Seismic PRA Methodology Development and Plant Applications

Nuclear Risk Research Center
Masato NAKAJIMA

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CRIEPI Central Research Institute of Electric Power Industry

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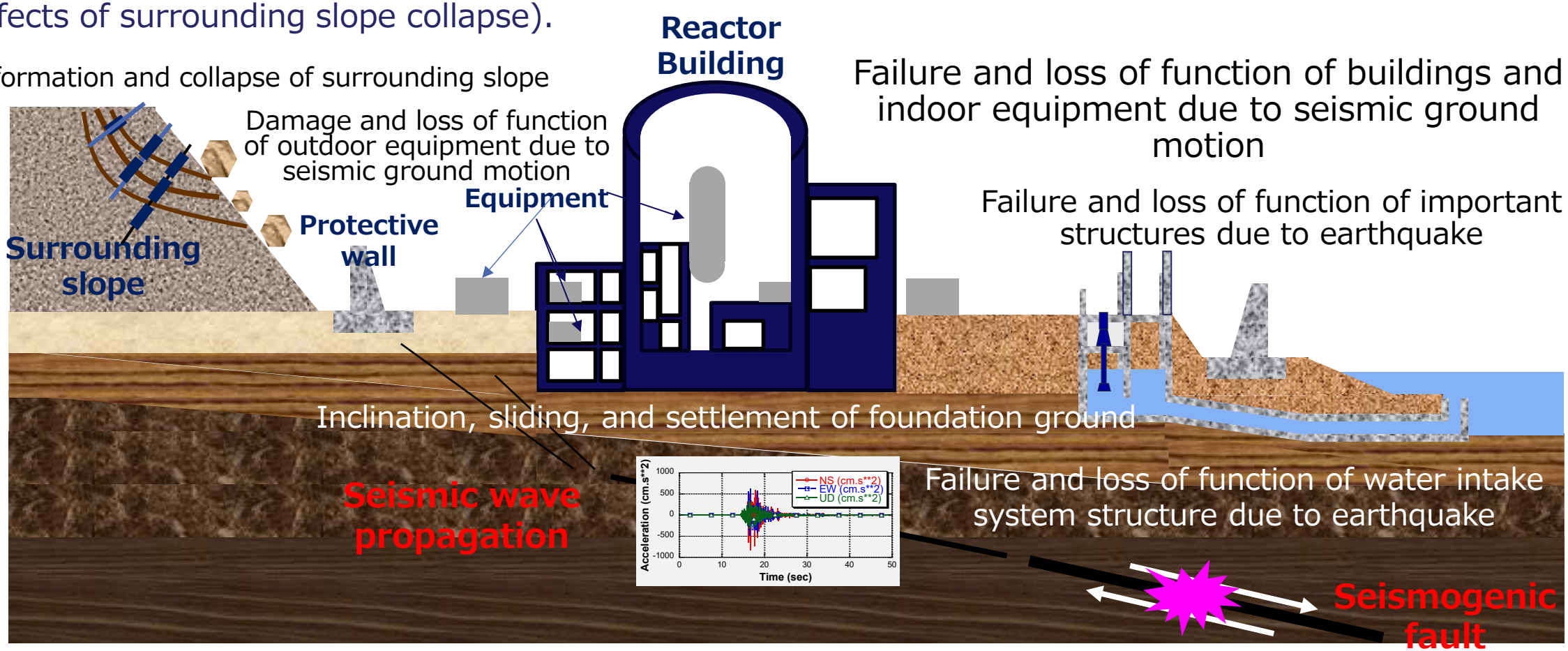
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1. Seismic PRA Overview

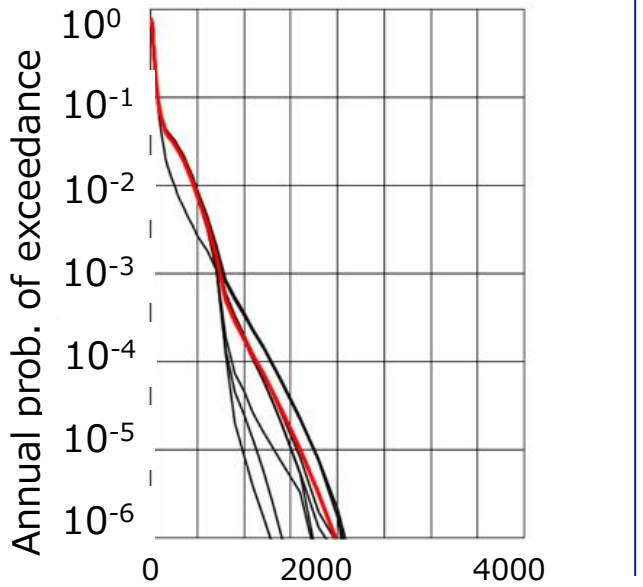
- Risk of target plant is assessed based on the possibility of damage, function loss, and other factors affecting the foundation ground, buildings, equipment, and structures from shaking (seismic ground motion) caused by earthquakes, and, if necessary, the possibility of effects induced by seismic hazards (effects of surrounding slope collapse).



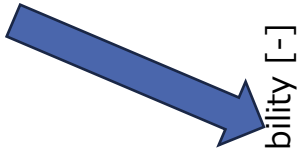
2. Seismic PRA Model Structure

- **Seismic hazard assessment**
  - Evaluate relationship between seismic ground motion (shaking) and its frequency/exceedance probability potentially occurring at target location in the future

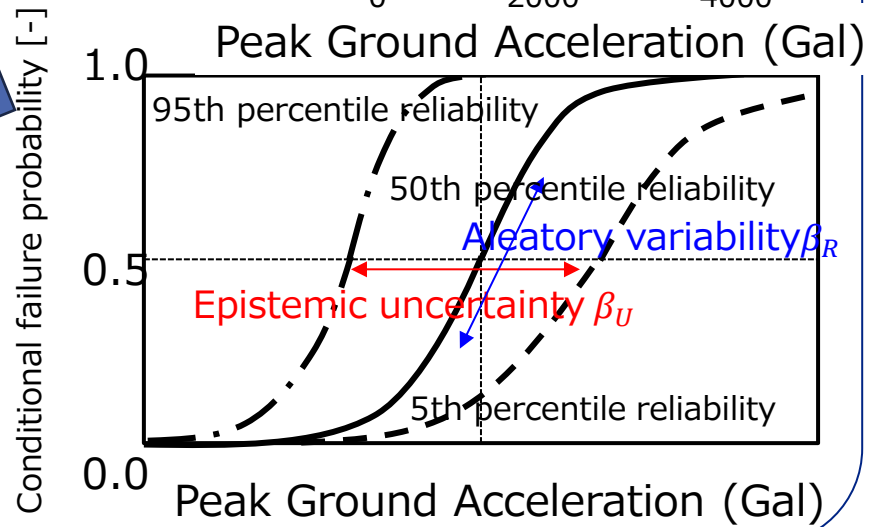




- **Seismic fragility assessment**
  - Evaluate conditional probability of failure or loss of function of power plant equipment and structures corresponding to the level of seismic ground motion



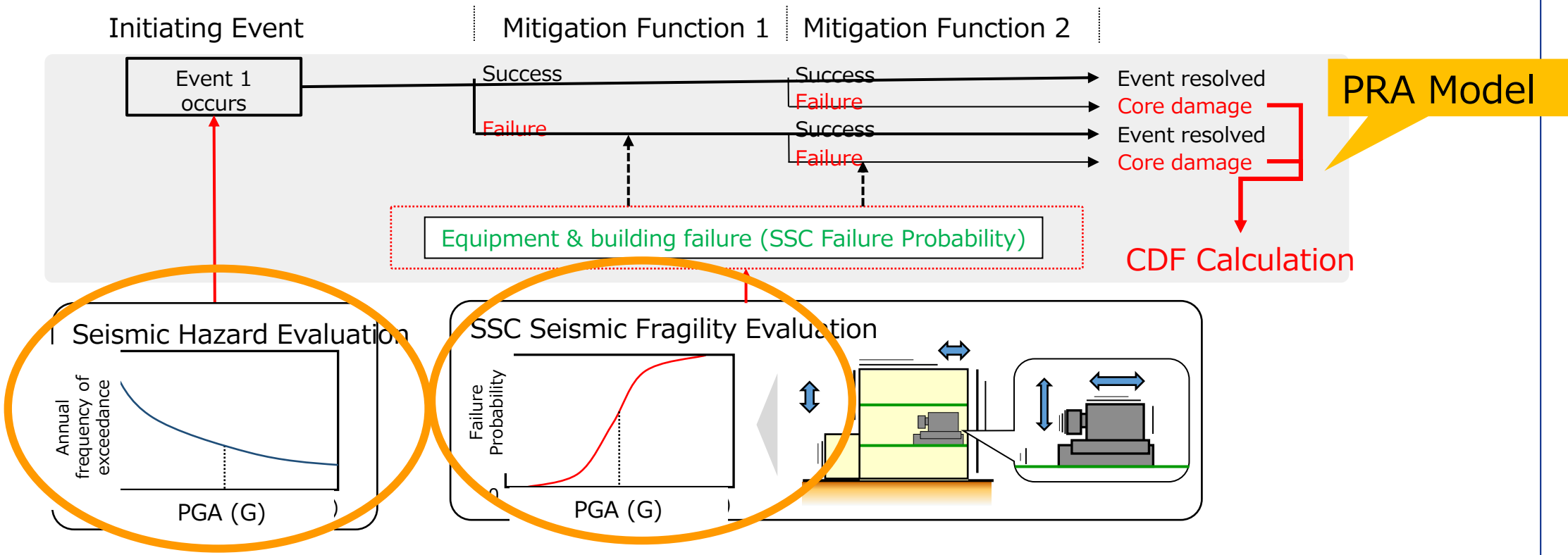
- **Accident sequence assessment**
  - For each magnitude of earthquake vibration, the impact (accident scenario) and frequency of core damage are evaluated where safety-critical equipment, structures, and facilities at the power plant lose functionality.



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2. Seismic PRA Model Structure

- Seismic PRA model is based on Internal Events PRA model and incorporates seismic-specific considerations (seismic hazard assessment, equipment/building fragility assessment).



- Seismic PRA is characterized by significant impact on risk of dominant core damage sequence*

  ***Dominant core damage sequence: Sequence where no mitigating functions work, and damage to equipment or structures leads directly to core damage.**

3. Seismic PRA Background & Gaps

■ Background

- In the U.S., Seismic PRA was applied to actual plants during the 1990s during Individual Plant Examination of External Events (IPEEE) processes. Following the 2011 accident at TEPCO's Fukushima Daiichi Nuclear Power Station, Seismic PRAs have been conducted again after incorporating improvements to seismic hazard assessment methods in accordance with a directive from the U.S. Nuclear Regulatory Commission.
- In Japan, nuclear operators conduct Seismic PRA in accord with the Seismic PRA Implementation Standard of the Atomic Energy Society of Japan as part of processes that includes submission of safety enhancement assessments required under the New Regulatory Requirements.

Japan is situated in one of the world's most seismically active regions. Therefore, it is very important to develop more realistic and comprehensible evaluation technologies taking into account characteristics of each plant's location and level of seismic hazard in Japan in order to obtain risk information/insight to protect against seismic events.

■ Gaps to Overcome

- In utilizing Seismic PRA for Risk-Informed Decision Making (RIDM), gaps are present, such as the conservative nature of evaluations and a lack of sufficient explainability (instances where epistemic uncertainty is not evaluated such that the uncertainty is insufficiently explained) regarding assessment results based on plant-specific site characteristics.

*Epistemic uncertainty: Uncertainty arising from a lack of knowledge or data regarding a phenomenon. It is possible to reduce or resolve this uncertainty in the future as research progresses.

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4. Efforts to Overcome Gaps

We have conducted the following research to establish evaluation methods that take into account the characteristics of specific nuclear power plants and sites by incorporating technologies meeting international standards with the aim of implementing / deploying RIDM in Japan.

■ Enhancing PRA Model Explainability

- There are areas where the evaluation of uncertainty is insufficient, especially in seismic hazard assessments. → We have improved the quantitative selection method for ground motion models to more accurately assess epistemic uncertainty* associated with seismic hazard assessment. ⇒**【Research result (1)】**

■ Improving Conservative Evaluations in PRA Models

- In seismic fragility assessments, realistic evaluations of responses (deformation, stress, etc.) and load-bearing capacities (resistance strength) of structures and equipment have not yet been fully incorporated, resulting in conservative models that can significantly dominate the calculated frequency of earthquake-induced core damage.

→ We have improved fragility assessment methods for foundation ground to resolve issues directly linked to core damage. ⇒**【Research result (2)】**

- We quantified and analyzed seismic risk by applying the results of hazard and fragility assessment and other improvements to a nuclear power plant model that incorporates the characteristics of an actual plant**.** ⇒ **【Research result (2)】**

- There are other challenges faced in advancing Seismic PRA. This explanation only covers two items that NRRC has been working on.

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5. Research Results (1) Seismic Hazard Assessment Method Improvement and Development Based on Ikata SSHAC Project

■ Objectives and Overview of SSHAC Level 3 Methodology

- The seismic hazard assessment methodology was developed by SSHAC, a committee jointly established by the U.S. Nuclear Regulatory Commission (U.S. NRC), U.S. Department of Energy (DOE), and the Electrical Research Institute (EPRI) to address issues identified in seismic hazard assessments conducted in the United States in the 1980s. It is divided into four levels: 1 through 4 according to the subject matter importance, and U.S. NRC requires implementation of Level 3 and higher assessments.
- To eliminate bias and ensure objective assessments based on scientific evidence as much as possible, the qualifications, responsibilities, and roles of experts involved in the assessment as well as the assessment procedures (specifying workshop content and frequency) are clearly defined. Furthermore, complete documentation of the assessment and participatory peer review are required.

****SSHAC** (Senior Seismic Hazard Analysis Committee): A procedure and methodology for objectively and systematically integrating and synthesizing the insights and uncertainties of multiple experts during a seismic hazard assessment.

■ Ikata SSHAC Project

- **Implementation Period:** March 2016 - April 2020
- **Features**: Japan's first project applying SSHAC guidelines (Shikoku Electric Power/NRRC collaborative project) formed TI teams comprising 20 experts from Japan and abroad, and received the Atomic Energy Society of Japan's Society Award (Contribution Award) in 2021 for the research results.
- **NRRC's Contribution:** Provided technical support by appropriately managing the project based on SSHAC guidelines, providing and adopting research results on quantitative selection of GMMs, in addition to other assistance in reviewing relevant research outcomes.

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5. Research Results (1) Seismic Hazard Assessment Method Improvement and Development Based on Ikata SSHAC Project

■ Challenges in Probabilistic Seismic Hazard Assessment (Points of Insufficiency)

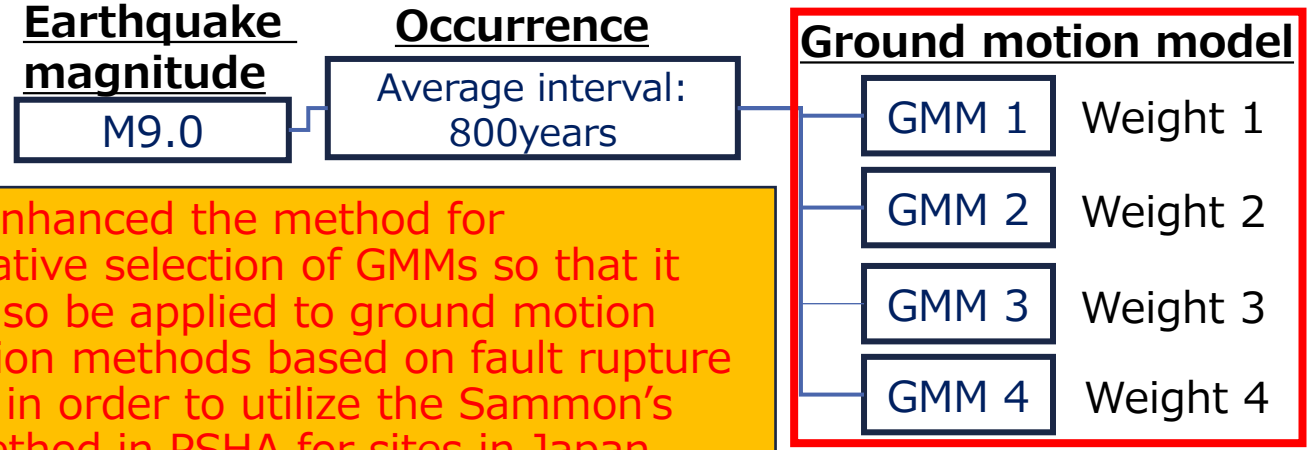
- Epistemic uncertainty assessment is not sufficiently evaluated/quantified.
- Ground motion models: Only a small number of limited ground motion models (Ground Motion Prediction Equation) are used.

■ NRRC Study

We provided the Ikata SSHAC project with technical support. Based gaps and unresolved issues in probabilistic seismic hazard assessments that were analyzed and identified during the project, we upgraded the method for evaluating epistemic uncertainty in ground motion models for PSHA. [1][2][3]

- **Improved quantitative selection methods for seismic motion models and enhanced practical applicability**
- Developed new variability model for ground motion model

Quantitative selection of ground motion models refers to determining which ground motion models to select and what weight to assign to each model when assessing seismic hazards at a specific location.



NRRC enhanced the method for quantitative selection of GMMs so that it could also be applied to ground motion simulation methods based on fault rupture models in order to utilize the Sammon's Map method in PSHA for sites in Japan.

Developed logic trees for ground motion models

6. Research Results (2) Development of More Realistic Seismic Fragility Assessment Methods

Solving Problems Faced in Applying Developed Methods to Seismic PRA of Real Sites

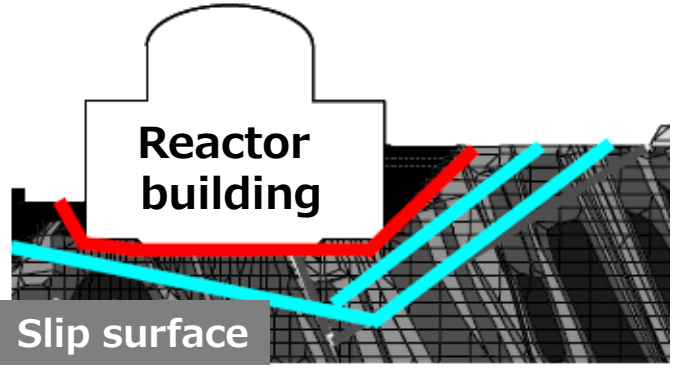
- If the reactor building or foundation supporting the reactor building is damaged, it is likely the reactor containment vessel, reactor pressure vessel, and other equipment or structures inside the building may sustain extensive damage. Therefore, this is treated as an accident scenario that leads directly to core damage.

Foundation Ground Fragility Evaluation Using Nonlinear Analysis and Deformation Index

Current situation: Elastic analysis without fracture consideration + safety factor evaluation
⇒ Directly leads to core damage

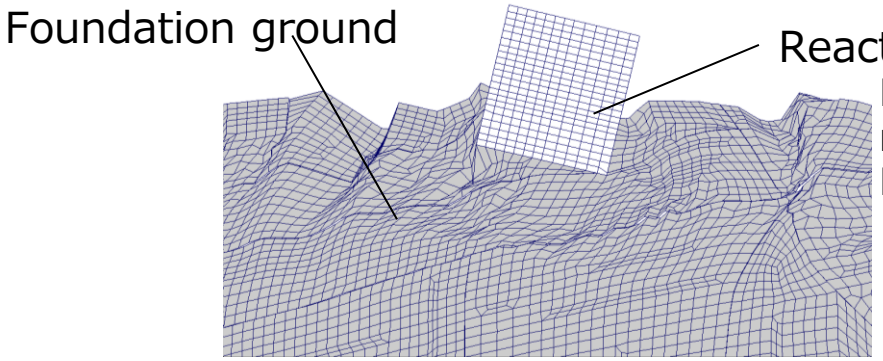
Safety factor for slipping Fs

$$= \frac{\text{Slip surface shear resistance}}{\text{Slip surface shear force}}$$



This only assesses whether there is slippage and does evaluate the effect on buildings or equipment.

Future (proposed method)[4][5]: Nonlinear analysis considering fracture + deformation evaluation
⇒ Building and equipment fragility evaluation



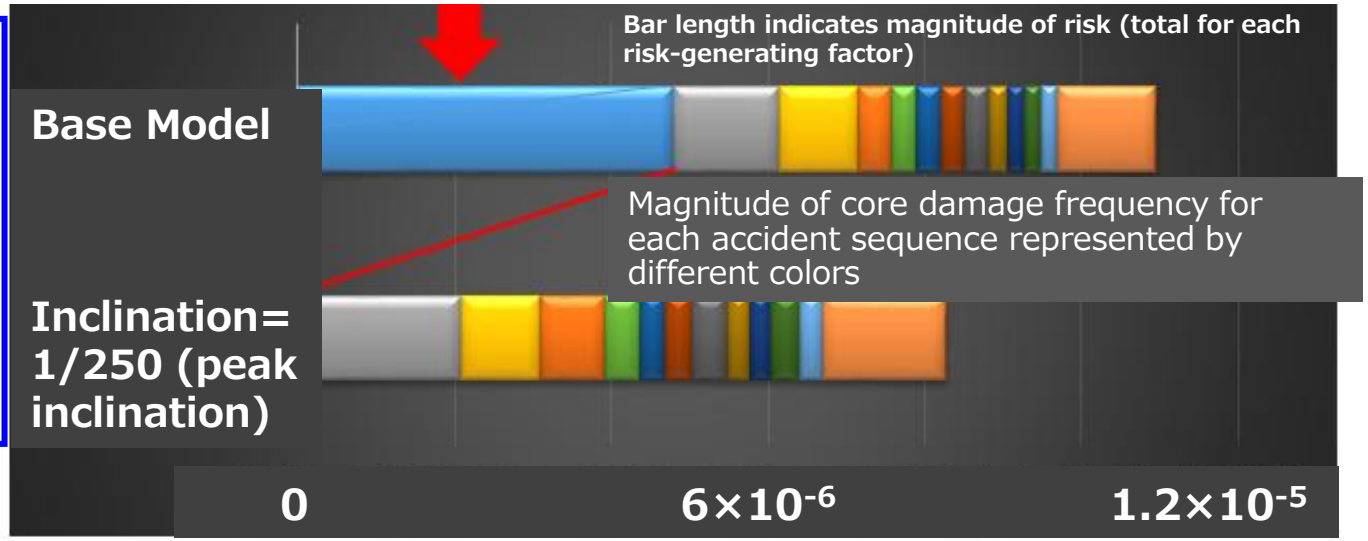
Developed method uses nonlinear analysis to predict ground deformation and evaluate building tilt due to ground deformation
→ to evaluating equipment damage resulting from ground inclination

6. Research Results (2) Development of More Realistic Seismic Fragility Assessment Methods

◆Based on actual BWR plant data, an improved fragility assessment method was used to evaluate seismic risks of a plant (core damage frequency).
◆While a conservative PRA model revealed sequences not actually dominant to appear significant (distorting the risk profile*), NRRC confirmed a more realistic assessment of foundation ground fragility enables a more accurate understanding of scenarios critical to seismic safety.

Risk Profile: Comprehensive identification of potential risk factors with their occurrence frequency and impact classified and quantified.

CDF in Accident Sequences Involving Foundation Ground Failure



CDF(/reactor*year)

Changes in risk profile focusing on accident sequences

■ Results:

- **Core damage frequency with maximum gradient (1/250, 1/500) input was lower than core damage frequency in the base case.**
- **Use of fragility functions accounting for inclination contributed to resolving issues directly linked to core damage.**

7. Current Achievements & Future Actions (in 5 years)

■ Current Achievements

- Now possible to perform Seismic PRA by taking into account specific site characteristics of each nuclear power plant, reducing conservatism and enhancing explainability. Therefore, we have reached a level capable of supporting practical use of risk information with realistic PRA models.

*The Japan Atomic Energy Society updated the SPRA Standard in 2024. Progress has also been made on standards and guidelines.

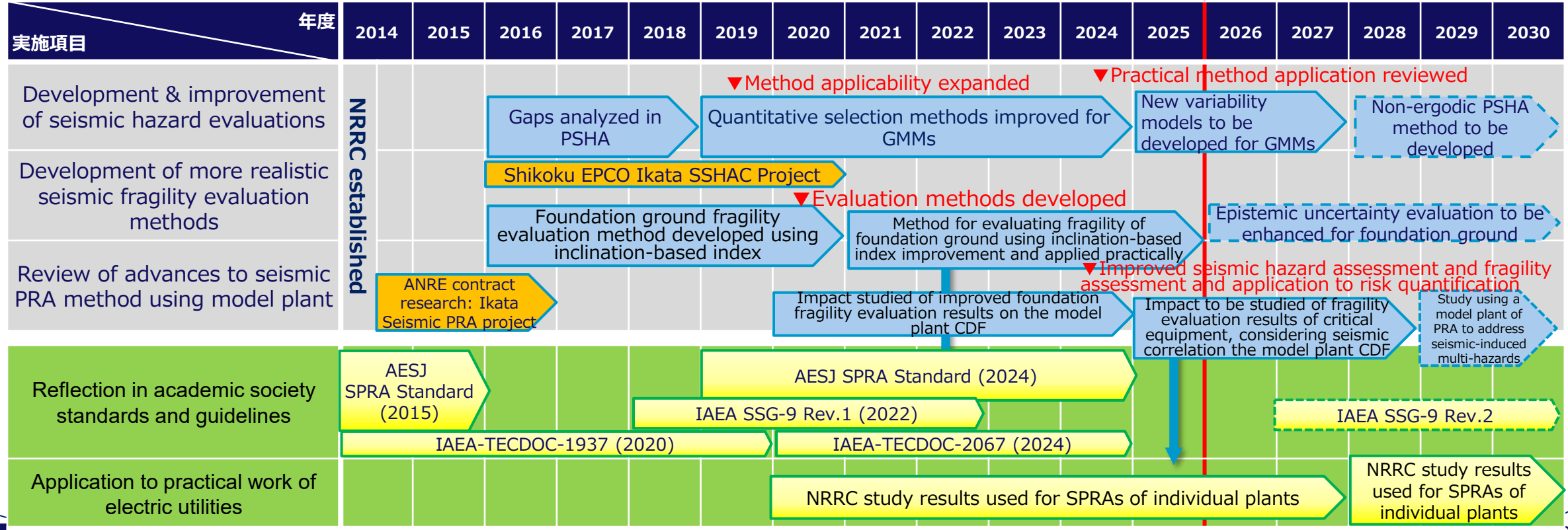
■ Future Actions

- Evaluate applicability of multi-sites SSHAC methodology in Japan. Improve and develop technologies required for seismic hazard assessment for high-seismicity areas (e.g., new variability model of ground motion modes)
- Expand scope to Level 1.5 Seismic PRA, taking into account technical gaps identified during actual plant evaluations conducted by utilities
- Draft NRRC Seismic PRA Guidelines to support SPRA conducted by utilities
- Develop PRA method to address seismic-induced superposed hazards

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[Appendix] Progress in Overcoming Gaps

- **Seismic Hazard Assessment**: We have reached a level equivalent to or higher than international standards for evaluating the epistemic uncertainty of GMMs, which was identified as a future challenge during the Ikata SSHAC project.
- **Seismic Fragility Assessment of Foundation Ground**: Introduction of nonlinear analysis deformation as an indicator has enabled more realistic fragility assessments equivalent to or higher than international standards.



[Appendix] Status of Initiatives

Gaps to Overcome	Description	Progress
Enhance seismic hazard evaluation method	Enhance quantitative selection methods for ground motion models	• Quantitative selection method significantly enhanced for PSHA in Japan. • Still a few technical issues to be upgraded for practical use.
	Develop a new variability model for ground motion models	• Ongoing
Enhance seismic fragility evaluation method	Improvement of seismic fragility evaluation for foundation ground	• Improvement of fragility evaluation method mostly finished. • Need to evaluate epistemic uncertainty.
	Improve seismic fragility evaluation for piping and equipment based on more realistic capacity and response	• Ongoing • Developing a simplified method of fragility evaluation considering non-linear effects for practical application.
	Develop seismic fragility evaluation for equipment that considers seismic correlation	• Ongoing

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[Appendix] Key References Pertaining to Results

■Seismic Hazard Evaluations

[1] Nakajima, M. and Abrahamson, N.: Enhancement of Sammon's Map Representation of Fault Rupture Model for Probabilistic Seismic Hazard Analysis," Transactions of SMiRT-26, (26th International Conference on Structural Mechanics in Reactor Technology) Potsdam, Germany, July 2022.

[2] Sakai, T., Yuyama A., Itoi, T., Miyakoshi, J.: Development of PSHA Implementation Guide in light of the Experiences of Ikata SSHAC Project, CRIEPI Report, NR22002, 2022.

[3] International Atomic Energy Agency: Evaluation of Probabilistic Seismic Hazard Analysis (PSHA) for Nuclear Installations Based on Observational Data, IAEA-TECDOC-2067, 2024.

■Seismic Fragility Evaluations of Foundation Ground

[4] Japan Society of Civil Engineers, Nuclear Engineering Committee: Stability Evaluation Technology for Foundation Ground and Surrounding Slopes of Nuclear Power Plants <Technical Document> "2020 Edition", 2021. (in Japanese)

[5] Sawada, M., Nakajima, M., Yoshida, T. and Ishimaru, M.: Fragility assessment of nuclear power plant foundation ground through dynamic nonlinear analysis and deformation-based verification, ARMS2026 International Symposium- The 14th Asian Rock Mechanics Symposium: Rock Mechanics, 2026.

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