Revision of the AESJ Standard for Seismic Probabilistic Risk Assessment (3) Fragility Evaluation

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Abstract: This paper introduces the following key issues on the fragility evaluation of SSCs in revision of the AESJ Standard for Seismic Probabilistic Risk Assessment.
1. Requirements for seismic induced other risk evaluations such as tsunami are clarified. For instance, the influence of structural damage due to main shock is considered as necessary to evaluate the realistic response by tsunamis after main shock.
2. Most recent findings are reflected based on the actual damage and simulation analyses of some earthquakes beyond design basis earthquake after 2007. For instance, seismic response analytical model is better suited for the realistic response evaluation up to damage limit paying attention to three dimensional responses of buildings / structures and its effect on equipment important to safety based on the seismic simulation analyses with observed records and usage experience. Floor deformation, torsion and rocking etc. are considered as three dimensional responses.
3. Requirements for the fragility evaluation of severe accident management equipment, its passageway, spent fuel pool and isolated important building are clarified based on the findings of Fukushima accident and so on.
4. Requirements for the fragility evaluation of aftershocks other than main shock and soil deformation due to fault displacement are clarified.

Keywords: PRA, Earthquake, Fragility, Standard.

1. INTRODUCTION

A standard for Procedure of Seismic Probabilistic Risk Assessment (PRA) for nuclear power plants 2007 had been already established and issued by the Atomic Energy Society of Japan (AESJ) through the discussions at the Seismic PRA Subcommittee under the Risk Technical Committee of the Standards Committee. As an enforcement standard based on the PRA procedure, the standard specifies the requirements which should have the PRA dealing with incidents resulting from earthquakes at nuclear power plants during power operation, and the concrete methods of meeting it.

In revising the 2007 version standard, we updated various requirements to reflect advancements in Seismic PRA techniques based on new technological findings after the publication of the previous standard and to improve the quality and transparency of this standard. In particular, the lessons learned and new findings from the severe accidents of Fukushima Dai-ichi nuclear power plants, which occurred on March 11 of 2011, were significant. The reason was that three cores were melted down and large amounts of FP were released in the accidents.

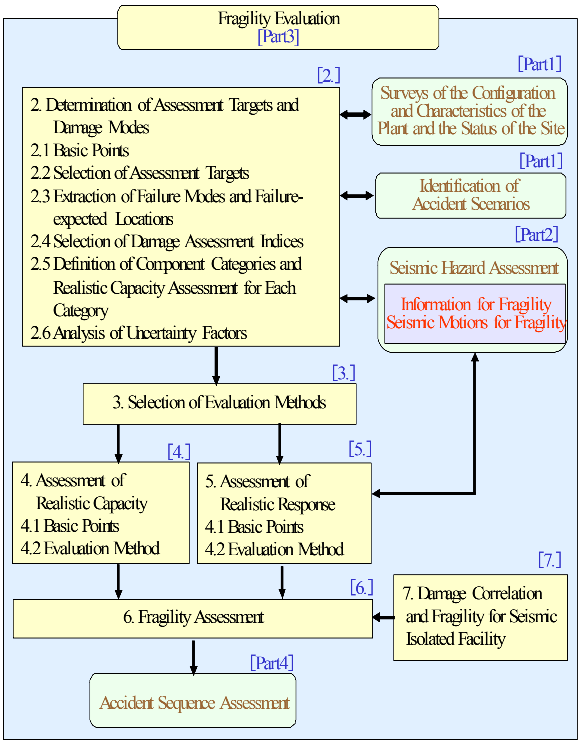

Fig.1 Procedures for Fragility Evaluation of Buildings and Components

The objective of this paper, Part3 fragility evaluation, is to evaluate the fragility of buildings and components for an accident sequence evaluation based on the following paper Prat4. For fragility evaluation of buildings and components, buildings and components to be assessed and the failure modes will be determined, and subsequently, the evaluation methods to be used for capacity evaluation and response evaluation will be selected to evaluate realistic capacity and response and thereby obtain fragility curves that show damage probabilities at which the response exceeds the capacity. This paper introduces the key issues on the above fragility evaluation of SSCs in revision of the AESJ Standard for Seismic PRA.

Fragility evaluation of buildings and components will be carried out according to the procedures shown in Fig. 1. In this revision, fragility curves not only for overall failure modes directly related to core damage but also for other local failure modes are strongly required if accident sequence evaluation needs the initiating events such as local SSC failures that consequentially influence core damage as well as the initiating events directly related to core damage such as reactor building collapse, reactor containment vessel collapse and reactor pressure vessel failure.

2. Determination of Assessment Targets and Failure Modes

2.1. Basic Points

The targets of fragility evaluation should be mainly selected on the basis of the lists of buildings and components extracted in "**Preparation of Lists of Buildings and Components**." Subsequently, dominant or potential failure modes and failure-expected locations should be extracted for the selected assessment targets. Damage assessment Indices should be also selected for fragility evaluation, appropriate to the selected failure modes and failure-expected locations.

Conditions for fragility evaluation specified here need to be arranged and shared with the evaluators of seismic hazard evaluation and accident sequence evaluation.

2.2. Selection of Assessment Targets

In addition to the above lists of buildings and components, the targets of fragility evaluation should also be selected on the basis of spent fuel damage outside reactor pressure vessel and other seismic induced PRA such as tsunami PRA. The targets except the lists include external and internal barriers against tsunamis, spent fuel pool and secondary equipment potential to become drifting articles by tsunamis after main shock.

2.3. Extraction of Failure modes and Failure-expected Locations

Failure modes and failure-expected locations to be assessed should be extracted by focusing on their failures that cause the direct and also indirect influence on the integrity of core, reactor containment vessel or spent fuel. Key issues in this revision are substantially as follows.

2.3.1. Buildings and Structures

The dominant modes of structural damage for the direct collapse (failure limit to support its own weight) and functional loss (equipment support functional loss and anti-leak functional loss etc.) of buildings and structures should be extracted. Not only failure modes such as overall collapse directly related to core damage but also other local failure modes should be evaluated in this revision. Fig.2 shows an example of the series of building failure modes from the viewpoint of combination between seismic and tsunami PRA.

2.3.2. Reactor Containment Vessel

Potential failure modes that are linked to the required functional loss in reactor containment vessel include overall structural collapse, structural failure modes due to functional loss of pressure resistance, functional failure modes due to loss of the containment vessel isolation and functional failure mode due to loss of the pressure suppressive function. From these, dominant failure modes and failure-expected locations to be assessed should be extracted.

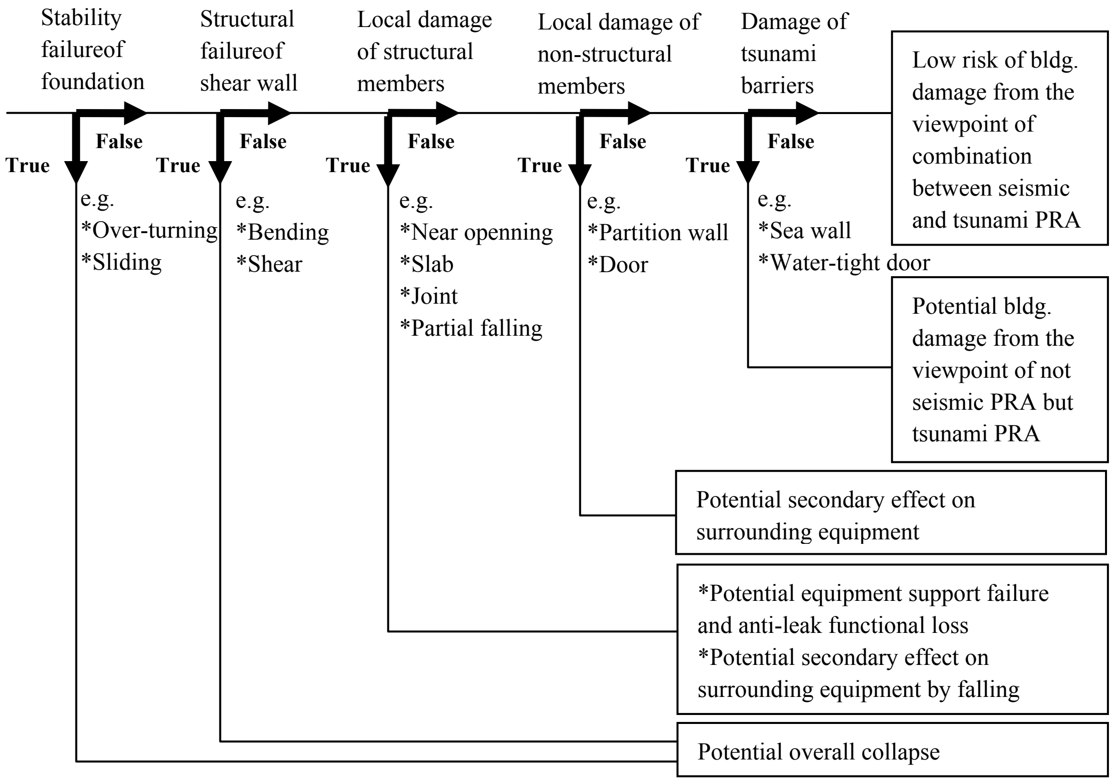

Fig.2 Example of the Series of Building Failure Modes

2.3.3. Components and Piping Systems

Failure modes and failure-expected locations to be assessed should be extracted based on the required functions of the item subject to evaluation. From the required functions of items subject to evaluation, failure modes are largely classified into two categories: structural failure modes and functional failure modes.

2.3.4. Soil

Soils to be assessed include foundation soil supporting the facilities important to safety, their surrounding slope and the passageway for severe accident management equipment. Failure modes and failure-expected locations to be assessed for each soil should be extracted based on the required functions of SSCs. Those for soil deformation due to fault displacement should be similarly extracted.

2.3.5. Tsunami Barriers

Potential structural failure modes that are linked to the required functional loss in external and internal barriers against tsunami such as sea wall include stability failure modes, overall structural collapse and failure modes due to their local damage. From these, dominant failure modes and failure-expected locations to be assessed should be extracted.

2.3.6. Spent Fuel Pool

Potential structural failure modes that are linked to the required functional loss in spent fuel pool include structural collapse and failure modes due to their local damage such as fracture of concrete and steel liner. From these, dominant failure modes and failure-expected locations to be assessed should be extracted. For example, bending or shear failure mode involving the appropriate story and the lower story collapse might be extracted as dominant failure modes and failure-expected locations that are linked to spent fuel damage.

2.3.7. Severe Accident Management Equipment

Failure modes are largely classified into two categories: structural failure modes and functional failure modes. Portable equipment such as power-supply car might be evaluated mainly for structural failure mode corresponding to over-turning against earthquake. That is because power-supply car is in storage during earthquake and will be used only for recovery work after earthquake.

2.4. Selection of Damage Assessment Indices

A realistic response quantity that can indicate the degree of damage in the target failure mode will be used as a damage assessment index. Damage assessment Indices will be selected appropriately from physical quantities used for describing the functional loss of buildings, structures and components due to seismic responses. As key issues in this revision, an example of damage assessment indices for various types of soils is shown in Table.1.

Table.1 Example of Damage Assessment Indices for Various Types of Soils

Soil		Damage assessment indices			Failure modes for SSCs
		Deemed limit states		Indecies necessary for fragility of SSCs	
		Instability limit for soil	Deformation limit for soil		
Foundation soil	Building	Safety factor for slip	Angle of slope of foundation	Movement distance of soil and rock mass	Structural or functional failure of buildings and switching station etc.
Foundation soil	Tsunami barrier	*Safety factor for slip/over-turning *Bearing capacity	-	-	Functional failure as tsunami barriers
Slope		*Safety factor for slip *Displacement of soil and rock mass	Displacement of soil and rock mass	Movement distance, volume and impact force of soil and rock mass	Structural or functional failure of buildings and switching station etc. Intake functional failure due to obstrction by falling soil to intake Functional failure as tsunami barriers of slope and dike reservoir functional failure by damage of reservoir bank
Soil for SAM equipment	Slope	*Bearing capacity *Safety factor for slip *Displacement of soil and rock mass	*Angle of slope of foundation *Displacement of soil and rock mass	Movement distance of soil and rock mass	Functional failure of SAM equipment
Soil for SAM equipment	Passageway	Safety factor for liquefaction	*Settlement and uneven distance *Displacement of soil and rock mass of slope	-	Functional failure of road surface as passageway
Soil deformation	Crustal movement	Safety factor for slip of slope	*Angle of slope of foundation *Displacement of soil and rock mass	Displacement of foundation soil	Structural or functional failure of buildings and switching station etc.
Soil deformation	Fault displacement	Safety factor for slip of slope	*Angle of slope of foundation *Displacement of soil and rock mass	*Displacement of foundation soil *Movement distance of soil and rock mass	Structural or functional failure of building, switching station and underground structures etc.

2.5. Definition of Component Categories and Realistic Capacity Assessment for Each Category

In fragility evaluation of components, realistic capacity and realistic response are generally assessed for each component separately. However, categorization according to the structures, dimensions, shapes, operation mechanisms etc., of components sometimes makes it possible to carry out the same assessment and examination for all items in the same category. Accordingly, assessment and examination may be carried out for each category separately.

2.6. Analysis of Uncertainty Factors

For assessment of realistic capacity and realistic response, factors that have an influence on the probabilistic quantities (medians and standard deviations) of realistic capacity and realistic response (hereafter, collectively called "uncertainty factors") will be analyzed and extracted.

It is preferable that uncertainty be organized by dividing it into the following two categories to the extent possible: uncertainty due to randomness inherent in data or phenomena (aleatory uncertainty) and uncertainty related to knowledge and recognition in analytic techniques or modelling (epistemic uncertainty).

From the extracted uncertainty factors, major factors that have a significant influence on the finally obtained realistic capacity and realistic response may be extracted to assess realistic capacity and realistic response by using only those major factors.

3. Selection of Evaluation Methods

This standard basically presents the following three types of fragility evaluation methods.

a) Method based on realistic capacity and realistic response e.g.[1]
b) Method based on realistic capacity and response factor [2]
c) Method based on capacity factor and response factor e.g. [3]

Fragility evaluation method for the realistic capacity and realistic response of SSCs should be selected depending on the application and accuracy required for the assessment. For selection of each evaluation method, any one of those techniques may be selected for use in the assessment, or a proper combination of several techniques may be used. A newly developed method except the above may be selected, but in such a case, the scientific rationality of the technique must be quantitatively shown.

4. Assessment of Realistic Capacity

4.1. Basic Points

Realistic capacity of SSCs should be evaluated for structural and functional failure modes of failure-expected locations. The following methods are presented in the standard.

a) Method based on experiments
b) Method based on empiricism including experiments
c) Method based on theories including analyses
d) Method based on engineering judgment

If only deterministic capacity is provided regardless of which method is used, realistic capacity with uncertainty should be evaluated by uncertainty analysis methods with material characteristics, etc. as aleatory variables.

4.2. Evaluation Method

This standard presents various evaluation methods and experimental data for realistic capacity of SSCs. As key issues in this revision, shaking table test data for realistic capacity of various types of components and piping systems are provided in the appendix. Furthermore, to evaluate realistic capacity such as soil deformation value, shaking table test data of scaled soil slope are also provided.

5. Assessment of Realistic Response

5.1. Basic Points

Realistic response of SSCs should be evaluated mainly based on the following two methods.

a) Method based on realistic response
b) Method based on response factor

Method based on realistic response is detail and exact one using new seismic response analyses. On the other hand, method based on response factor is relatively simple and approximate one using design response value.

As key issues in this revision, realistic response due to aftershocks other than main shock should be evaluated as necessary. Moreover, requirements for seismic induced other risk evaluations such as tsunami are clarified. For instance, the influence of structural damage due to main shock is considered as necessary to evaluate the realistic response by tsunamis after main shock.

5.2. Evaluation Method

This standard presents various evaluation methods for realistic response of SSCs. Some examples of key issues in this revision are the following.

a) Most recent findings are reflected based on the actual damage and simulation analyses of some earthquakes beyond design basis earthquake after 2007. For instance, the following requirement is clarified based on most recent findings. Seismic response analytical model is better suited for the realistic response evaluation up to damage limit paying attention to three dimensional responses of buildings / structures and its effect on equipment important to safety based on the seismic simulation analyses with observed records and usage experience. Floor deformation, torsion and rocking etc. are considered as three dimensional responses.

b) Not only indirect slope stability evaluation for effects on facilities due to seismic induced slope failure but also direct evaluation with sliding soil mass after failure and its impact force acting on facilities are specifically required.

c) Requirements for the fragility evaluation of soil deformation due to fault displacement are clarified.

6. Fragility Evaluation

Fragility curve should be calculated by the evaluation methods for realistic capacity and realistic response selected in "**3. Selection of Evaluation Methods"**. The results of fragility evaluation of SSCs are used in accident sequence evaluation. In addition, many examples of fragility evaluation of SSCs are provided in the appendix. In this revision, fragility curves not only for overall failure modes directly related to core damage but also for other local failure modes are strongly required if accident sequence evaluation needs the initiating events such as local SSC failures that consequentially influence core damage as well as the initiating events directly related to core damage such as reactor building collapse, reactor containment vessel collapse and reactor pressure vessel failure.

7. Damage Correlation and Fragility Evaluation of Seismic Isolation Facilities

Under strong seismic ground motion, multiple components are damaged at the same time and it is assumed that so-called common cause failure will occur. Because of this, the interrelationships and correlations of damage between multiple components should be considered in the accident sequence evaluation.

Also, the vibration characteristics according to the seismic isolation types should be considered and evaluated in fragility evaluation of seismic isolation facilities. In this revision, requirements for the fragility evaluation of the isolated important building is clarified based on the findings of Fukushima accident and so on.

8. CONCLUSION

Revision of the AESJ Standard for the Seismic PRA standard will be established by AESJ in near future. It is expect to become the support of the decision making process in the wide field of the thing such as a safety design, operation management, safety regulation.

Acknowledgements

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