Tsunami PRA Methodology Development and Plant Applications

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1. Tsunami PRA Overview

- Tsunami PRA is performed using a framework similar to seismic PRA.
- Tsunami PRA systematically takes into account uncertainties to evaluate plant risk (CDF, etc.) potentially caused by tsunami that strike a site while in service.
- When evaluating the fragility of SSCs, damage modes specific to tsunami are considered, such as functional damage to electric equipment due to immersion and physical damage of static facilities due to hydrodynamic loads and water-born debris collisions.

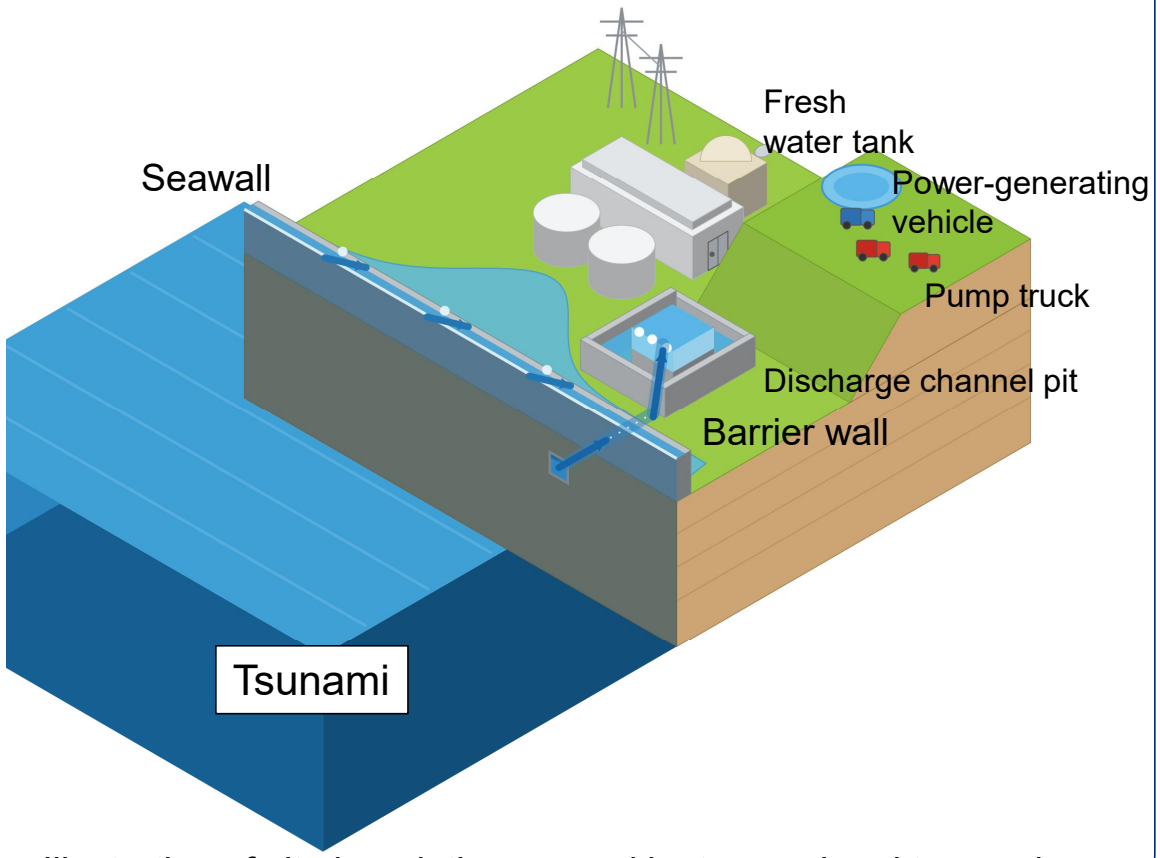


Illustration of site inundation caused by tsunami and tsunami mitigation measures subject to tsunami PRA

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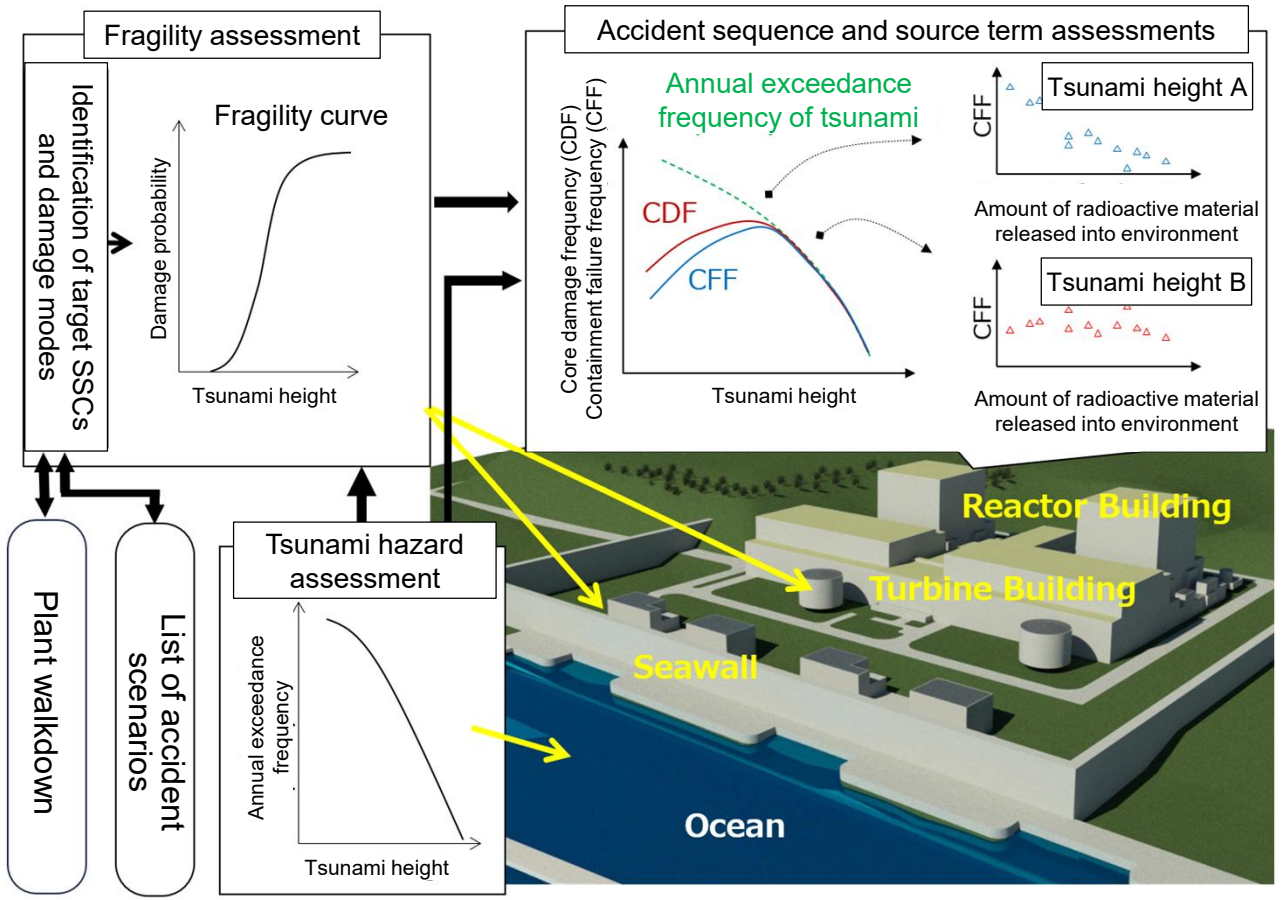
2. Tsunami PRA Model Structure

Tsunami hazard assessment: Evaluates relationship between height and frequency of tsunami reaching the site

Fragility assessment: Evaluates SSC damage probability due to tsunami impact

Accident sequence assessment: Evaluates plant risks (CDF, etc.) caused by tsunami

Source term assessment: Estimates release timing and released nuclides and amounts from containment vessel or reactor building when containment function is lost

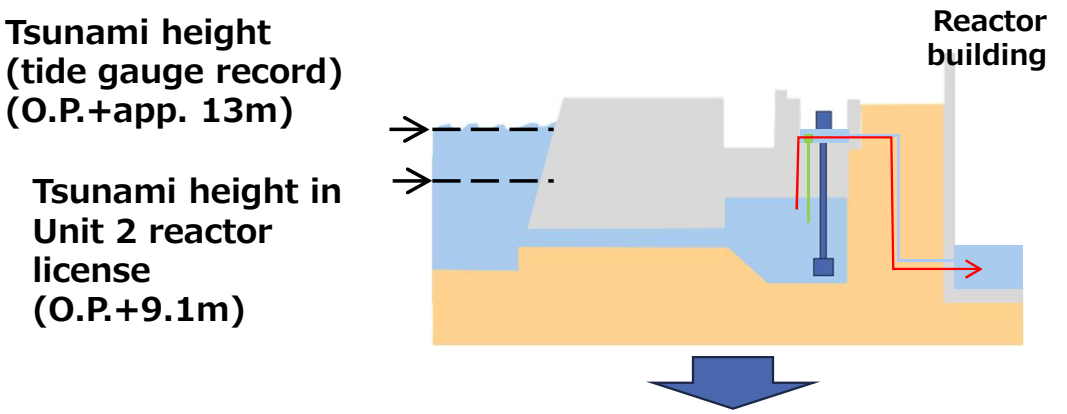


3. Tsunami PRA Background & Gaps

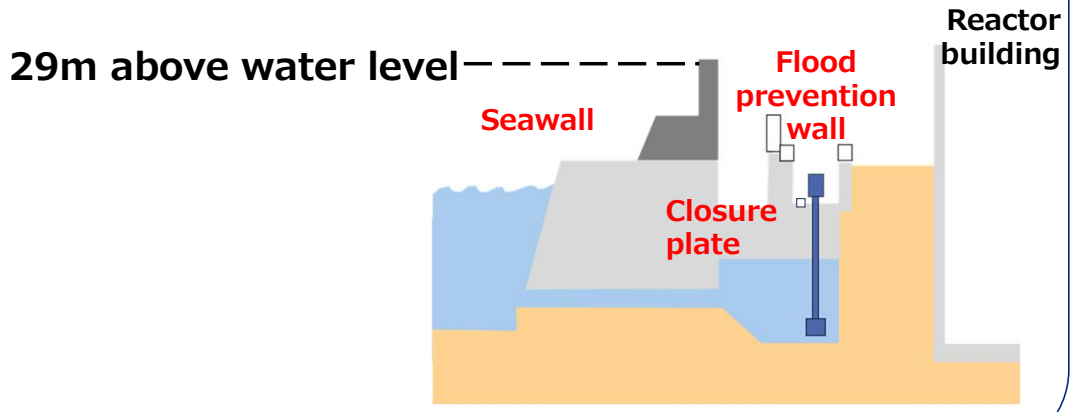
■Why is tsunami PRA necessary?

- One key lesson learned from the Fukushima Daiichi nuclear accident triggered by the 2011 Tohoku earthquake and tsunami was that **tsunami risk assessments and countermeasures against events exceeding the design basis had been insufficient.**
- Tsunami PRAs are performed to identify plant vulnerabilities and obtain risk information to effectively enhance safety against tsunami.
- Japan is situated in the most seismically active regions in the world, and nuclear power plants are sited on tsunami-prone coasts. It is therefore **important to develop technologies for realistic assessments that reflect the site characteristics of each plant.**

During 2011 Tohoku Tsunami



After 2011 Tohoku Tsunami



Tohoku Electric Power Co., Inc.'s Onagawa Nuclear Power Station

3. Tsunami PRA Background & Gaps

■ Background

- Prior to 2011, no practical tsunami PRAs had been conducted.
- Following the Fukushima Daiichi nuclear accident, AESJ established a tsunami PRA standard, based on knowledge of internal event and seismic PRAs. However, the evaluation methodology for tsunami PRA was still not well developed due to little R&D.
- Although tsunami PRAs were conducted in practice, these were simplified assessments that did not take into account the effectiveness of seawalls, watertight doors, and other tsunami protection equipment.

■ Gaps to Overcome

- When utilized for RIDM, previous tsunami PRAs presented challenges as assessments were too conservative and unrealistic given the specific characteristics of nuclear power plants.

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4. Efforts to Overcome Gaps

- **A realistic tsunami PRA methodology needs to be established taking into account plant characteristics and knowledge gathered from evaluation case studies to construct an assessment capable of identifying realistic risks and handling detailed accident scenarios.**
  - Conventional tsunami PRA conducted the main assessments (hazard assessment, fragility assessment, and accident sequence assessment) independently, which results in limited sharing of information. For example, uncertainties in the hazard assessment—such as differences in tsunami sources—were not reflected in assessments of on-site flooding or flooding inside reactor buildings.
  - The assessments were simplistic, failing to consider the effectiveness of tsunami protection equipment (seawalls, watertight doors, etc.). Damage to equipment inside buildings was evaluated without considering the internal inundation distribution.
  - No Level 2 tsunami PRA experience had taken into consideration the effects of building internal inundation on how radioactive materials might migrate.



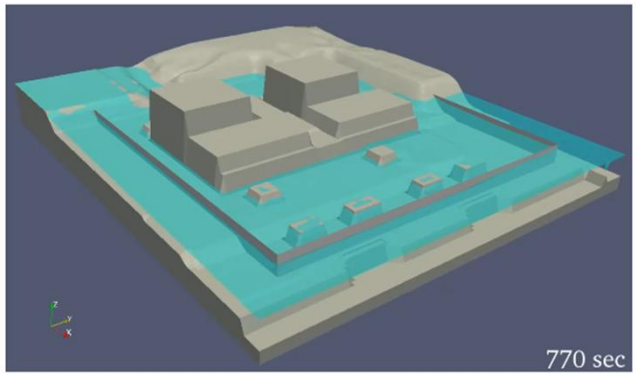
- **Propose site inundation evaluation scheme that accounts for site characteristics which connect the hazard and fragility assessments → [Research Result (1)]**
- **Gather knowledge of Level 1 to Level 2 tsunami PRA of realistic accident scenarios → [Research Result (2)]**

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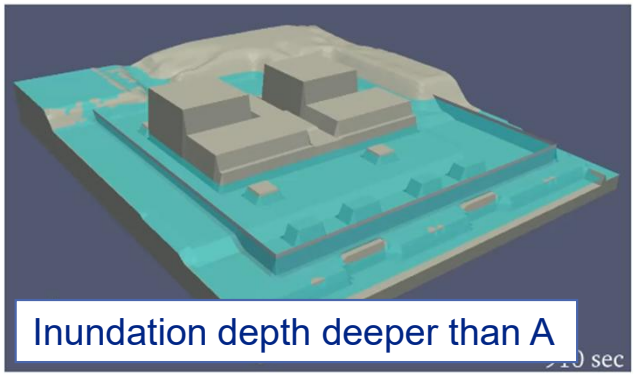
5. Research Result (1) Proposal of Method Capable of Considering Site Characteristics to Evaluate Site Inundation

- **Propose method for connecting hazard and fragility assessments by evaluating site inundation to account for seawalls and other tsunami protection functions [1]**
  - ✓ Site inundation evaluation links hazard and fragility assessments
  - ✓ Information from tsunami hazard assessment, the dominant source of uncertainty in the tsunami PRA, may be reflected in more detail in the fragility and accident sequence assessments by incorporating inundation simulations in the site inundation evaluation.
  - ✓ Inundation simulations may also consider effectiveness of tsunami protection functions and site layout in the assessment.

Tsunami Source A

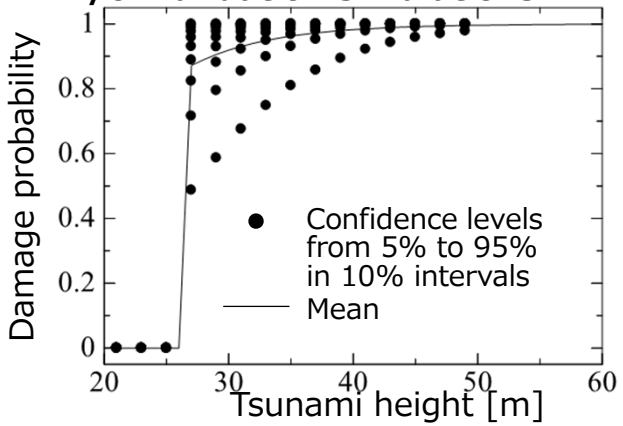


Tsunami Source B

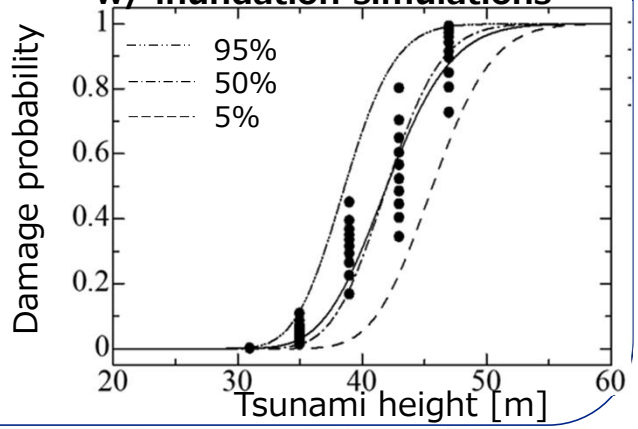


Inundation Simulations
At same tsunami height, but from different tsunami sources

Result of site-inundation evaluation w/o inundation simulations



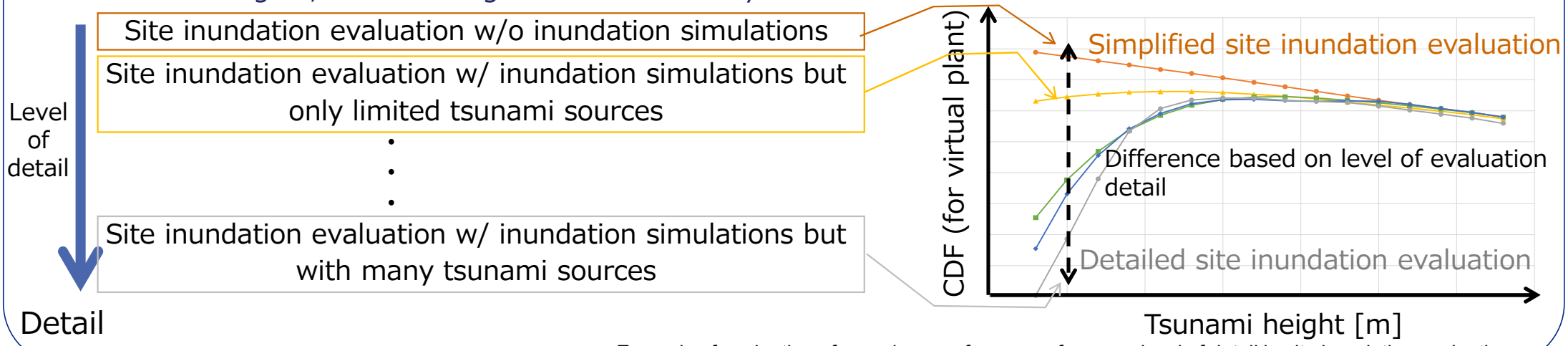
Result of site-inundation evaluation w/ inundation simulations



5. Research Result (1) Proposal of Method Capable of Considering Site Characteristics to Evaluate Site Inundation

■ **Propose risk assessment framework based on a graded approach that selects the level of detail to be evaluated according to the anticipated tsunami risk level [2]**

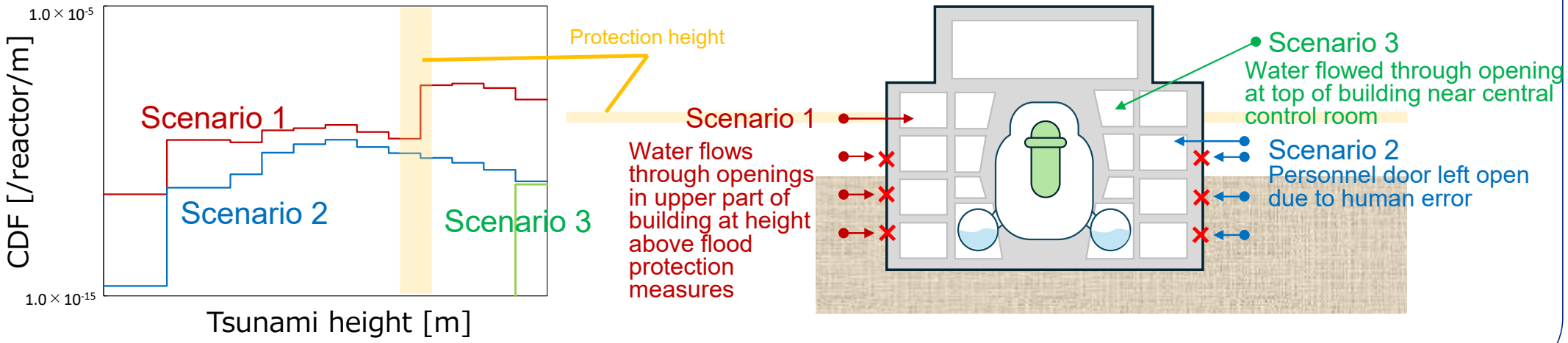
- ✓ Tsunami hazard and risk levels differ significantly from site to site for nuclear power plants in Japan.
- ✓ Level of detail for the evaluation method should be selected based on the site's tsunami hazard level, risk level evaluated by preliminary/simplified assessment, and risk information obtained through tsunami PRA. (Conversely, it would be irrational to conduct a detailed evaluation if the expected tsunami risk is low.) **Thus, it is effective to adopt a graded approach.**
- ✓ A simplified evaluation method not incorporating inundation simulations tends to overestimate CDF at low tsunami heights, so increasing the level of detail yields more realistic evaluation results.



Example of evaluation of core damage frequency for some level of detail in site inundation evaluation

6. Research Result (2) Tsunami PRA Conducted of Realistic Accident Scenarios

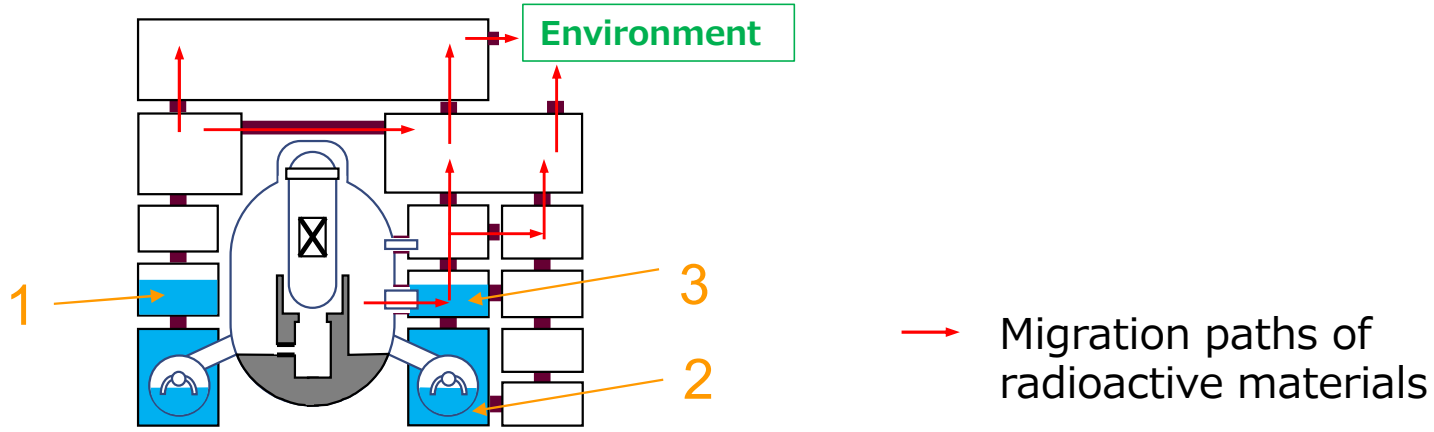
- **Level 1 to Level 2 tsunami PRA conducted for model plant classified into scenarios based on tsunami inundation pathways into major buildings and initiating events** [3]
  - Detailing building internal flooding scenarios revealed risk factors (risk significant components, events, and scenarios accounting for the following items) that cannot be specified in conventional tsunami PRA.
    - Inundation pathways
    - Effectiveness of inundation equipment inside buildings



Ex. of Evaluation of Core Damage Frequency for Specific Building Flooding Patterns

6. Research Result (2) Tsunami PRA Conducted of Realistic Accident Scenarios

- **Level 2 PRA accounting for tsunami inundation pathways into buildings evaluates plant particulars, allowing for a more realistic evaluation**
  - Building internal flooding states assessed in detail are reflected in the source term evaluation where impact due to the following is considered in evaluating release timing, amount, and migration path of radioactive materials.
    1. Building internal flooding volume estimated by building internal flooding simulation
    2. Radioactive material captured in seawater in the building (scrubbing effect)
    3. External cooling of containment (suppression chambre)



Source term evaluation accounting for flooding inside reactor building

8. Current Achievements & Future Actions

■ Current Achievements

- It is now possible to perform Level 1 to Level 2 tsunami PRA that captures risk and accident scenarios more realistically, reflecting the characteristics of each site and plant.

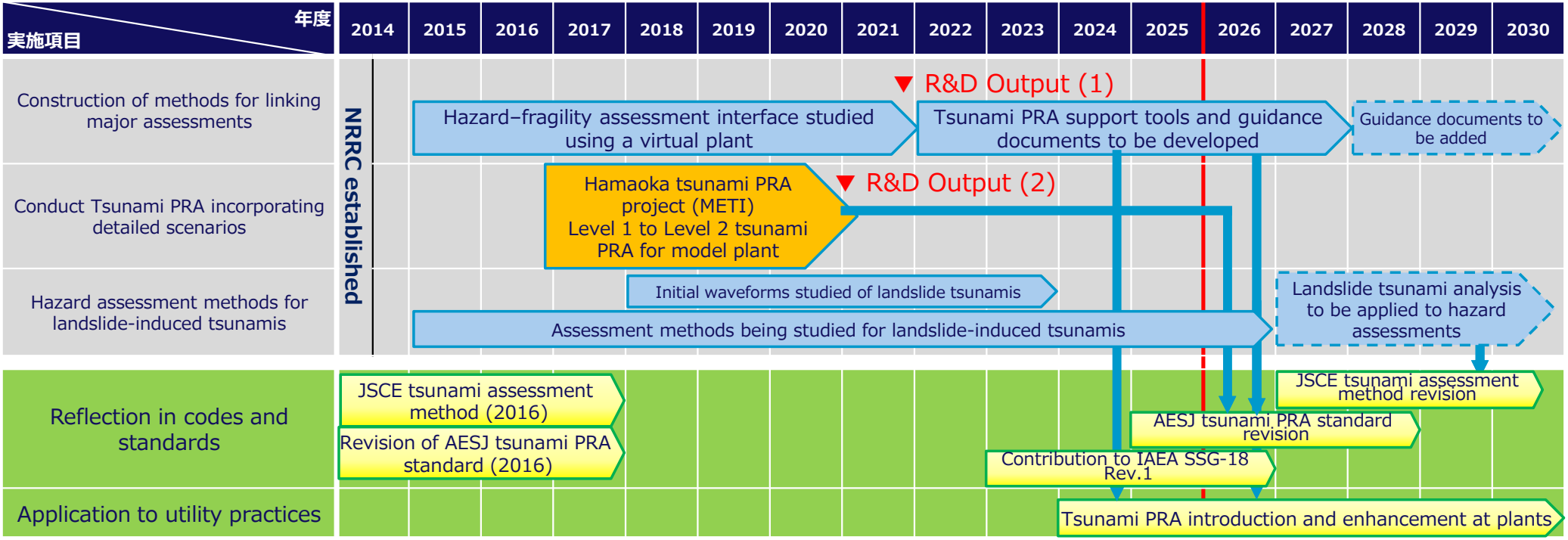
■ Future Actions

- Prepare guidance documents compiling knowledge and research outputs of tsunami PRA (Atomic Energy Society of Japan)
- Standardize probabilistic hazard assessment methods for landslide-induced tsunamis (Japan Society of Civil Engineers)[4]
- Develop detailed evaluation methods for impact of tsunami-borne debris in fragility assessments and for building internal inundation

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[Appendix] Progress in Overcoming Gaps

- Develop scheme connecting hazard and subsequent assessments, or fragility and accident sequence assessments, using site inundation analysis methods
- Demonstrate tsunami PRA with detailed scenarios classified based on tsunami inundation pathways into the site and major buildings as well as initiating events
- Share knowledge gained in these studies with utilities via CRIEPI reports and other publications



[Appendix] Status of Initiatives

Gaps to Overcome	Description	Progress
Methods linking major assessments	Development of site inundation evaluation methods	Completed in 2021
	Enhancement of analysis techniques for building internal inundation	Ongoing
Landslide tsunami hazard assessment	Development of probabilistic tsunami hazard assessment methods for landslide tsunamis	Ongoing
Tsunami PRA using detailed accident scenarios	Level 1 to Level 2 tsunami PRA covering wide range of accident scenarios for model plant	Completed in 2020

Completed outcomes are set to be reflected in revisions of AESJ Tsunami PRA Standard, technical reports, and JSCE Tsunami Assessment Method.

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[Appendix] Key References Relating to R&D Output

[Linking hazard, fragility, and plant response analyses]

[1] Takahashi et al., Uncertainty quantification of tsunami parameters for tsunami fragility assessment based on tsunami hazard assessment and inundation simulation, PSAM, (2020)

[2] Kihara et al., Tsunami flooding analysis graded-approach framework for tsunami probabilistic risk assessment, J. Nucl. Sci. Technol., 60, 1454–1480 (2023)

[Tsunami PRA]

[3] Yamada et al., Development of evaluation technology for conducting integrated tsunami PRA from level 1 through level 2, CRIEPI Report, NR25010, (2026)

[Hazard analyses]

[4] JSCE, The Nuclear Civil Engineering Committee, The Tsunami Evaluation Subcommittee, Tsunami Assessment Method for Nuclear Power Plants in Japan 2016, https://committees.jsce.or.jp/ceofnp/node/140, 2016.

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