Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

INTRODUCTION OF IMPACT ASSESSMENT TECHNOLOGY AND EVALUATION EXAMPLES FOR FAULT DISPLACEMENT OF CRITICAL CIVIL ENGINEERING STRUCTURES

Kazuhide Yamaguchi[1], Hiroyuki Kumata[2], Takahiro Tsutsumiuchi[3] and Hideki Nagai[3]

[1] Central Research Institute of Electric Power Industry, Sustainable System Research Laboratory, Chiba, JAPAN (yamaguchi3876@criepi.denken.or.jp)
[2] Tohoku Electric Power Co.,Inc. Civil and Architectural Engineering Dept., Miyagi, JAPAN
[3] Obayashi Corporation, Nuclear Facilities Division, Tokyo, JAPAN

ABSTRACT

In October 2021, with the revision of the Seismic Performance Verification Guidelines Reinforced Concrete Underground Structures in Nuclear Power Plants of the Japan Society of Civil Engineers, it was published the impact assessment techniques and valuation example for fault displacement of underground RC culverts as a separate volume. This paper introduces the outline of the impact assessment technology and the evaluation examples for fault displacement.

PREFACE

According to the new regulatory standards for nuclear facilities, if important seismic facilities are installed on the ground with outcrops such as faults that may be active in the future, the activities of the faults may have a significant impact on safety functions. Therefore, it is required to install the facilities on the ground where they have been confirmed that there are no outcrops. The facilities are installed on the ground where there is no risk of fault displacement, on the other hand, it is important to construct a method to quantitatively evaluate the impact on the facilities with respect to the residual risk of fault displacement. This impact assessment technology is a method for quantitatively evaluating the margin for damage and destroy according to the required performance of the structure when a fault displacement acts on the ground directly.

TARGET STRUCTURE FOR EVALUATION

In this study, among the critical civil engineering structures of nuclear power plants, underground reinforced concrete box culverts such as intake channels and seawater pipe ducts are targeted. Examples of critical civil engineering structures are shown in Figure 1 and Figure 2.

FLOW OF PERFORMANCE EVALUATION FOR FAULT DISPLACEMENT

In the impact assessment, the target performance is that the structure does not collapse with respect to the design fault displacement of δ_S given as a given condition from fault surveys. Flow of performance evaluation for fault displacement is shown in Figure 3.

Fault displacement analysis is performed in the following steps.

In Step 1, as shown in Figure 4, the structure to be evaluated and the surrounding ground are modelled as a three-dimensional nonlinear analysis model with structure-ground coupling, and the given fault displacement δ_s is input from the bottom surface of the analysis model.

In Step2, the damage mode of the structure is grasped from the analysis result. Considering this damage mode and functionality required for the structure, the damage index used for evaluation is selected with reference to Figure5. In Figure 5, the target range of the damage index is on the horizontal axis

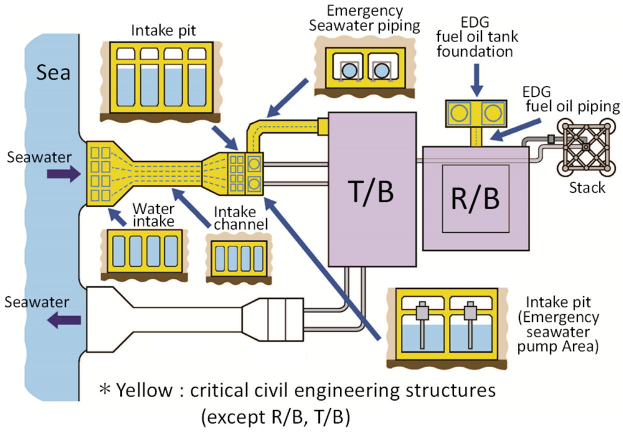

Figure 1. Floor plan of critical civil engineering structures

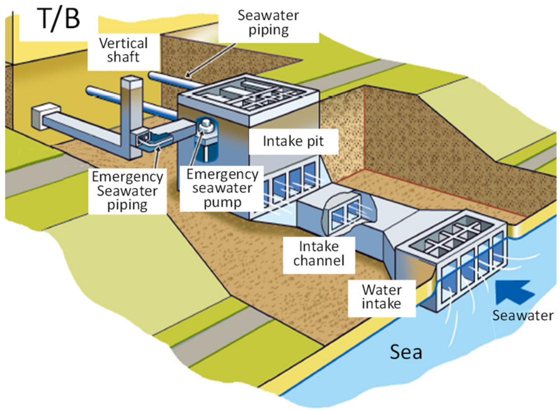

Figure 2. Bird's-eye view of intake channels, etc.

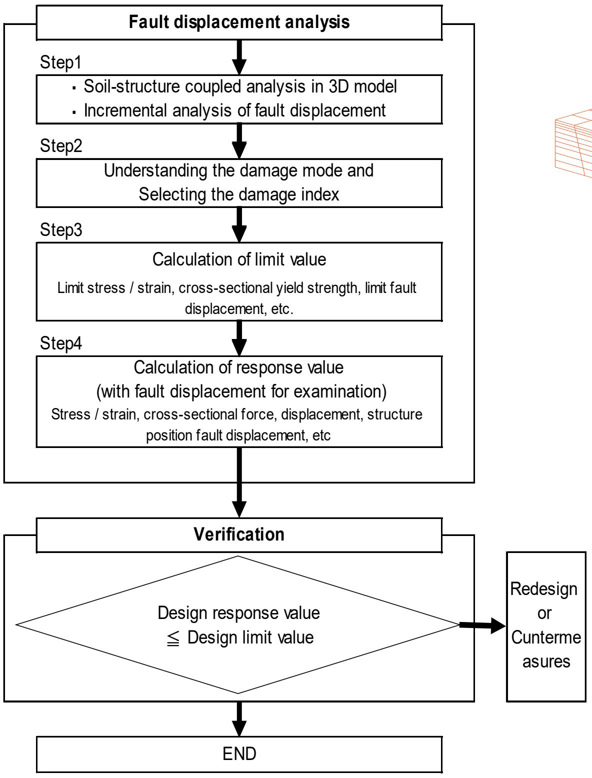

Figure 3. Flow of evaluation

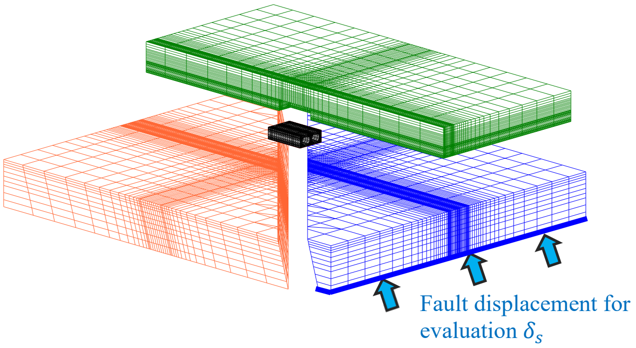

Figure 4. Analysis model

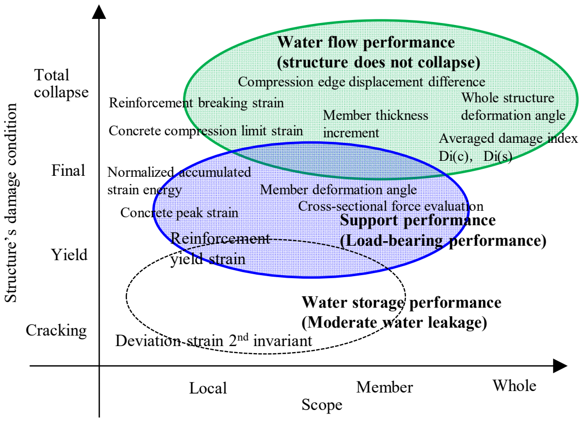

Figure 5. Damage index for each function and its threshold

(classified into three types: local index, index indicating damage to members, and index indicating damage to the entire structure), the damage status of the structure is classified into four types on the vertical axis as crack, yield state, ultimate state, and total collapse; and the functionality required for the structure and its damage index are organized.

In Step3, the limit fault displacement δ_u is calculated by gradually increasing the given fault displacement amount from δ_s. The limit fault displacement amount δ_u is the input fault displacement amount immediately before the structure or the ground exceeds the allowable limit state. The allowable limit state is determined based on the damage index of the structure and the strain condition of the ground in consideration of the damage mode of the structure and the stability of the analysis.

In Step4, the stress/strain, section force, response displacement and fault displacement at structure position etc. at the given fault displacement δ_s are calculated. The amount of fault displacement at the structure position is determined by the fact that the target structure is installed on the bedrock. If it is judged to be equivalent to the given fault displacement δ_s, then δ_s may be used.

As a verification, "Check for damage to the entire system" or "Check for damage to structural members" is carried out for verification of the water flow function. Furthermore, if it is required to maintain the functions of equipment and piping, "Check for damage to structural members" will be conducted to confirm the indirect support function. In "Check for damage to the entire system", a verification is performed by comparing the amount of fault displacements at structure position at the time of given fault displacement δ_s with at the time of the limit fault displacement δ_u (Figure 6). In "Check for damage to structural members", the damage index (strain, etc.), which is calculated using the given fault displacement δ_s is compared with the threshold value (Figure 7).

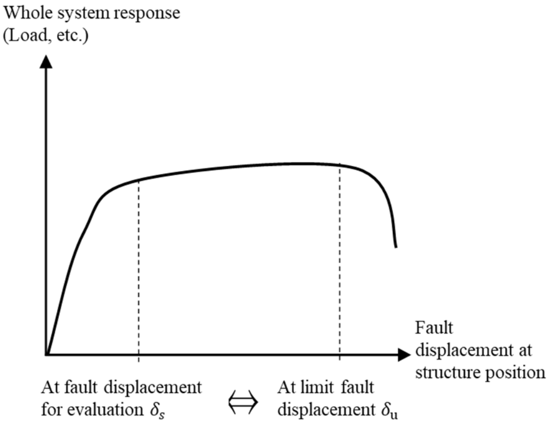

Figure 6. Schematic diagram of verification for damage to the entire system

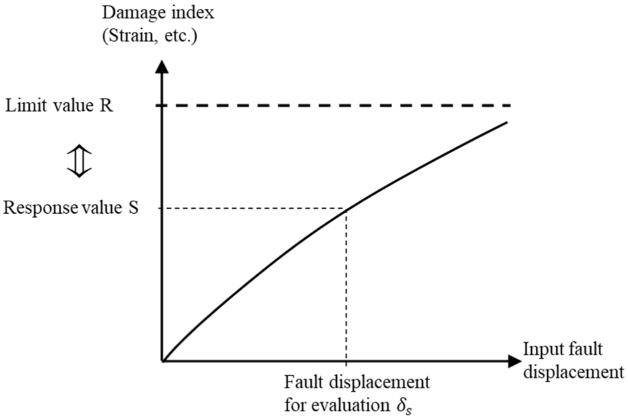

Figure 7. Schematic diagram of verification for damage to structural members

EVALUATION EXAMPLE

In this study, an evaluation example for the intake channel among the critical civil engineering structures is explained.

The function required for the intake channel is a water flow function that it can take in the necessary seawater even if it is affected by fault displacement.

As mentioned above, "Check for damage to the entire system" or "Check for damage to structural members" may be carried out for verification of the water flow function, however in this paper an example of "Check for damage to the entire system" is shown.

Evaluation conditions

a. Target structure

The intake channel is a reinforced concrete double cell box culvert installed on the bedrock. The structural dimensions are 10.0m in width x 5.0m in height x 15.0m in depth (1 block), and the internal dimensions are 3.5m in width x 3.0m in height. The member thickness for the top plate, side wall, and partition wall is 1.0m. The overburden is 8m.

Figure 8 shows the reinforcement details of the target structure. Reinforcement (yield stress of 345N/mm^2) was determined by standard seismic design. The main reinforcement bar is D29@200 (Pw=0.37%), the distribution bar is D22@200 (Pw=0.23%), and the shear reinforcement is D13s400@200 (s: bar arrangement pitch in the longitudinal direction, Pw=0.16%). The concrete has a design standard strength of 24 N/mm^2.

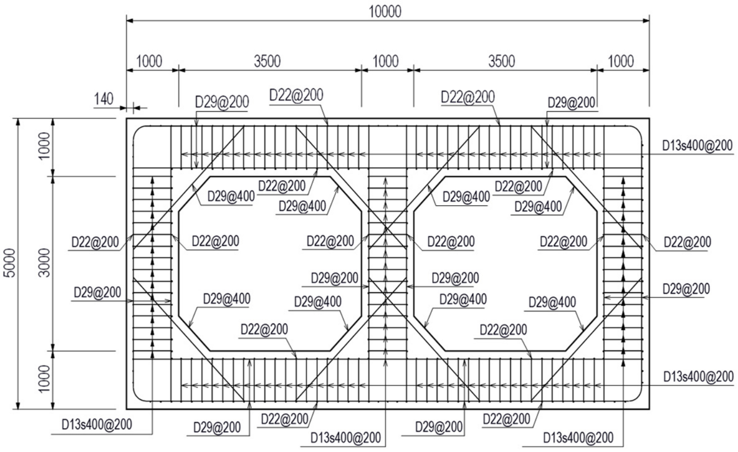

Figure 8. Reinforcement details

b. Ground and bedrock conditions

For the ground (fill & surface soil layer), an elasto-plastic model is applied with consideration of the depth distribution based on the law of power 0.5 to the Young's modulus and Drucker-Prager fracture condition.

For the bedrock (upper and lower), hard rock is assumed. From the upper surface of the bedrock to 9m the shear wave velocity of Vs = 1500m/s, and deeper than that the linear physical properties assumed and Vs = 2250m/s is set.

c. Fault

The fault in this analysis is a reverse fault that intersects the structure near the centre of it. The strike is 45° with respect to the axis direction of the structure, and the inclination angle is 80°. The amount of fault displacement is assumed as δ_s = 200 mm depending on geological surveys.

Fault displacement analysis

Step1

a. Analytical model

Structures subject to fault displacement often studied as a three-dimensional problem due to their geometrical positional relationship with the fault and loads act from the bedrock and the ground. Hence, a soil-structure coupled three-dimensional nonlinear FEM model with 3D solid elements is selected. Structure is modelled as follows: hexahedral element for concrete, truss element for the main and haunch reinforcement bars in the cross-section of the structure, and embedded reinforcement element for distribution and shear reinforcement. Non-linear characteristics and strength by material tests are considered for each of concrete and reinforcement. The analysis model is shown in Figure 9, and the material constitutive laws for concrete and reinforcement are given in Table 1.

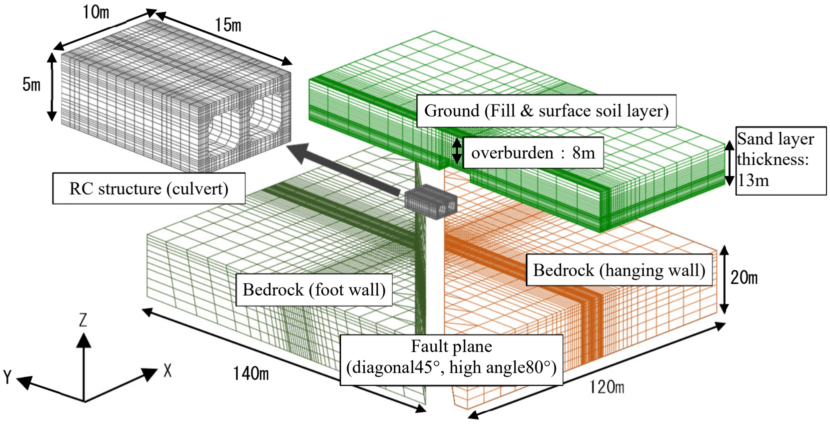

Figure 9. Analysis model

Table1 Material constitutive laws for concrete and reinforcement

Material	Material constitutive law
Concrete	Tension stiffening characteristics: Izumo model (C = 1.0) Up to compression strength: Modified Ahmad model Compression failure condition: Ottosen's 4 parameter model (Hatanaka et al.'s coefficient) Compression softening zone: Nakamura-Higai model Shear transmission after cracking: Naganuma model Softened area after cracking: Softening characteristics based on concrete fracture energy
Reinforcement	Bilinear (secondary stiffness is 1/100)

b. Incremental analysis of fault displacement

For the analysis, the amount of reverse fault displacement is input in 0.2 mm increments to the bottom of the bedrock (hanging wall) of the analysis model.

Step2

a. Understanding the damage mode

Analysis results of 200mm fault displacement are shown in Figure 10.

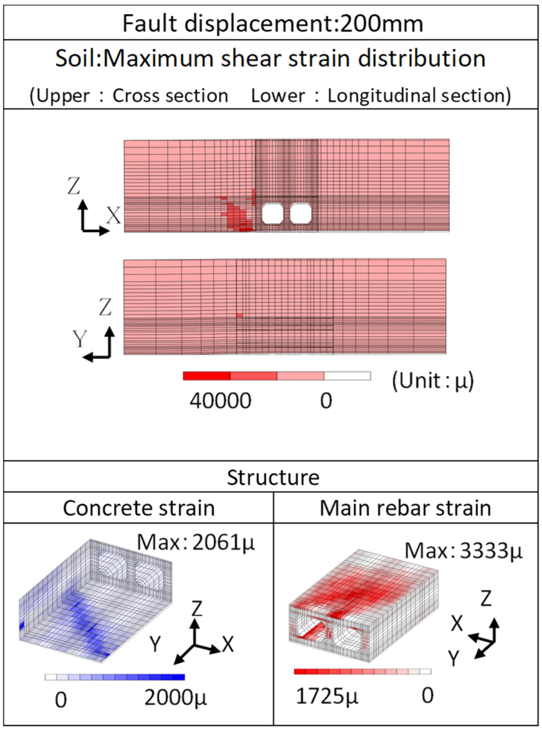

Figure 10. Analysis results

Although a ground shear strain over 20,000μ is distributed along a part of the fault extension line, it can be said that the ground is sound as a whole. The tensile strain of the distribution reinforcement exceeds the yield strain in a wide range from a part of the side wall on the fault extension line to the top plate but does not reach the breaking strain. The tensile strain of the main reinforcement exceeds the yield strain in a part of the top plate on the foot wall side from the fault line but does not reach the breaking strain. The compressive strain of concrete is slightly higher than the compressive peak strain near the fault line.

b. Selecting the damage index

The damage index for water flow function is selected from Figure 4.

In this paper, the compression limit strain of concrete and the breaking strain of the reinforcement are selected as damage indexes for bending damage with consideration of the structure to be evaluated is in the bending damage mode of the entire structure.

Step3

In this paper, in order to perform "Check for damage to the entire system", the amount of limit fault displacement δ_u used for verification is calculated from the analysis in which the input fault displacement amount δ is gradually increased.

Figure 11 shows the response value of the damage index when the input fault displacement δ=500mm, and Figure 12 shows the shear strain distribution of the ground.

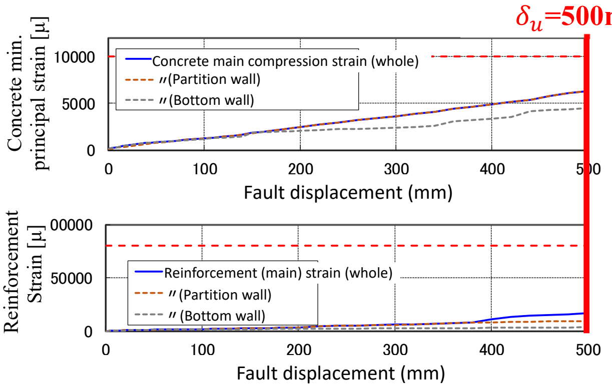

Figure 11. Damage index response value

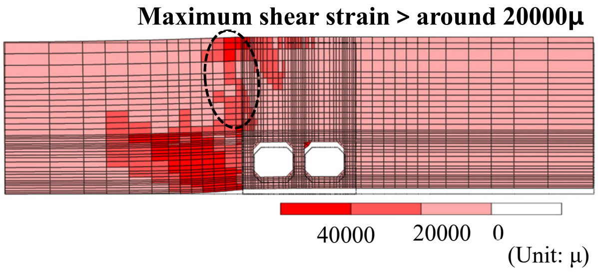

Figure 12. Ground shear strain distribution (δ=500mm)

Since none of the damage indexes reached the threshold value, the target structure maintains the water flow function up to the input fault displacement of 500 mm. On the other hand, in the ground, large shear strain regions are distributed from the upper surface of the structure to the ground surface. If the fault displacement exceeds 500 mm, the stability of the analysis is impaired in the ground part, hence it is judged that the reliability as a numerical analysis will not be ensured.

Therefore, the limit fault displacement δ_u is set to 500mm.

Step4

In this evaluation example, since the target structure is installed on the bedrock, the given fault displacement δ_s is used for fault displacement at the structure position to evaluate "Check for damage to the entire system".

Verification

In "Check for damage to the entire system", the fault displacement for evaluation δ_s and the fault displacement at structure position (= fault displacement for evaluation δ_s) are compared for verification.

Table2 Verification results for fault displacement

Response value	Given fault displacement δ_s	200
	Structure analysis factor γ_a	1.2
	Design response value δ_{sd}	240
Limit value	Limit fault displacement δ_u	500
	Member factor γ_{b1}	1.3
	Material factor γ_{b2}	1.1
	Design limit value δ_{ud}	350
Verification	Structure factor γ_i	1.0
	Verification $\gamma_i \cdot \delta_{sd}/\delta_{su}$	0.69
	Judge for safety	OK

CONCLUSIONS

In this study, a method is proposed to evaluate the quantitative safety against fault displacement for reinforced concrete box culverts buried underground among critical civil engineering structures.

The results of this research were summarized and published in the "Impact Assessment Technology for Fault Displacement 2021" and made publicized as a separate volume of the "Guidelines for Seismic Performance Verification of critical civil engineering structures of Nuclear Power Plants 2021".

The evaluation method can be applied to general structures other than critical civil engineering structures.

Regarding the application of this evaluation method, it is necessary to pay attention to the following:

If it is judged that the impact of an earthquake or an adjacent structure is large, it is necessary to consider this impact appropriately.

This evaluation method is intended for cases where the target structure is subjected to fault displacement and undergoes total bending deformation or rigid body displacement. Its applicability needs to be confirmed when shear deformation is predominant, such as when the structure is installed in the bedrock.

We hope that the proposed evaluation method will be widely used in the future.

ACKNOWLEDGEMENTS

This research is a part of the project research ‘Research on establishment of evaluation method for fault displacement of critical civil engineering structures’ which was jointly carried out by Tohoku Electric Power Co. Inc., Hokkaido Electric Power Co. Inc., Tokyo Electric Power Company Holdings, Inc., Chubu Electric Power Co. Inc., Hokuriku Electric Power Co. Inc., Kansai Electric Power Co. Inc., Chugoku Electric Power Co. Inc., Shikoku Electric Power Co. Inc., Kyusyu Electric Power Co. Inc., The Japan Atomic Power Company, Electric Power Development Co., Ltd. and Japan Nuclear Fuel Limited. The authors are grateful for the interest and advice by the above power companies, as well as to the members of the evaluation committee, which was organized by the Japan Society of Civil Engineers and chaired by Professor K. Maekawa of Yokohama National University.

REFERENCES

Japan Society of Civil Engineers, *Seismic Performance Verification Guidelines Reinforced Concrete Underground Structures in Nuclear Power Plants*, 2005.6.