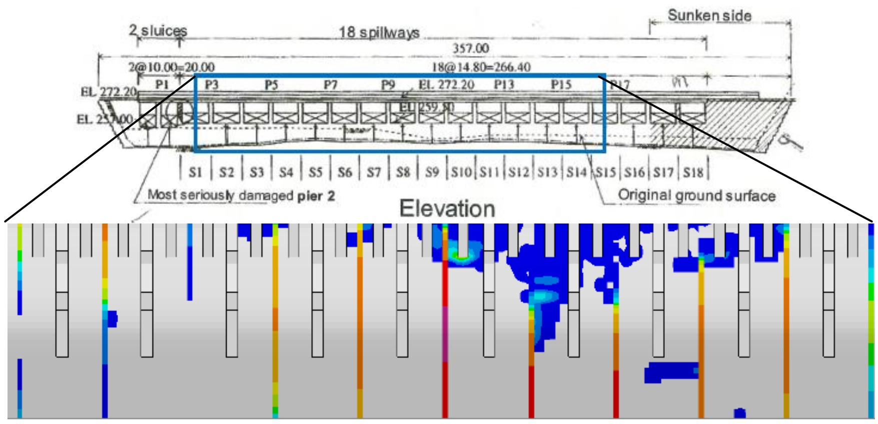
As the condition for the calculation of crack damage (Case A), forced displacement 1m obtained by damage survey was given to the bottom of the body part shown in Fig. 11 (a). We performed iteration by sensitivity analysis to approximate the sketch of the cut-off wall crack shown in Fig. 11 (b). The analysis result is shown in Fig. 11 (c). A median image model for case A was set based on the analysis result.



(a) Crack analysis model(Case A)



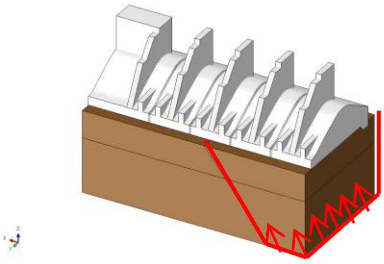
(b) Outline of Sketch of Cracks on Dam Body



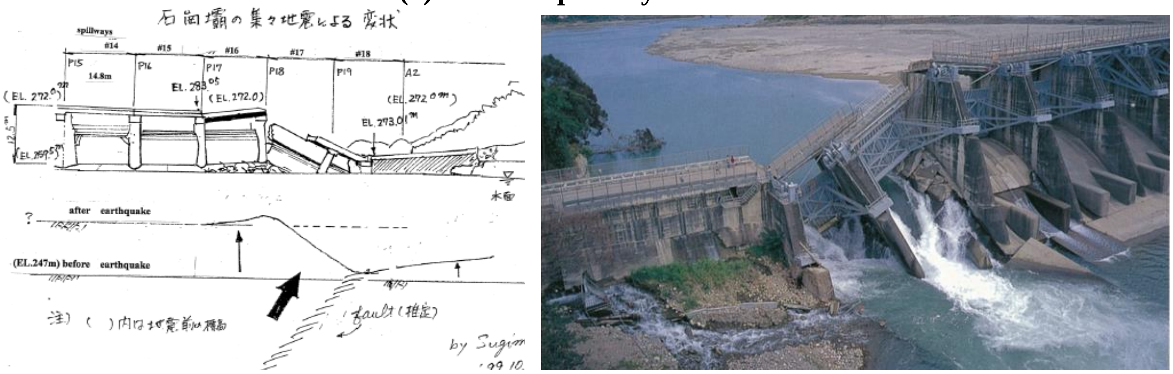
(c) Example of result of numerical analysis

Fig.11 Crack Analysis Model, Crack Sketch and FE Analysis Result

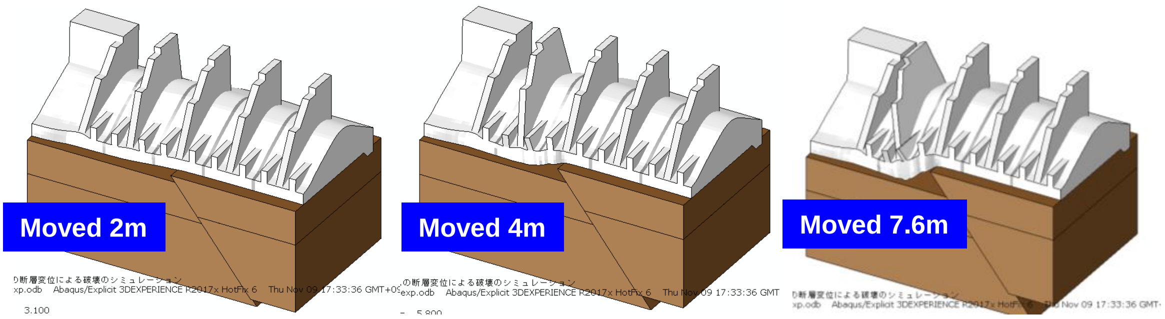
As the condition for the calculation of fault rise damage (Case B), the fault slip rate is 7.6 meters for vertical upward, 6 meters toward the dam axial direction (left bank to right bank), the 2 meters toward downstream direction, and the slip speed of 1 m/s. We performed iteration by sensitivity analysis so as to approximate the sketch or pictures of the damage of the dam body section shown in Fig. 12 (b). The analysis results are shown in Fig. 12 (c). Fig. 12 (d) shows the relationship between the hardness of the foundation ground and soft rocks (shear rate Vs 134 m / s) and hard rocks (Vs 1200 m / s) for contact and peeling of the cut-off wall body and foundation ground as one example of many attempts of sensitivity analysis. In the case of hard rock, the ground surface tends to be hardly deformed and showed different state from survey. Throughout many attempts, a median image model was set.



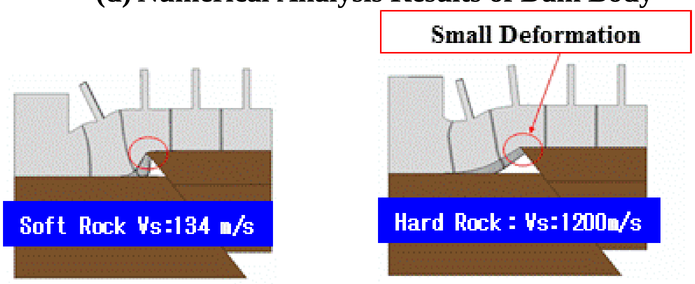
(a) Strike Slip Analysis Model



(c) Outline of Sketch of Dam Block Damage Damage



(d) Numerical Analysis Results of Dam Body



(d) Analysis Result of Contact/Peel of Dam Body and Supporting Ground

Fig.12 Strike Slip Analysis Model, Sketch and Photo, and FE Analysis Result

(3) 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 cases A and B have been studied.

3.5 Step4:Set rational relationship between the parameters to evaluate the strength and response

(1) Step4-1: First analysis on overlap between the range of strength and response and setting

As a criterion for reinforced concrete (RC) is shown and each failure mode in the displacement curve (a: cracking occurrence, b: reinforcing steel yield, c: maximum yield strength, d: Peeling of concrete, e: collapse) in Fig.13 (left figure). Though there is a difference between reinforced and lean concrete, Point c corresponds to case A, Point b and c corresponds to case B were targeted.
The progress of collapse of the dam body can also be expressed by the FD-Axial Force relationship shown in Fig. 13 (right). The loss-of-function modes from a through d and FE analysis results are shown in Fig.14. 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 occur 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.
It is under consideration whether the range of lower limit value overlaps the upper limit value of the response and the range of the strength set in Step2-2. An coefficient indicating the overlapping situation is also under consideration.

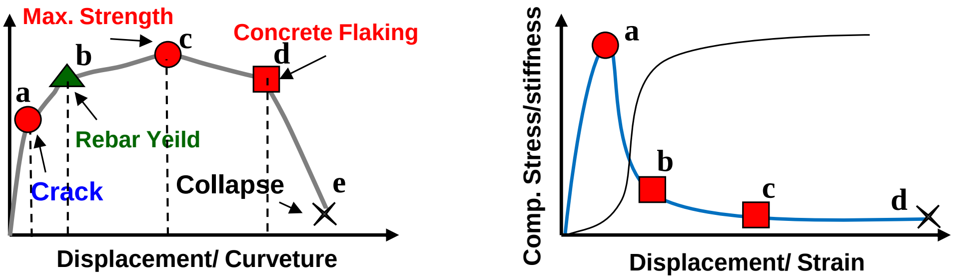


Fig.13 Function Loss Diagram RC (left) and LC Under Uniaxial Compression (right)

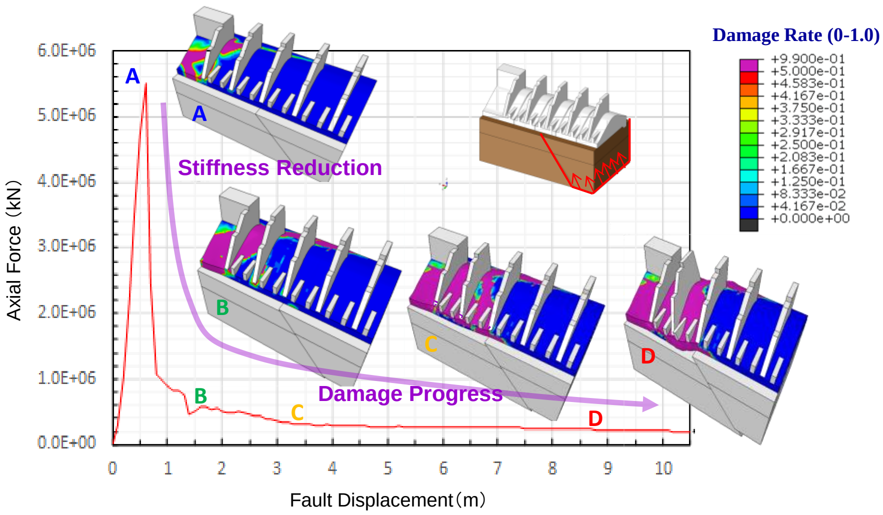


Fig.14 Diagram of the relation between fault slip and axial force in each damage mode

3.6 Step4-2: Reestablishment of overlap between the range of strength and response and setting Step4-3: Set rules for the tentative framework Step5: Set rules for the tentative framework

Step4-2 and Step4-3 are prepared for further study based on the result from Step4-1. For Step5, we are also preparing to consider the following contents:
In the stress term and the response term in the specifications for the nuclear power industry described in 2.3 (3), although the latter does not make a big difference, the former has an effect, which is expected to reflect the recognition on the next report.

4. Summary and future plan

The results of this research are as follows;
1) In addition to establishing basic policies for FDFEM verification, proposed the composition and procedure of the tentative FDFEM verification framework. The configuration/procedure consists of 5 Steps.
2) 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 damage structure of the Shin-Kang Dam in Chi-Chi Earthquake (Taiwan, 1999). Chelongpu Fault. The scope of its application in this paper is in the middle of Step4.
3) As important data of the Shin-Kang Dam, the surrounding topography / geological structure, the shape and characteristics of the structure, and the damage 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 the future, we will 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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