Toward Standardizing Probabilistic Risk Assessment Procedures for Combined External Hazards : A Focus on Screening Procedures

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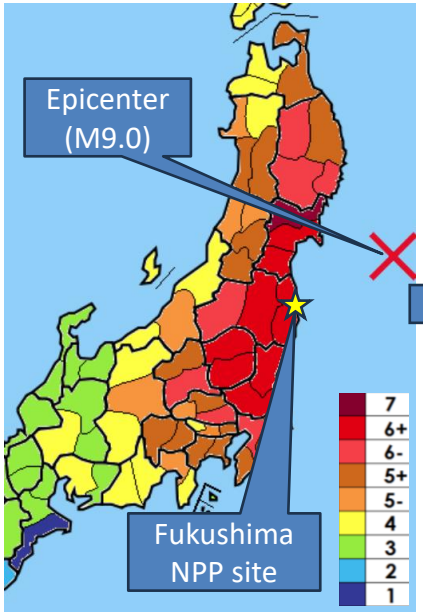
Background

- The Fukushima Daiichi Nuclear Power Plant accident in 2011 highlighted the vulnerability of nuclear facilities to combined earthquake and tsunami hazards.
- Although various methodologies for combined hazard assessment have been developed [1,2], standardized procedures for implementing combined hazard PRA have not yet been established.
- The large number of possible hazard combinations requires a systematic screening framework.



JMA seismic intensity of 2011 Tohoku Earthquake



Earthquake Damage



Tsunami-Induced Flooding



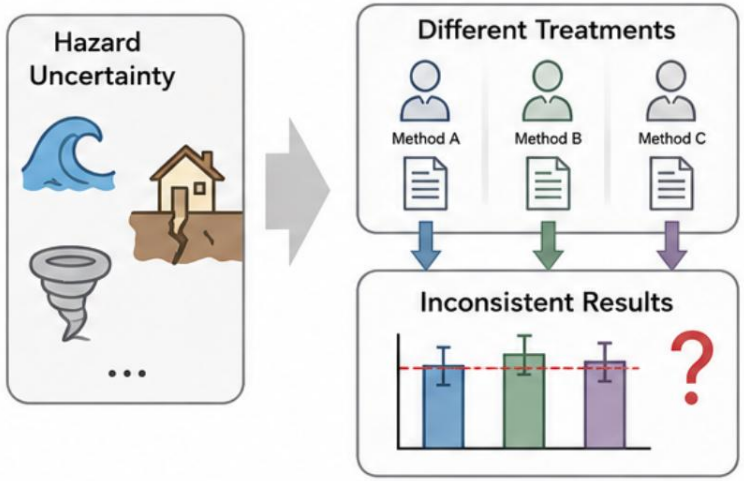
Hydrogen explosion at Fukushima NPP

[1] ASAMPSA_E (2017): List of external hazards to be considered in ASAMPSA_E.
[2] IAEA (2026): Safety Assessment of Nuclear Installations Against Combinations of Hazards Induced by External Events, TECDOC-2129, Vienna, Austria.

Objectives

- Challenges
  - Lack of a systematic assessment framework for combined hazard PRA.
  - Lack of standardized procedures for implementing combined hazard PRA.
  - Limited practical applications of combined hazard PRA methods.

- Objectives
  - Establish a fundamental assessment framework for combined hazard PRA.
  - Propose a structure for standardized PRA procedures based on the assessment framework.
  - Examine the applicability of the proposed framework through application examples.



Assessment Framework for Combined Hazard PRA (1/5)

- Classification method of Combined Hazard PRA
  - Existing studies mainly classify combined hazards based on hazard dependency (consequential, associated and independent hazards) and temporal relationships [1, 2].
  - However, hazard classification alone is not sufficient for PRA because interactions may also occur at the fragility and system levels.
  - Extend the framework to include hazard, fragility, and system dependencies.

Classification of combined hazard PRA

Hazard	Fragility	System
Dependent	Dependent	Dependent
		Independent
	Independent	Dependent
		Independent
Independent	Dependent	Dependent
		Independent
	Independent	Dependent
		Independent

Example of combined hazard PRA

Phase		Example
Hazard	Dependent (consequential)	EQ (shaking) → Tsunami (pressure), Mainshock (shaking) → Aftershocks (shaking)
	Dependent (associated)	(EQ) Tsunami + Liquefaction, (Typhoon) Heavy rainfall + strong wind
	Independent	EQ (shaking) + Tornado (pressure)
Fragility	Dependent	Accumulated damage due to mainshock and aftershocks
	Independent	Damage due to EQ and Tsunami
System	Dependent	Reduced availability of operators due to EQ
	Independent	No shared support systems

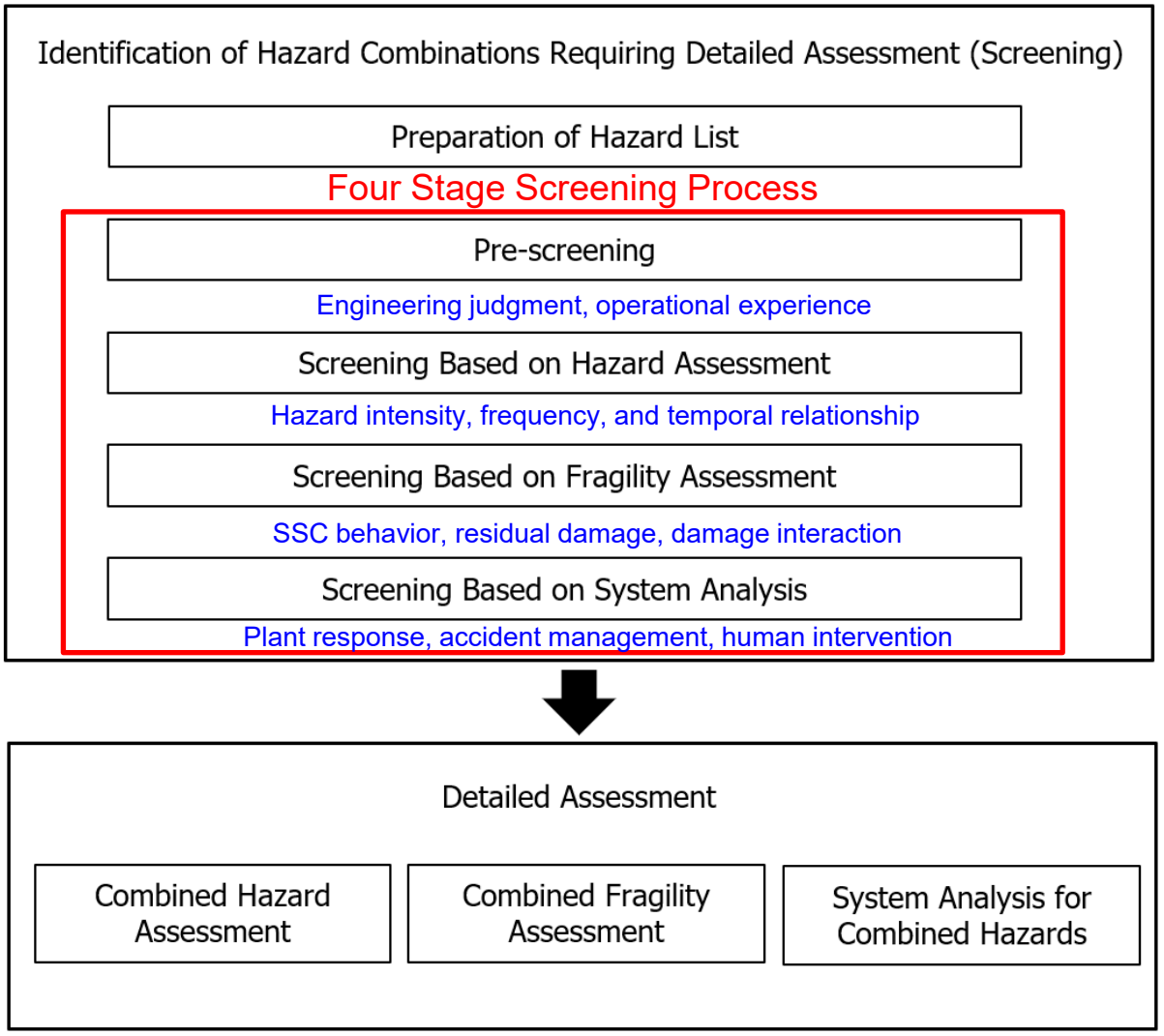
・Consequential hazards: One hazard triggers another
・Associated hazards: Hazards originate from a common source
・Independent hazards: No causal or common-source relationship

[1] ASAMPSA_E (2017): List of external hazards to be considered in ASAMPSA_E.
[2] IAEA (2026): Safety Assessment of Nuclear Installations Against Combinations of Hazards Induced by External Events, TECDOC-2129, Vienna, Austria.

Assessment Framework for Combined Hazard PRA (2/5)

- Screening Method for Combined Hazard PRA

- The proposed assessment flow starts with the preparation of a hazard list, followed by a four-stage screening process.
- The four-stage screening process ensures completeness while maintaining practical feasibility by reducing unnecessary assessments.
- After screening, the remaining combinations are evaluated through hazard assessment, fragility assessment, and system analysis.



Assessment flow for combined hazard PRA

Assessment Framework for Combined Hazard PRA (3/5)

- Hazard List and Grouping
  - Direct evaluation of all possible hazard combinations is impractical.
  - Comprehensively identify combined hazard scenarios, including both natural and human-induced hazards.

101 Candidate External Hazards [1]
- 77 Natural hazards
- 24 Human-induced hazards

↓ Preliminary Screening
- Applicability to Japanese NPP sites
- Potential impact on plant safety
- Relevance to combined hazard assessment
- Treatment in Japanese regulations and design practices

25 Individual Hazards
- 17 Natural hazards
- 8 Human-induced hazards

↓ Hazard Grouping
- Based on hazard source and characteristics

16 Hazard Groups
- 12 Natural hazard groups
- 4 Human-induced hazard groups

Hazard List for Screening

	Group	Hazards Screened In Through Preliminary Screening for Single Hazards
Natural Hazards	G1 Seismic / Ground	N1 Seismic Ground Motion
		N6 Ground Deformation
	G2a Seawater (Tsunami)	N7 Tsunami
		N61 Submarine Landslide
	G2b Seawater (Tide)	N18 Sea Water Level (High Waves, Tide)
	G3 Wind (Tornado)	N41 Tornado
		N46 Tornado-Generated Missiles
	G4 Rain	N8 Flash Flood / Flooding
	G5a Snow (Snow Accumulation)	N25 Heavy Snowfall
	G5b Snow (Avalanche)	N47 Avalanche
	G6 Biological Hazards	N56 HVAC Failure Caused by Birds or Insects
		N57 Cable Damage Caused by Rats or Moles
	G7 Volcano	N69 Volcanic Ash (Including Reduced Visibility)
	G8 Solar	N52 Geomagnetic Storm Caused by Solar Flare
	G9 Lightning	N39 Lightning Strike
	G10 Fog / Mist	N51 Fog (Whiteout)
Human-Induced Hazards	G11 Chemical Substances	M12 Chemical Release Caused by Vehicle Accident Near the Site
	G12 Ship	M7 Collision with Seawall
		M8 Impact on Water Intake
	G13 Offsite Power Supply	M18 Underground Cable Damage Caused by Construction Work
		M19 Disturbance of Offsite Power Grid
		M21 Electromagnetic Interference
		M22 High-Voltage Eddy Current
	G14 Fire	M73 Toxic Gas / Fire Spread Caused by Forest Fire
		M24 Human-Induced Forest Fire

[1] ASAMPSA_E (2017): List of external hazards to be considered in ASAMPSA_E.

Assessment Framework for Combined Hazard PRA (4/5)

- Prescreening Matrix

- Screening covers not only combinations of natural hazards, but also combinations of natural and human-induced hazards.
- Hazard combinations are classified as associated, consequential, or independent based on their dependency characteristics.
- This matrix is a conceptual framework rather than a site-specific evaluation.

Example of Prescreening for G1 (Earthquake / Ground)

Combination with G1	Prescreening Decision
G2a Tsunami	Screened in: causal relationship
G7 Volcano	Site-specific evaluation
G13 Off-site Power	Check overlap with seismic PRA
G14 Fire	Further evaluation: earthquake-induced fire
G3 Tornado	Candidate for screening out
…	…

Prescreening matrix for Japanese nuclear power plant sites

Preceding / Subsequent	G1	G2a	G2b	G3	G4	G5a	G5b	G6	G7	G8	G9	G10	G11	G12	G13	G14
G1 Earthquake / Ground	■	(b)				(b)	(c)		(b) (c)				(b)		(b)	(b)
G2a Seawater (Tsunami)		■											(b)	(a)		
G2b Seawater (Tide)			■													
G3 Wind (Tornado)				■									(b)		(b)	(b)
G4 Rain (Flood)					■				(c)							
G5a Snow (Avalanche)						■							(b)		(b)	
G5b Snow (Snowfall)	(c)						■								(b)	
G6 Biological Hazards								■								
G7 Volcano (Volcanic Ash)	(c)				(c)				■						(b)	
G8 Solar Hazards										■					(b)	
G9 Lightning											■				(b)	(b)
G10 Fog / Mist							(b)		(b)			■				
G11 Chemical Substances							(b)		(b)				■			
G12 Ships / Marine Vessels		(a)												■		
G13 Off-site Power Supply															■	
G14 Fire							(b)		(b)						(b)	■

※(a): Common-cause hazards, (b): Consequential hazards, (c): Independent hazards (long duration)
※Blank cells indicate independent hazards with a short duration.
※Gray cells indicate combinations that do not occur as preceding events for consequential hazards.

Assessment Framework for Combined Hazard PRA (5/5)

- Screening Criteria
- Representative screening criteria identified from previous studies are summarized below.

Screening Criteria [1,3]

Screening method	Example / Criterion
Mutually exclusive	Physically impossible to occur simultaneously (e.g., High temperature + Snow)
Hazard Inclusion	One hazard is already included in the assessment of the other (e.g., Aircraft Accident + Fog)
Enveloping	The additional impact of one hazard is enveloped by the impact of the other
Progression rate	Sufficient time is available for mitigation measures
Hazard frequency	Design-level hazard frequency < 10^{-5}/year and CCDP < 10^{-1}[3]
CDF / LERF	CDF < 10^{-6}/year or LERF <10^{-7}/year based on simplified/bounding analysis [3]

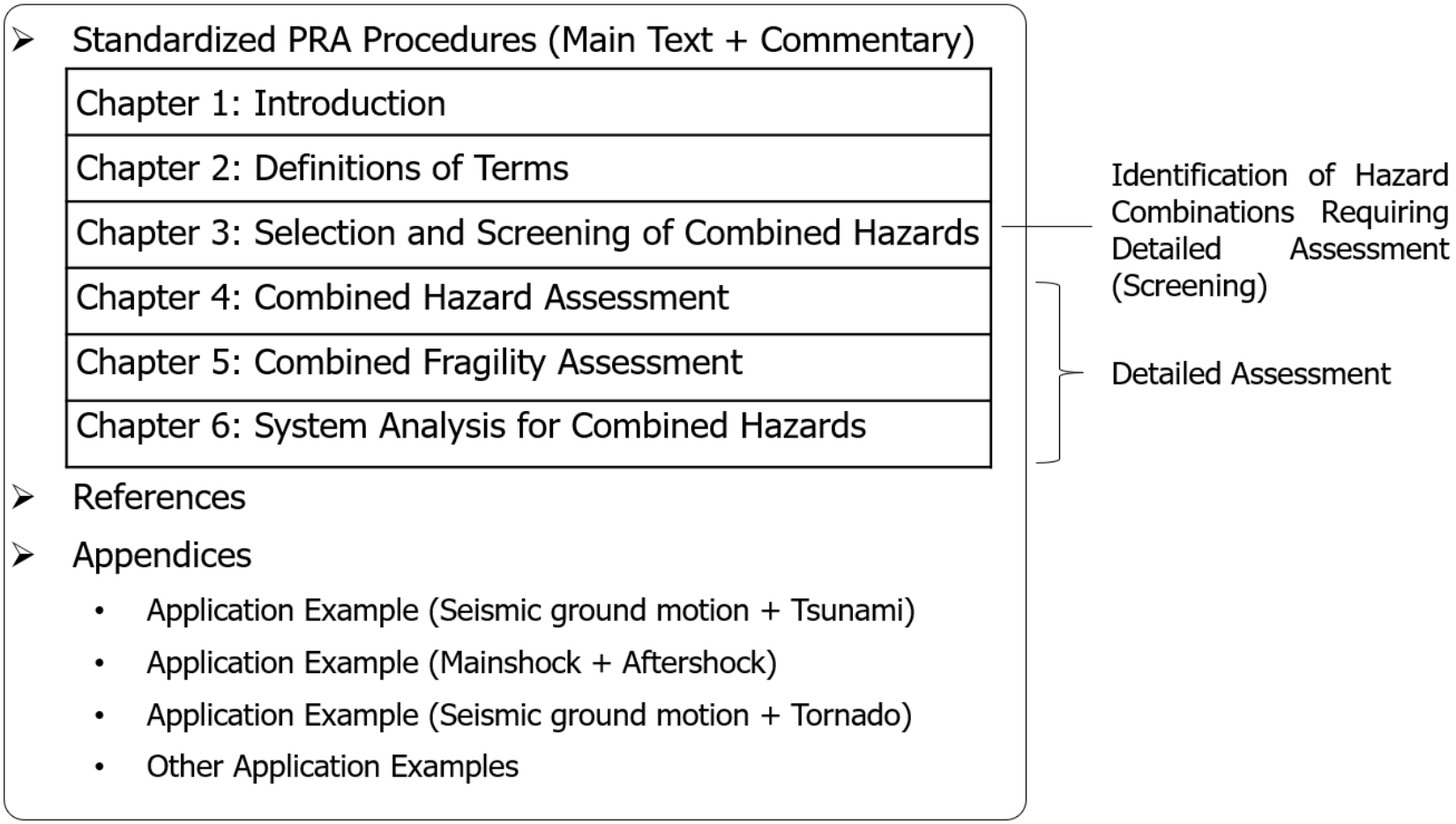
※ The quantitative criteria shown above are examples from existing literature and should be established considering the objectives and conditions of the assessment.

These screening criteria provide practical guidance for systematically reducing the number of hazard combinations before detailed combined hazard PRA.

[1] ASAMPSA_E (2017): List of external hazards to be considered in ASAMPSA_E.
[3] EPRI (2015): Identification of External Hazards for Analysis in Probabilistic Risk Assessment.

Standardized Procedures for Combined Hazard PRA

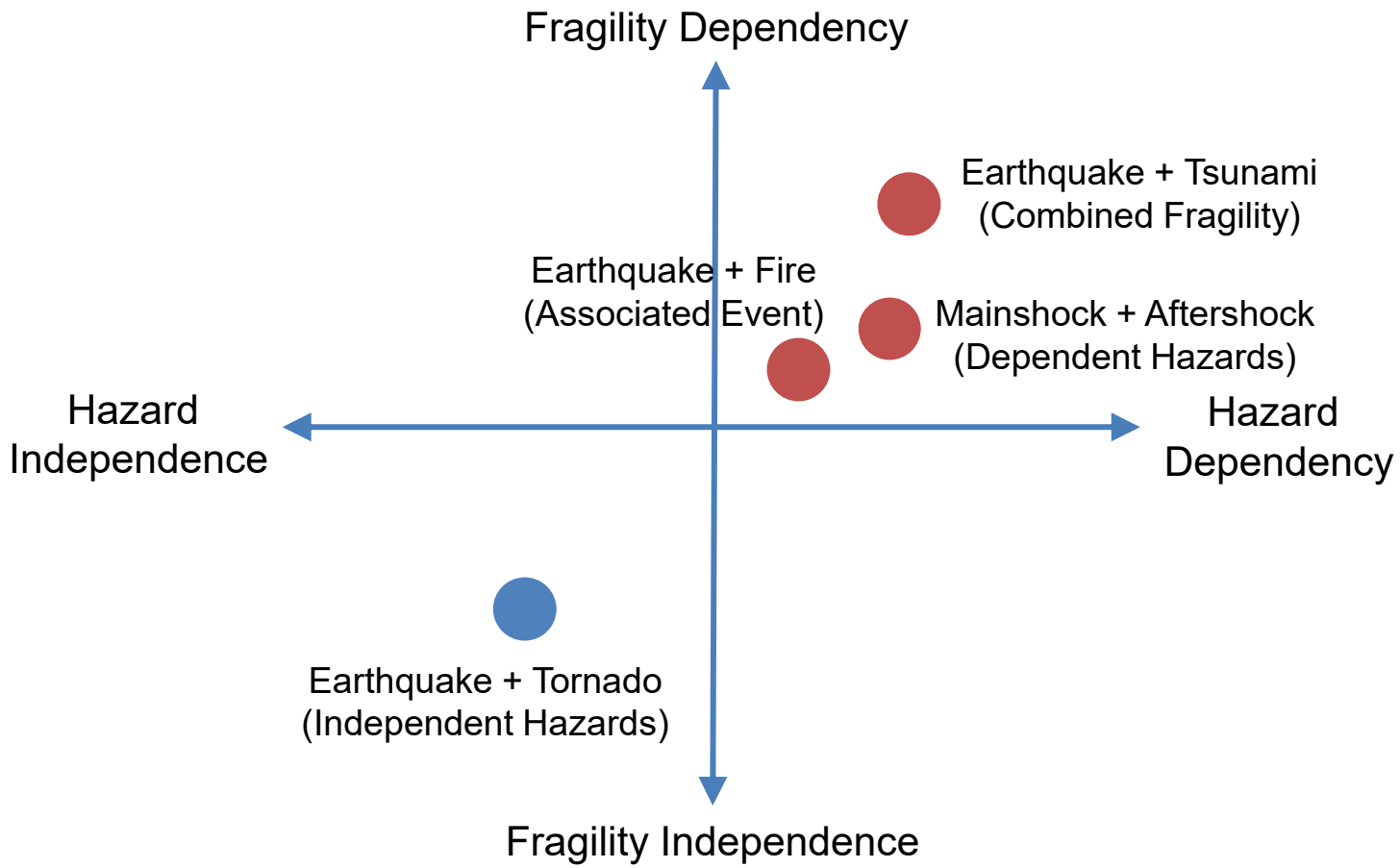
- Proposed Structure of Standardized Procedures
- Standardized PRA procedures will be developed based on the proposed assessment framework and screening methods.



Proposed structure of standardized procedures for combined hazard PRA

Application Examples (1/3)

- Four application examples
- Four representative combined events were analyzed to examine the applicability of the proposed framework to actual plant models.

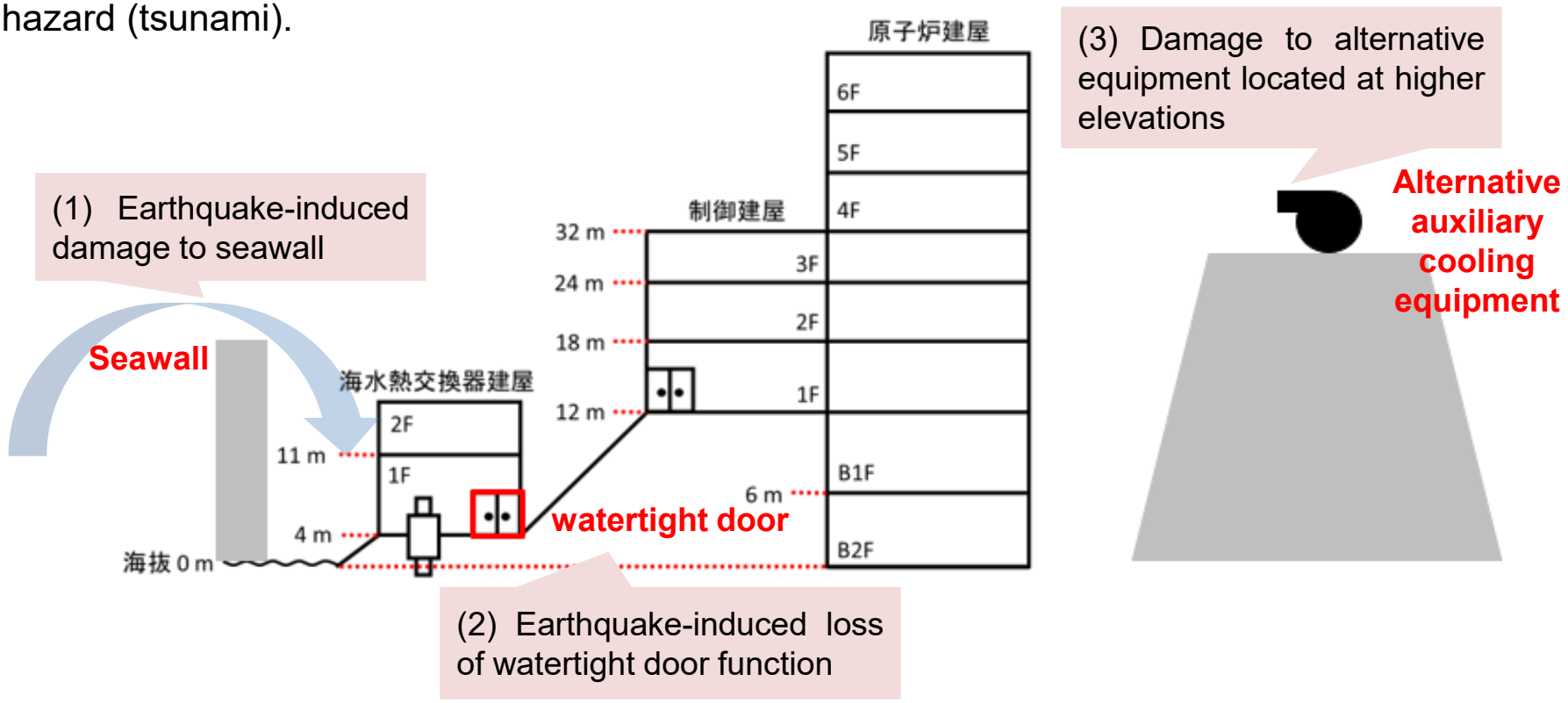


Four Representative Combined Events

Application Examples (2/3)

- Earthquake + Tsunami (Combined Fragility)

- Investigation of combined fragility effects that may be overlooked by simply combining single-hazard assessments
- This application example focuses on earthquake-induced damage or degradation of tsunami protection features.
- The integrated assessment approach enables direct modeling of dynamic accident sequences in which a preceding hazard (earthquake) degrades protective functions against a subsequent hazard (tsunami).



Application Example (Earthquake + Tsunami)

Application Examples (3/3)

Comparison of Application Examples

	Mainshock + Aftershock	Earthquake + Tornado	Earthquake + Fire
Hazard Characteristics	Dependent hazards	Independent hazards	Associated event
Assessment Approach	Integrated assessment	Separate assessment	Integrated assessment
Key Technical Element	Conditional aftershock probability model	Combination of individual-event PRA results	FDS (Fire Dynamics Simulator) analysis
Key Feature	Explicit consideration of time after the mainshock and accumulation of SSC damage	Efficient system assessment using Boolean combination of existing PRA models	Fire progression analysis considering spatial changes in fire barriers due to earthquake damage

- Separate assessment may be sufficient for physically and temporally independent hazards.
- Screening can reduce the computational burden when interaction effects are negligible.
- Integrated assessment is essential when a preceding hazard degrades protective functions.
- Combined effects may lead to risk underestimation if assessed separately.

Conclusions

- Assessment Framework

  A fundamental framework for combined hazard PRA was proposed, including classification and screening methods.

- Standardized Procedures

  A preliminary structure for standardized PRA procedures was proposed based on the assessment framework.

- Application examples

  Four representative combined events were examined to demonstrate the applicability of the proposed framework.

- These results provide a foundation for future standardization and practical implementation of combined hazard PRA.

- Future Work

- Further develop standardized PRA procedures and refine the screening methods based on application examples and expert review.
- Extension of the framework toward Level 3 PRA, including off-site consequence and public health impacts.

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Thank you

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