Probabilistic Tsunami Hazard Assessment and Deaggregation for the Eastern Coast of Korea

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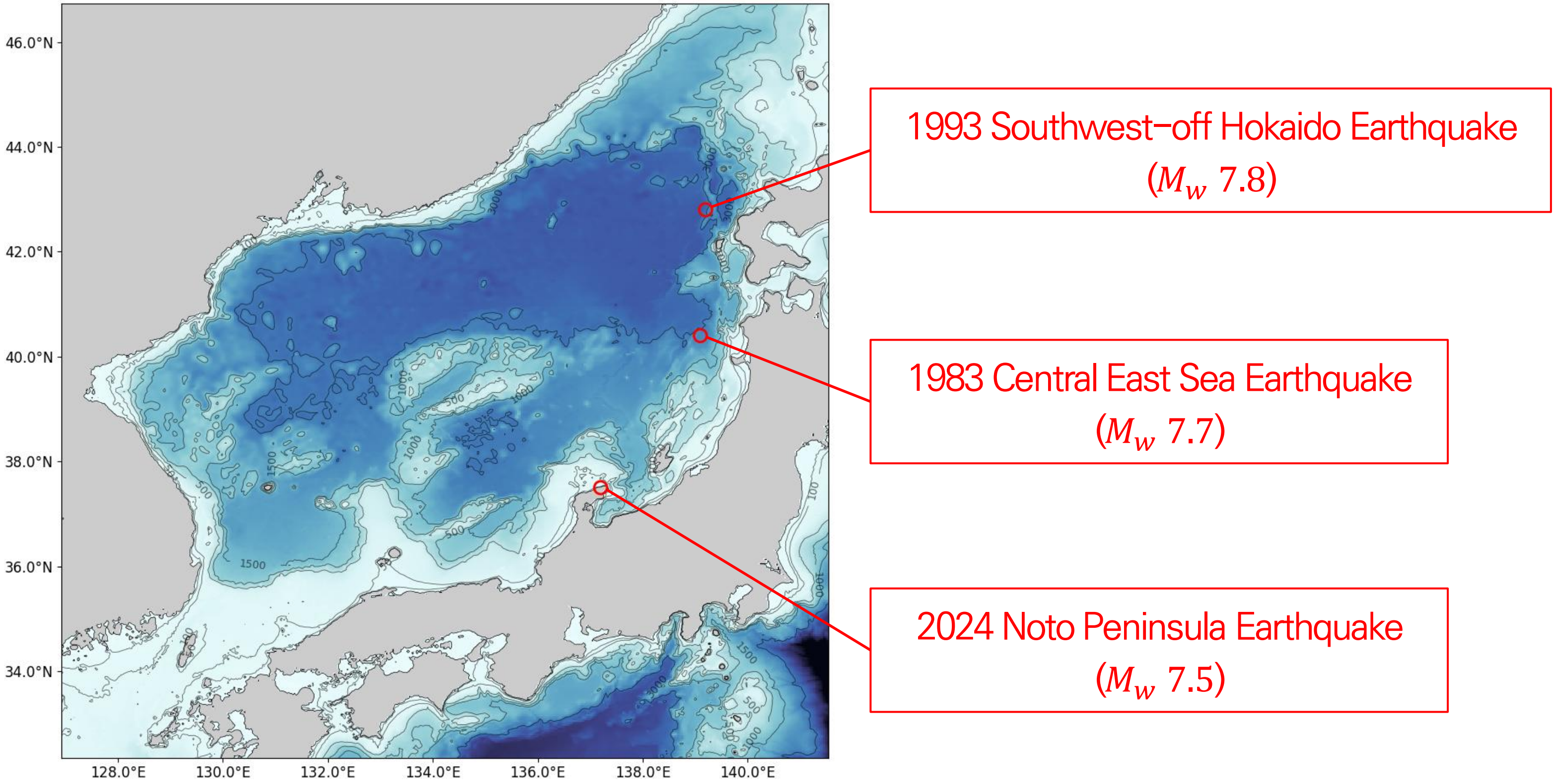
Chapter 1

Introduction

Motivation

Historical Background

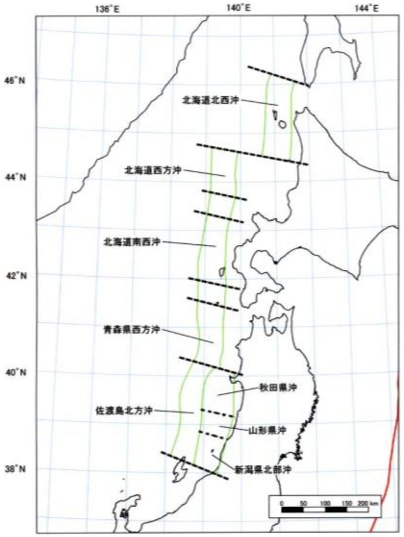
- ✓ Tsunamis are low-frequency but high-impact hazards capable of causing catastrophic damage
- ✓ Large-scale tsunamis that have directly impacted Korea's eastern coast occur periodically. Based on both historical records and modern observational data, the eastern coast of Korea can no longer be considered a tsunami-safe zone
- ✓ Therefore, it is necessary to conduct a hazard assessment for the eastern coast of Korea



1993 Southwest-off Hokaido Earthquake (M_w 7.8)

1983 Central East Sea Earthquake (M_w 7.7)

2024 Noto Peninsula Earthquake (M_w 7.5)



[Eastern Margin Fault Zone of the East Sea]

Background

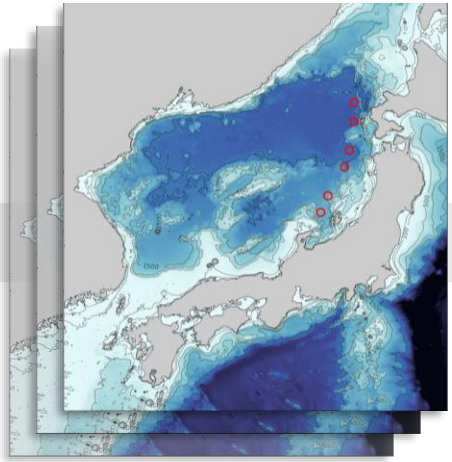
- Deterministic vs. Probabilistic Approach

✓ Limitations of the Deterministic Approach

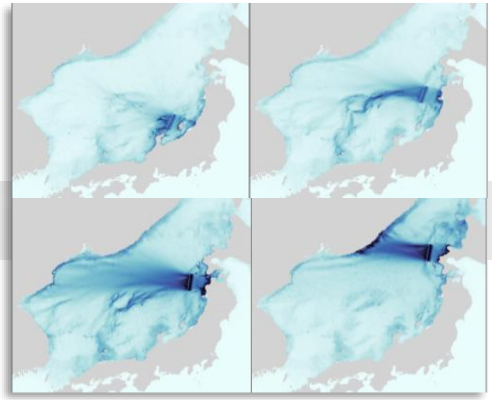
  - Single scenario dependency
  - Inadequate treatment of uncertainty
  - Under or over design

✓ Necessity of the Probabilistic Approach (PTHA, Probabilistic Tsunami Hazard Assessment)

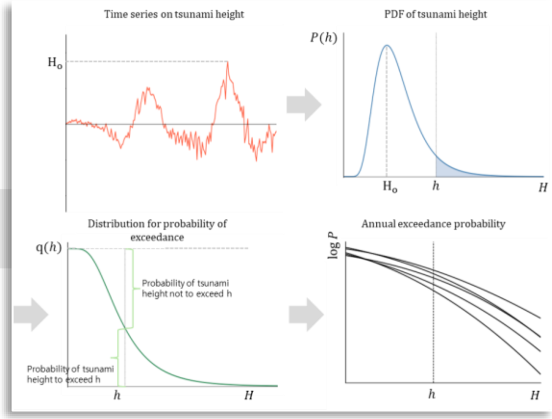
  - Comprehensive scenario integration
  - Return period–based hazard estimation
  - Rational decision–making



[Setting Parameters]



[Propagation]



[PTHA Process]

Objective

- Quantitative Hazard Analysis and Identification of Dominant Sesmic Source for Korea’s Eastern Coast through PTHA

- Detailed Research Objectives
  - ✓ Hazard Curve Derivation
  - ✓ Deaggregation analysis
  - ✓ Bathymetric amplification

- Research Workflow

Seismic Source Scenario DB construction

- ✓ Generation of virtual seismic sources using a Logic Tree framework accounting for epistemic uncertainty

Tsunami Numerical Simulation

- ✓ Computation of Zmax for each Logic Tree branch using COMCOT, based on nonlinear shallow water equations

Probabilistic Tsunami Hazard Assessment (PTHA)

- ✓ **Quantification of tsunami hazard** at target sites by integrating possible earthquake scenarios and their occurrence frequencies

Deaggregation & Source Analysis

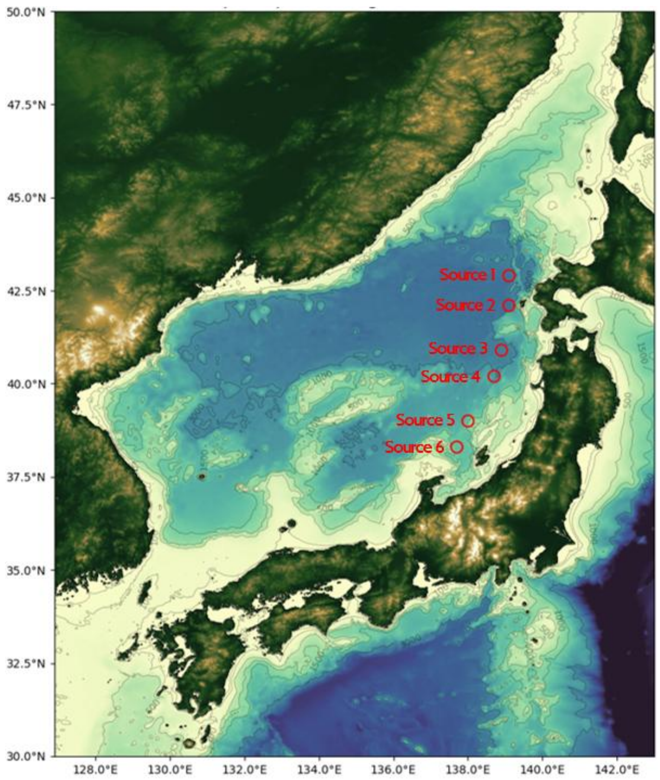
- ✓ **Identification of dominant seismic sources** influencing the target hazard level, and confirmation of energy focusing due to bathymetric and coastal topographic effects

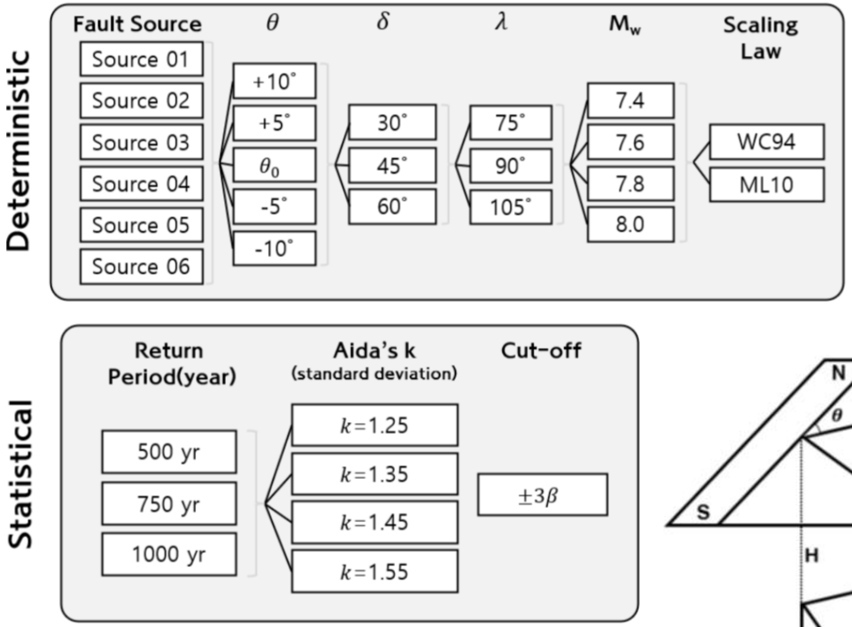
Chapter 2

Methodology

1. Logic Tree

- Selection of Tsunami Source Regions and Logic Tree Construction




Deterministic

Fault Source: Source 01, Source 02, Source 03, Source 04, Source 05, Source 06

θ: +10°, +5°, θ_0, -5°, -10°

δ: 30°, 45°, 60°

λ: 75°, 90°, 105°

M_w: 7.4, 7.6, 7.8, 8.0

Scaling Law: WC94, ML10

Statistical

Return Period(year): 500 yr, 750 yr, 1000 yr

Aida's k (standard deviation): k=1.25, k=1.35, k=1.45, k=1.55

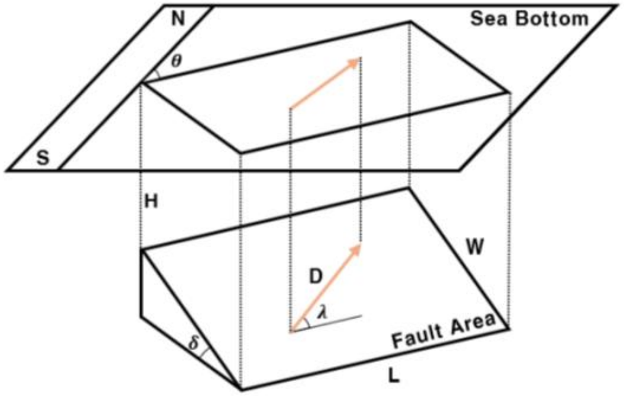
Cut-off: $\pm 3\beta$

θ : Strike angle
δ : Dip angle
λ : Rake angle
D : Slip

H : Focal depth
W : Fault width
L : Fault Length

$$6 \times 5 \times 3 \times 3 \times 4 \times 2 = 2{,}160$$

$$2{,}160 \times 3 \times 4 = 25{,}920$$



✓ Fault sources covering the eastern margin fault zone of the East Sea were adopted based on KEDO (1999)

✓ A Logic Tree framework was employed to account for both physical uncertainty and statistical variability of seismic sources, generating fault models using strike, dip, rake, and magnitude–dependent fault geometry defined by Scaling Laws.

2. Propagation

- Numerical Simulation of Tsunami

1. Initial Displacement

- ✓ Okada Model (1985) : Computes seafloor deformation using fault parameters as input values

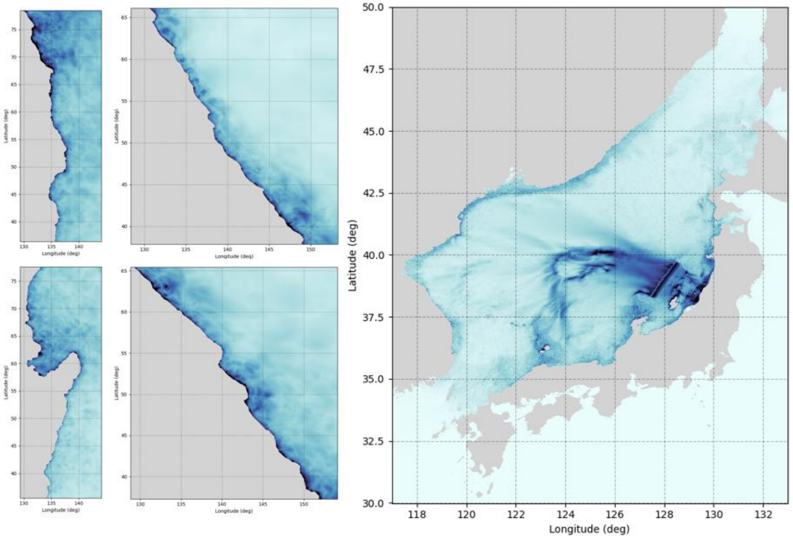
2. Tsunami Propagation

- ✓ COMCOT(Cornell Multi-grid Coupled Tsunami Model) : Numerically solves tsunami propagation using linear/nonlinear Shallow Water Equations.
- ✓ Governing equations (Nonlinear Shallow Water Equations):

$$\frac{\partial \eta}{\partial t} + \left(\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y}\right) = -\frac{\partial h}{\partial t}$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x}\left(\frac{P^2}{H}\right) + \frac{\partial}{\partial y}\left(\frac{PQ}{H}\right) + gH\frac{\partial \eta}{\partial x} + F_x = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{PQ}{H}\right) + \frac{\partial}{\partial y}\left(\frac{Q^2}{H}\right) + gH\frac{\partial \eta}{\partial y} + F_y = 0$$

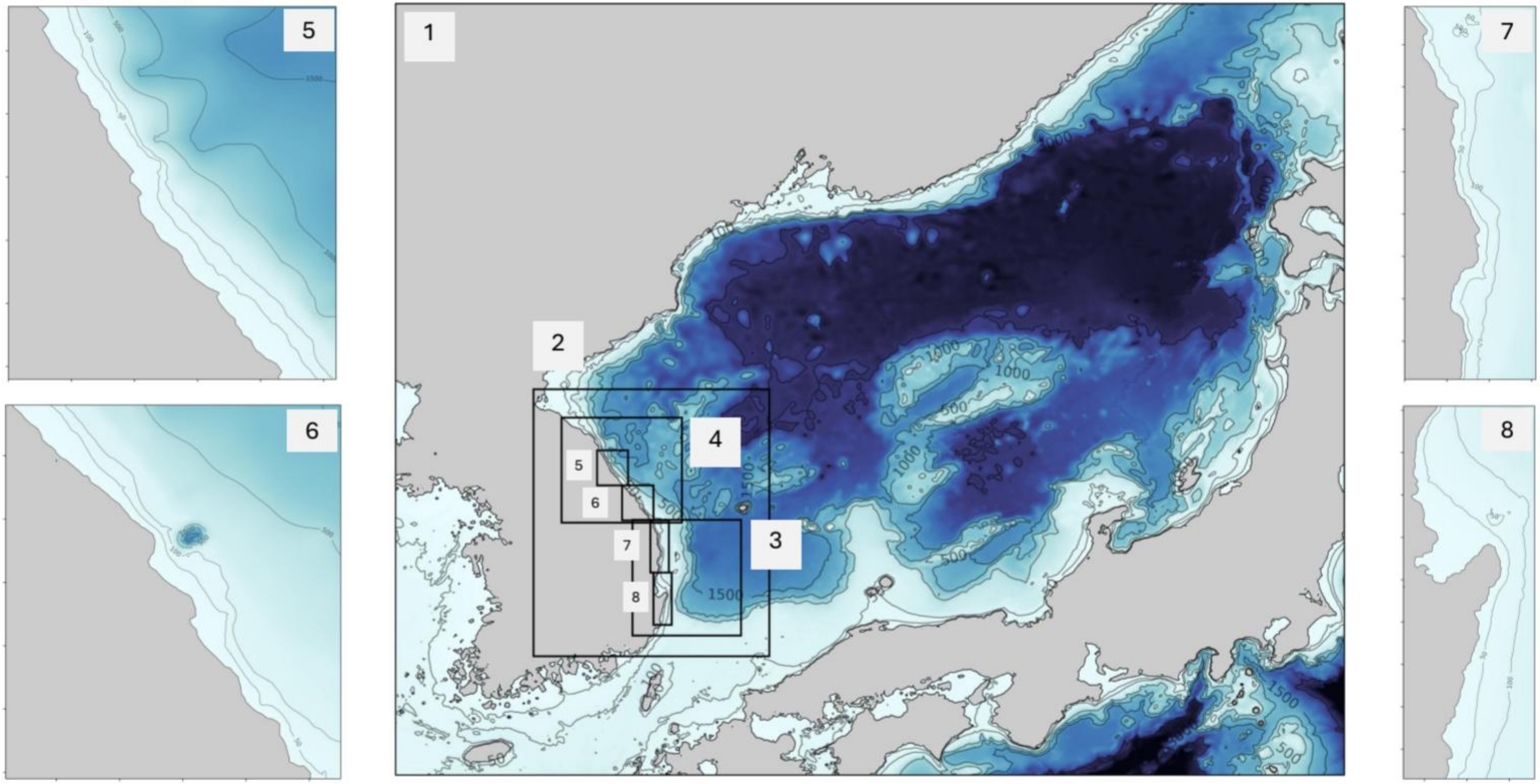


3. Maximum Wave Height

- ✓ For each simulation branch, the maximum wave height Zmax at every grid point is extracted over the entire computation period, and used as the fundamental input data for deriving **PTHA Fractile curves**.

2. Propagation

- Numerical Simulation Domain



✓ Grid Resolution : Layer01(~2.5km) 〉 Layer02(~0.625km) 〉 Layer03~04(~0.156km) 〉 Layer05~08(~0.040km)

3. PTHA

- Probabilistic Tsunami Hazard Assessment

✓ Lognormal PDF of Maximum Wave Height

$$P(h) = \frac{1}{h\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln h - \ln H_{max})^2}{2\sigma^2}\right)$$

$P(h)$: Probability density
h : Wave height
Z_{max} : Simulated maximum wave height
σ : Log-standard deviation; magnitude of uncertainty, $\sigma = \ln(k)$

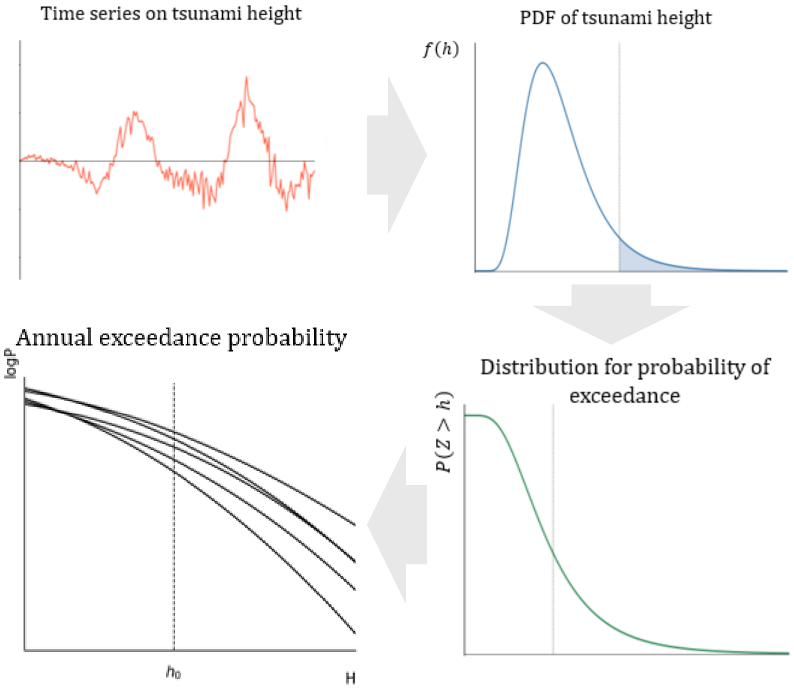
✓ Annual Exceedance Probability (AEP)

$$AEP(h) = 1 - \exp(-\nu \cdot P(H > h))$$

$AEP(h)$: Annual exceedance probability
ν : Annual occurrence rate; reciprocal of return period

✓ Exceedance Probability Distribution

$$P(H > h^*) = 1 - \Phi\left(\frac{\ln h^* - \ln H_{max}}{\sigma}\right)$$



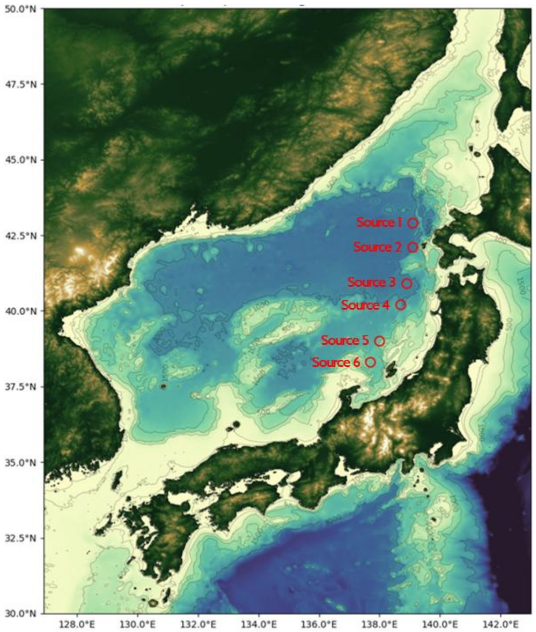
✓ By integrating seismic source uncertainties through the Logic Tree, quantitative tsunami hazard curves and design wave heights are derived for each target site.

4. Deaggregation

- ✓ Total Annual Rate of Exceedance

$$AEP_{Total}(h > h^*) = \sum \nu_i \cdot P(h > h^* \,|Scenario_i) \cdot W_i$$

ν_i: Annual occurrence rate of seismic source (1/500, 1/750, 1/1000)
$P(h > h^*|Scenario_i)$: Probability that wave height exceeds h* for scenario i
W_i: Integrated logic−tree weight assigned to scenario i

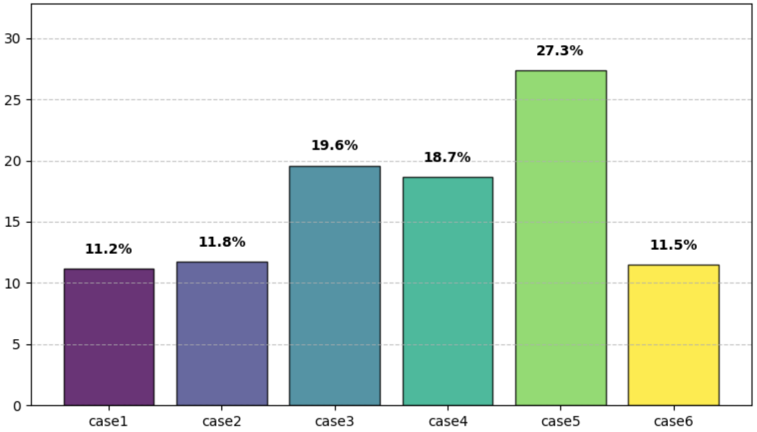


- ✓ Contribution of a Specific Source

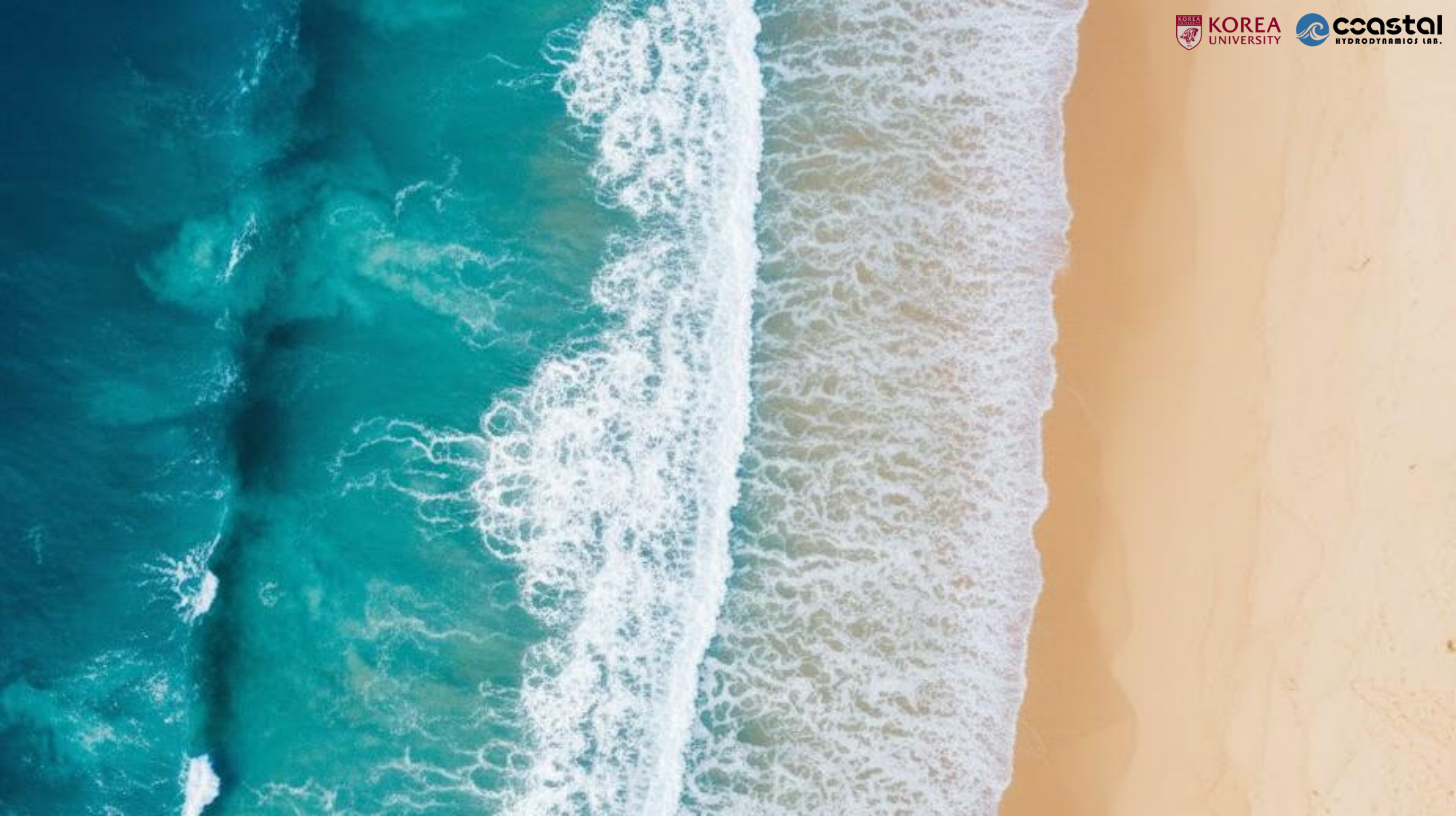
$$AEP_{Source}(h > h^*) = \sum_{i \in Source} \nu_i \cdot P(h > h^* \,|Scenario_i) \cdot W_i$$

- ✓ Relative Contribution (%)

$$\mathrm{D_c}(\%) = \frac{AEP_{Source}(h > h^*)}{AEP_{Total}(h > h^*)} \times 100$$



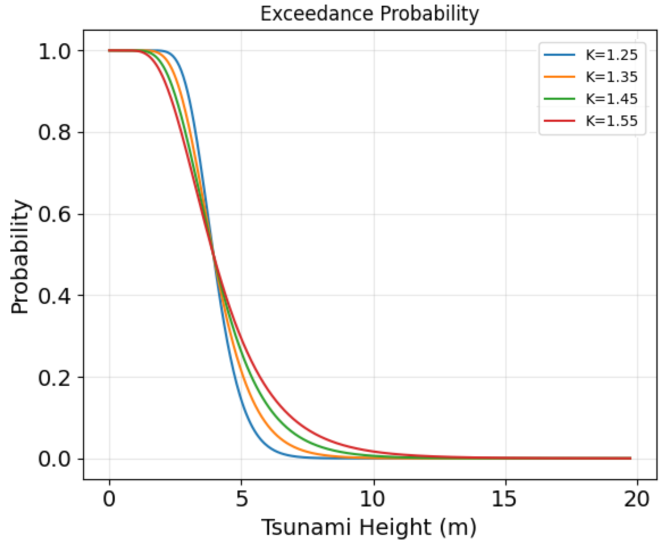
- ✓ By decomposing the integrated hazard into individual scenarios, dominant seismic sources and bathymetric contributing factors responsible for specific wave heights are identified.

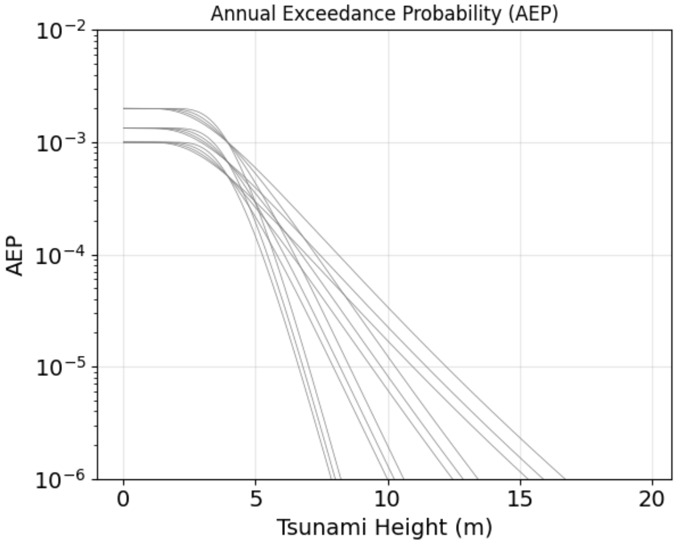


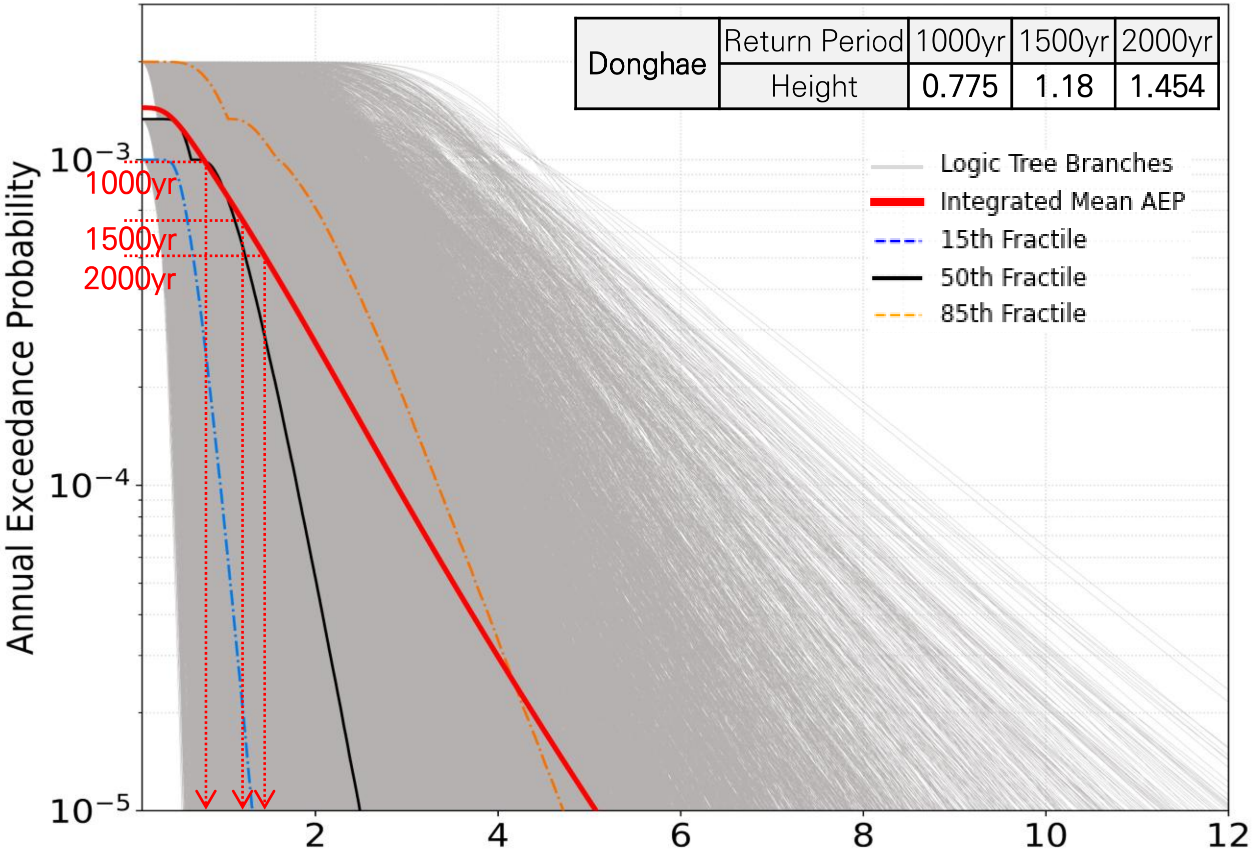
Chapter 3

Result

1. Hazard Curve



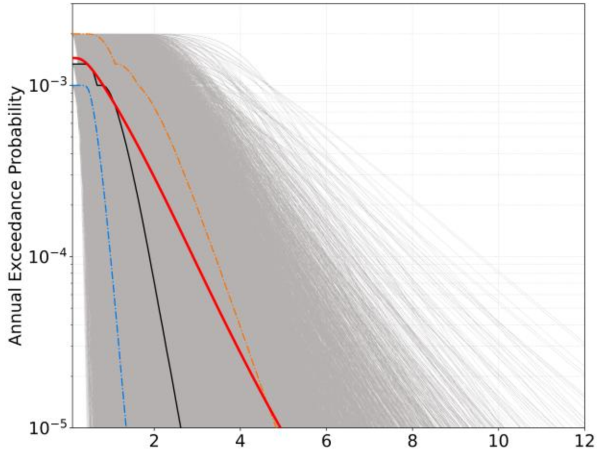




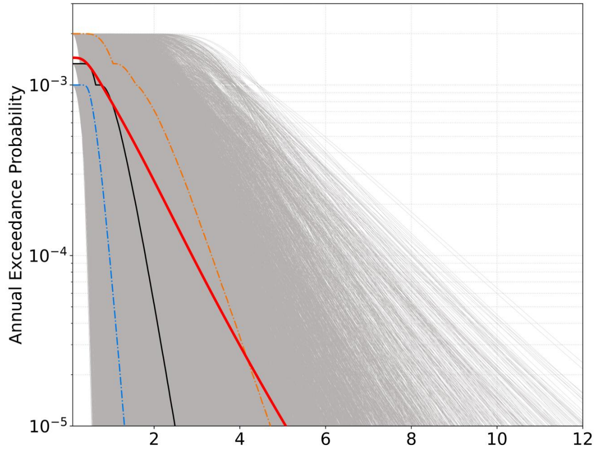
Donghae	Return Period	1000yr	1500yr	2000yr
	Height	0.775	1.18	1.454

✓ Four representative ports (Sokcho, Donghae, Imwon, and Pohang) were selected, and expected wave heights for each return period were determined using the method described above.

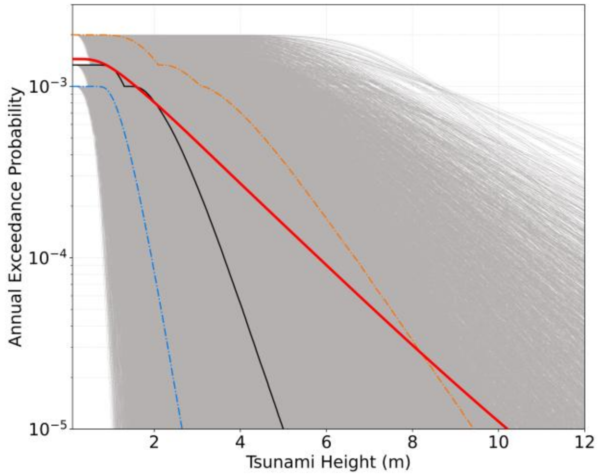
1. Hazard Curve



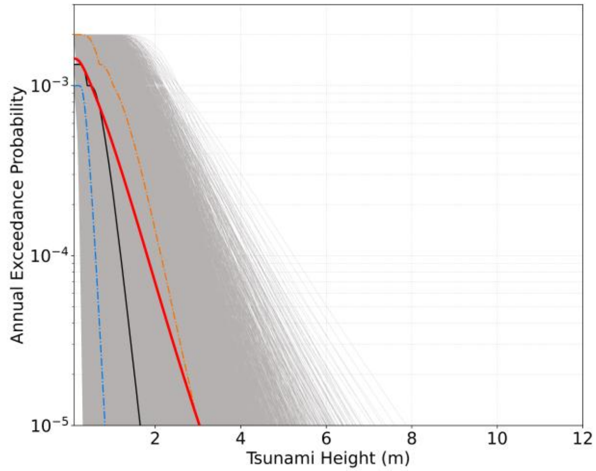
Sokcho	Return Period	1000yr	1500yr	2000yr
	Height	0.813	1.234	1.511



Donghae	Return Period	1000yr	1500yr	2000yr
	Height	0.775	1.18	1.454

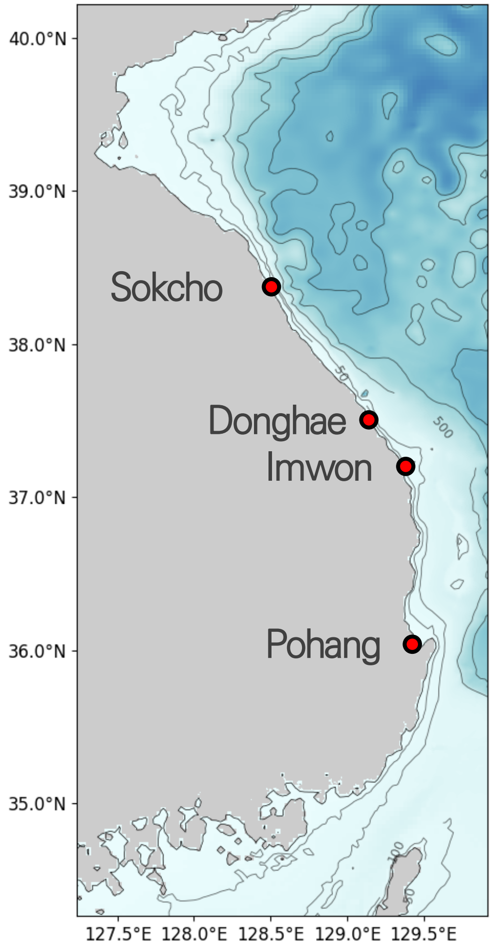


Imwon	Return Period	1000yr	1500yr	2000yr
	Height	1.572	2.366	2.895

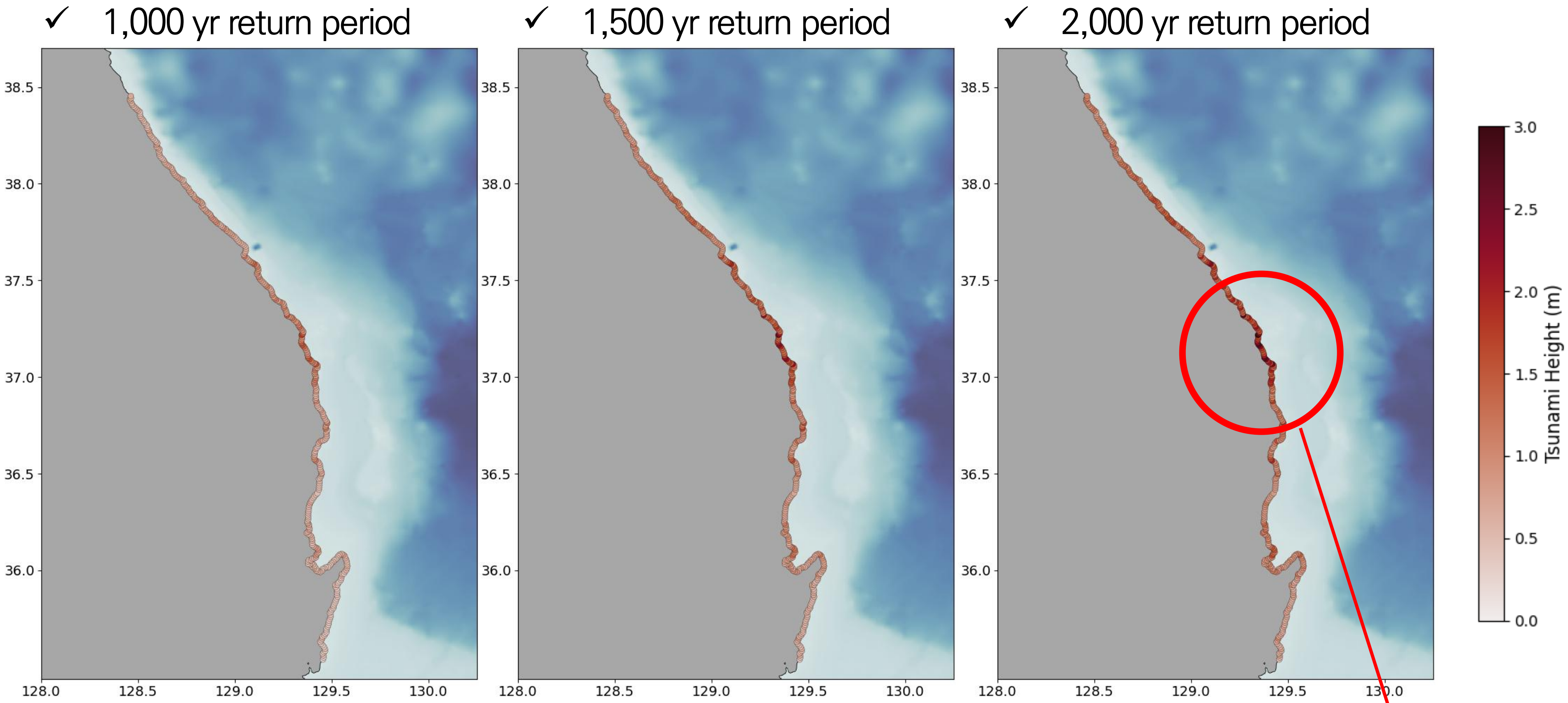


Pohang	Return Period	1000yr	1500yr	2000yr
	Height	0.504	0.775	0.949

- Logic Tree Branches
- Integrated Mean AEP
- 15th Fractile
- 50th Fractile
- 85th Fractile



2. Hazard Map



✓ 1,000 yr return period

✓ 1,500 yr return period

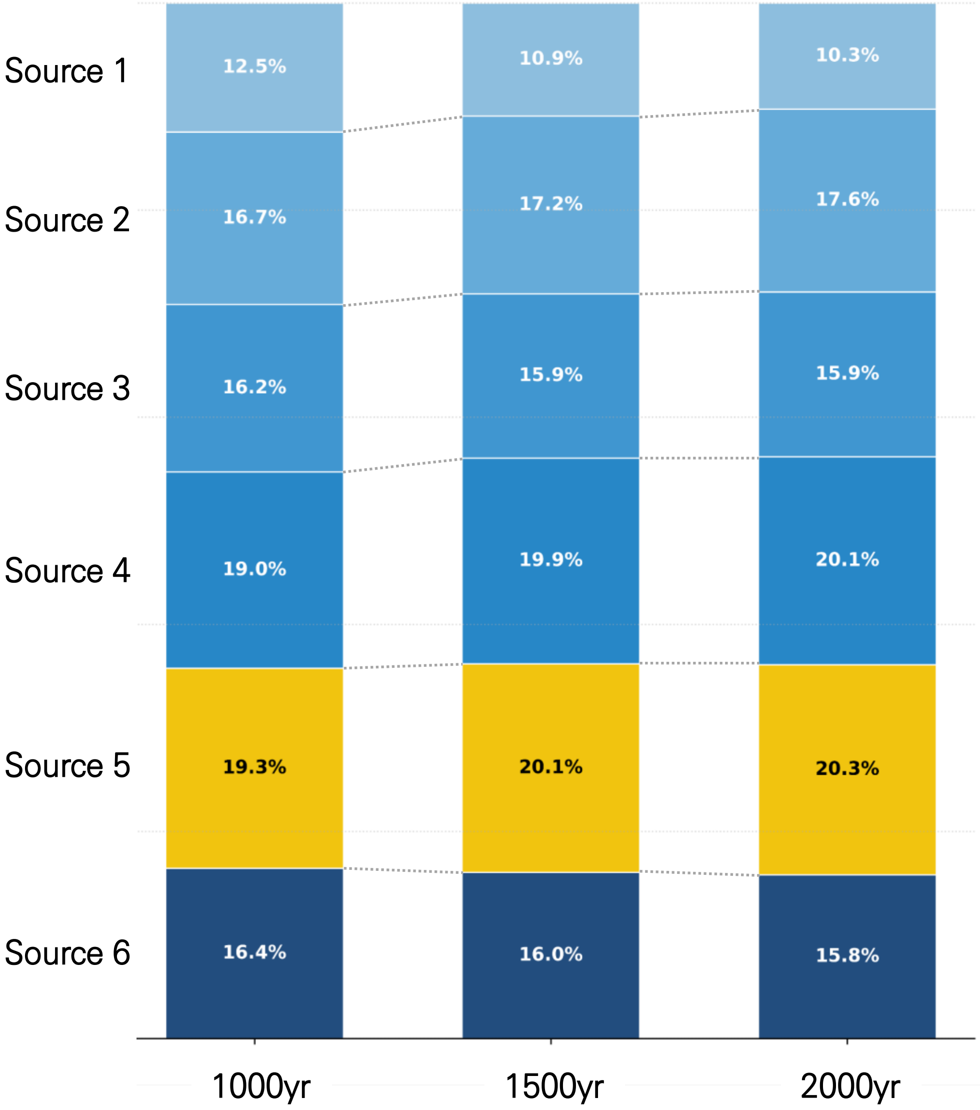
✓ 2,000 yr return period

- ✓ Expected wave heights at major ports along the eastern coast increase significantly as the return period increases.
- ✓ The area near Imwon port shows a notably higher hazard rate compared to other regions.
- ✓ The high-hazard zone is geographically consistent with the damage recorded at Imwon port during the 1983 Akita-Oki tsunami.

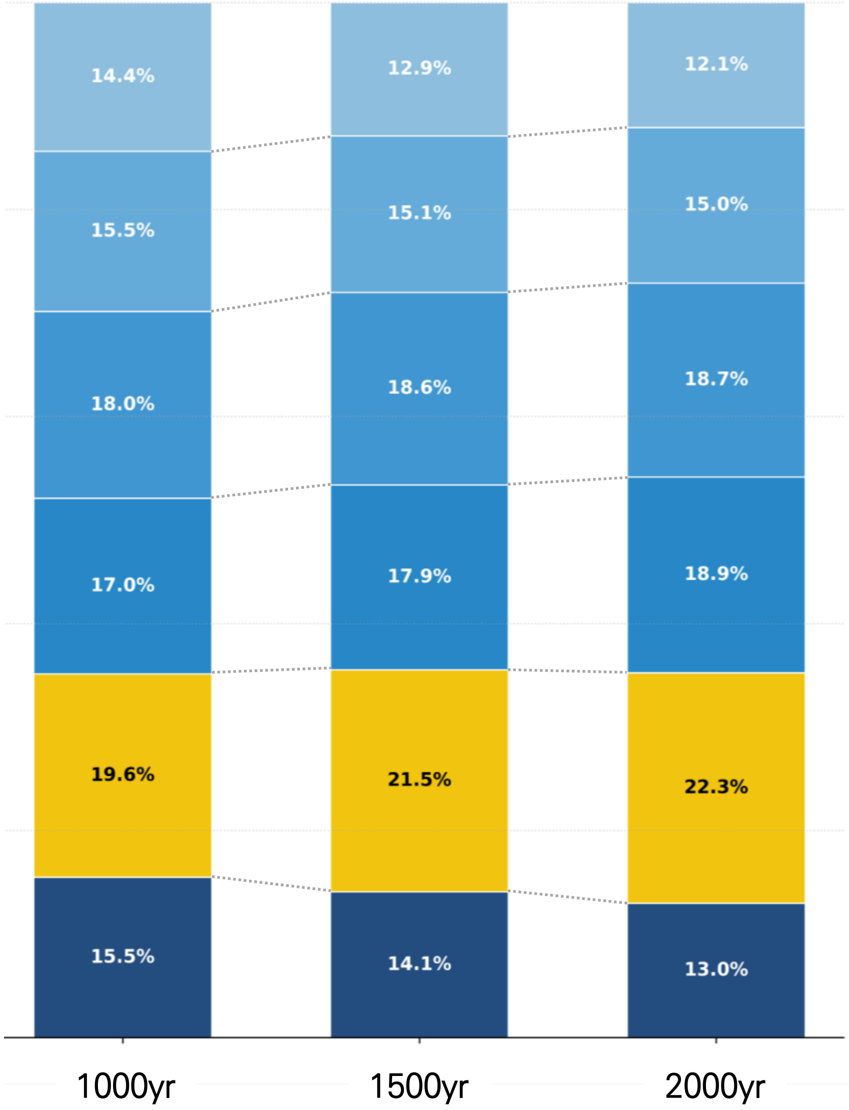
(Imwon port during the 1983 Akita-Oki tsunami)

3. Deaggregation

- Sokcho port

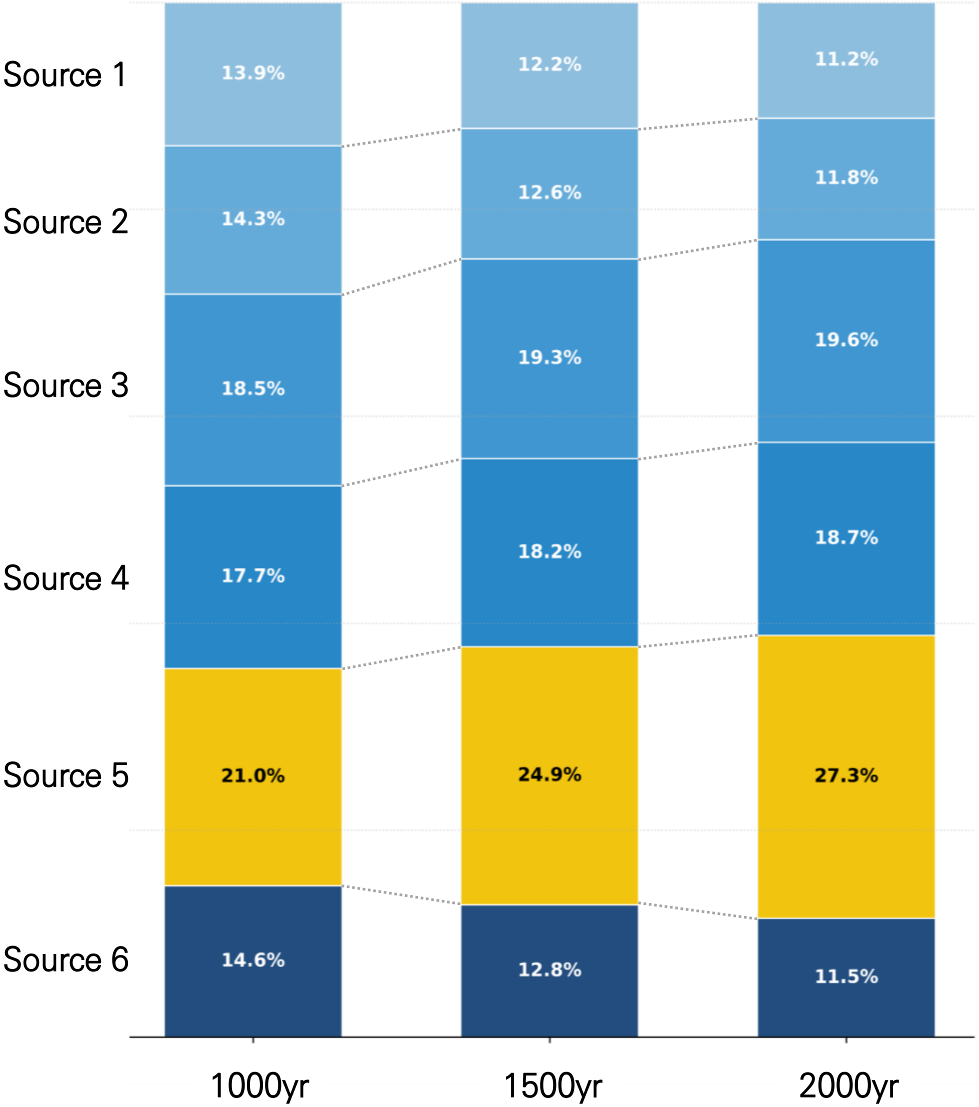


- Donghae port

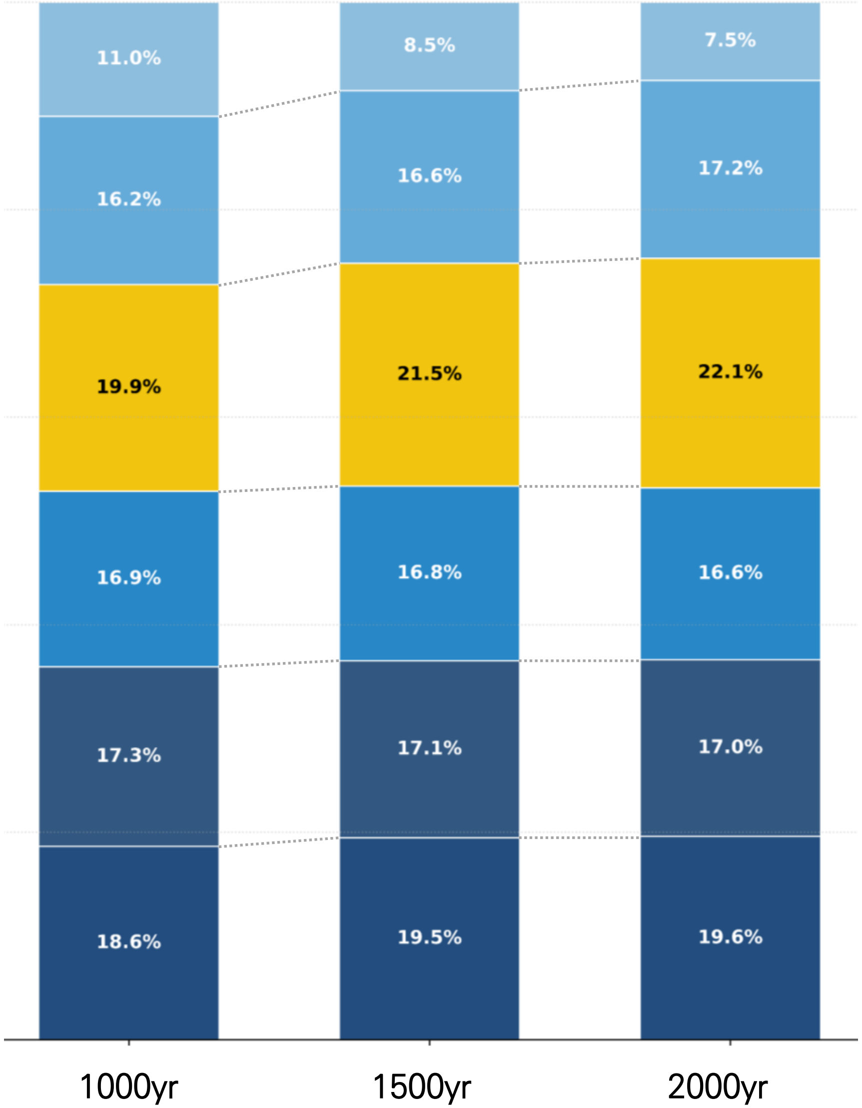


3. Deaggregation

- Imwon port

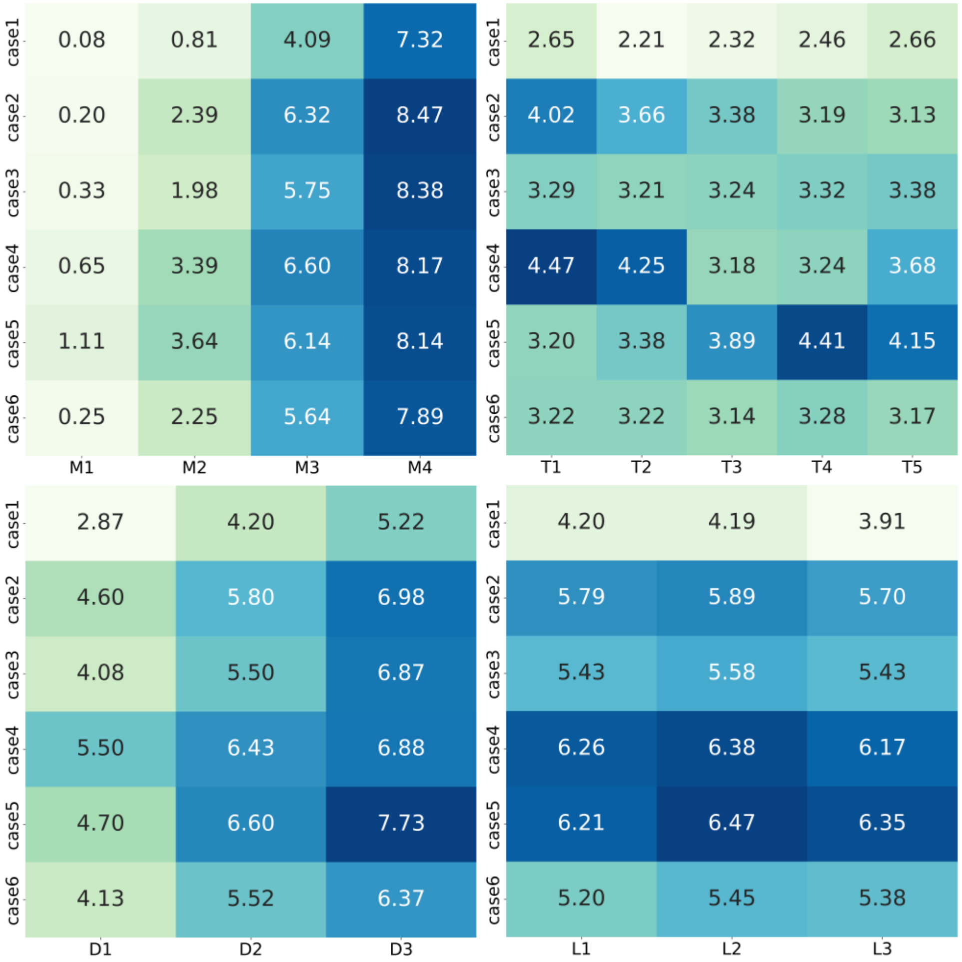


- Pohang port



3. Deaggregation

- Sokcho port (M/T/D/L)



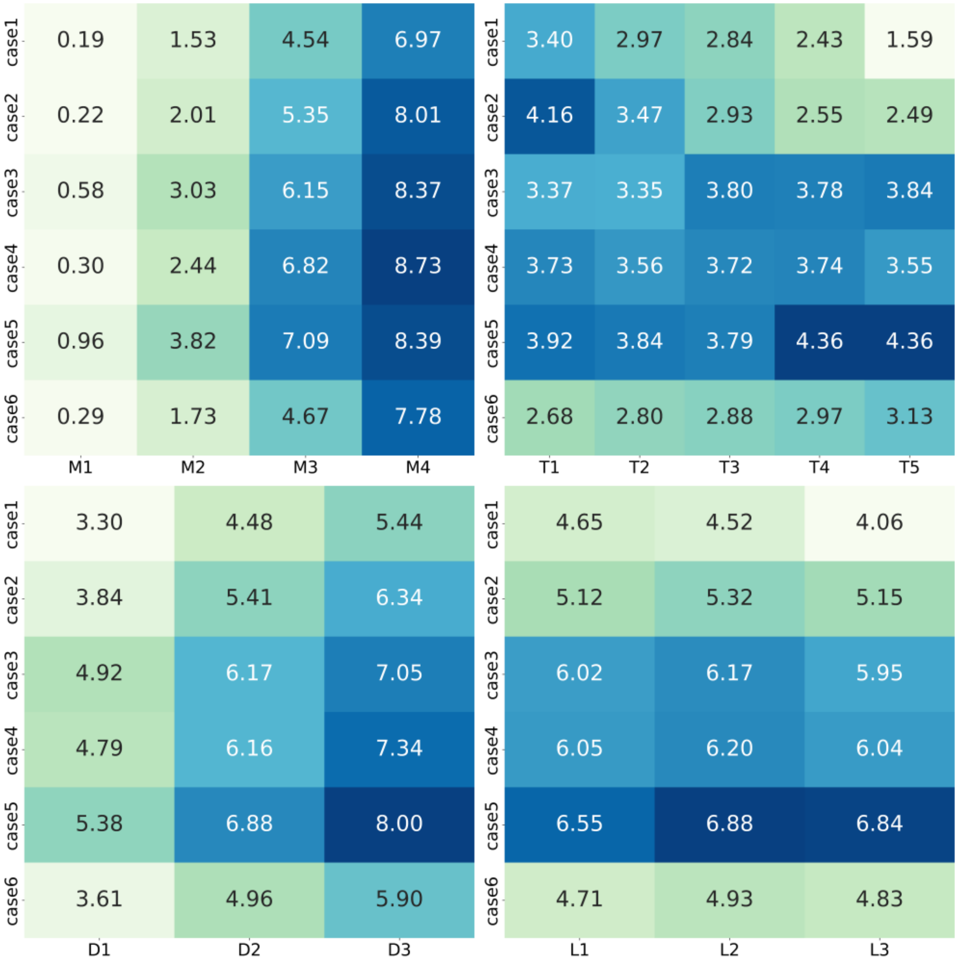
	M1	M2	M3	M4
case1	0.08	0.81	4.09	7.32
case2	0.20	2.39	6.32	8.47
case3	0.33	1.98	5.75	8.38
case4	0.65	3.39	6.60	8.17
case5	1.11	3.64	6.14	8.14
case6	0.25	2.25	5.64	7.89

	T1	T2	T3	T4	T5
case1	2.65	2.21	2.32	2.46	2.66
case2	4.02	3.66	3.38	3.19	3.13
case3	3.29	3.21	3.24	3.32	3.38
case4	4.47	4.25	3.18	3.24	3.68
case5	3.20	3.38	3.89	4.41	4.15
case6	3.22	3.22	3.14	3.28	3.17

	D1	D2	D3
case1	2.87	4.20	5.22
case2	4.60	5.80	6.98
case3	4.08	5.50	6.87
case4	5.50	6.43	6.88
case5	4.70	6.60	7.73
case6	4.13	5.52	6.37

	L1	L2	L3
case1	4.20	4.19	3.91
case2	5.79	5.89	5.70
case3	5.43	5.58	5.43
case4	6.26	6.38	6.17
case5	6.21	6.47	6.35
case6	5.20	5.45	5.38

- Donghae port (M/T/D/L)



	M1	M2	M3	M4
case1	0.19	1.53	4.54	6.97
case2	0.22	2.01	5.35	8.01
case3	0.58	3.03	6.15	8.37
case4	0.30	2.44	6.82	8.73
case5	0.96	3.82	7.09	8.39
case6	0.29	1.73	4.67	7.78

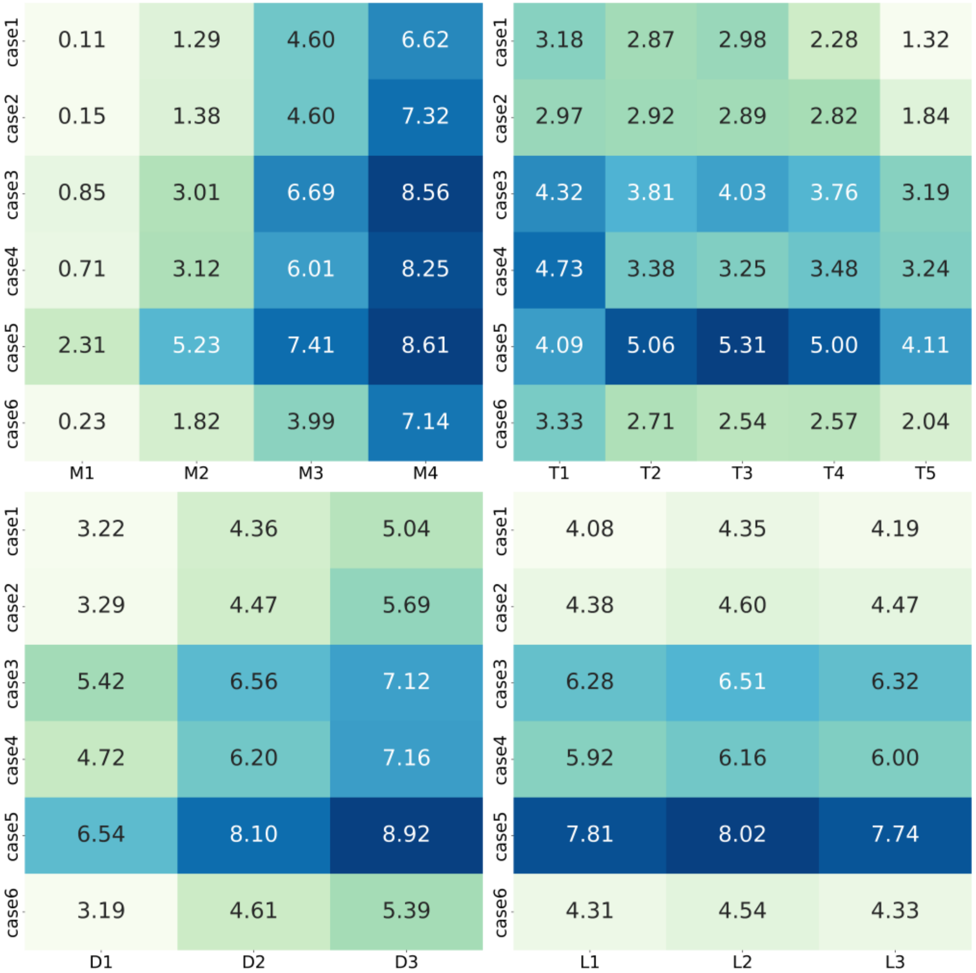
	T1	T2	T3	T4	T5
case1	3.40	2.97	2.84	2.43	1.59
case2	4.16	3.47	2.93	2.55	2.49
case3	3.37	3.35	3.80	3.78	3.84
case4	3.73	3.56	3.72	3.74	3.55
case5	3.92	3.84	3.79	4.36	4.36
case6	2.68	2.80	2.88	2.97	3.13

	D1	D2	D3
case1	3.30	4.48	5.44
case2	3.84	5.41	6.34
case3	4.92	6.17	7.05
case4	4.79	6.16	7.34
case5	5.38	6.88	8.00
case6	3.61	4.96	5.90

	L1	L2	L3
case1	4.65	4.52	4.06
case2	5.12	5.32	5.15
case3	6.02	6.17	5.95
case4	6.05	6.20	6.04
case5	6.55	6.88	6.84
case6	4.71	4.93	4.83

3. Deaggregation

- Imwon port (M/T/D/L)



	M1	M2	M3	M4
case1	0.11	1.29	4.60	6.62
case2	0.15	1.38	4.60	7.32
case3	0.85	3.01	6.69	8.56
case4	0.71	3.12	6.01	8.25
case5	2.31	5.23	7.41	8.61
case6	0.23	1.82	3.99	7.14

	T1	T2	T3	T4	T5
case1	3.18	2.87	2.98	2.28	1.32
case2	2.97	2.92	2.89	2.82	1.84
case3	4.32	3.81	4.03	3.76	3.19
case4	4.73	3.38	3.25	3.48	3.24
case5	4.09	5.06	5.31	5.00	4.11
case6	3.33	2.71	2.54	2.57	2.04

	D1	D2	D3
case1	3.22	4.36	5.04
case2	3.29	4.47	5.69
case3	5.42	6.56	7.12
case4	4.72	6.20	7.16
case5	6.54	8.10	8.92
case6	3.19	4.61	5.39

	L1	L2	L3
case1	4.08	4.35	4.19
case2	4.38	4.60	4.47
case3	6.28	6.51	6.32
case4	5.92	6.16	6.00
case5	7.81	8.02	7.74
case6	4.31	4.54	4.33

- Pohang port (M/T/D/L)

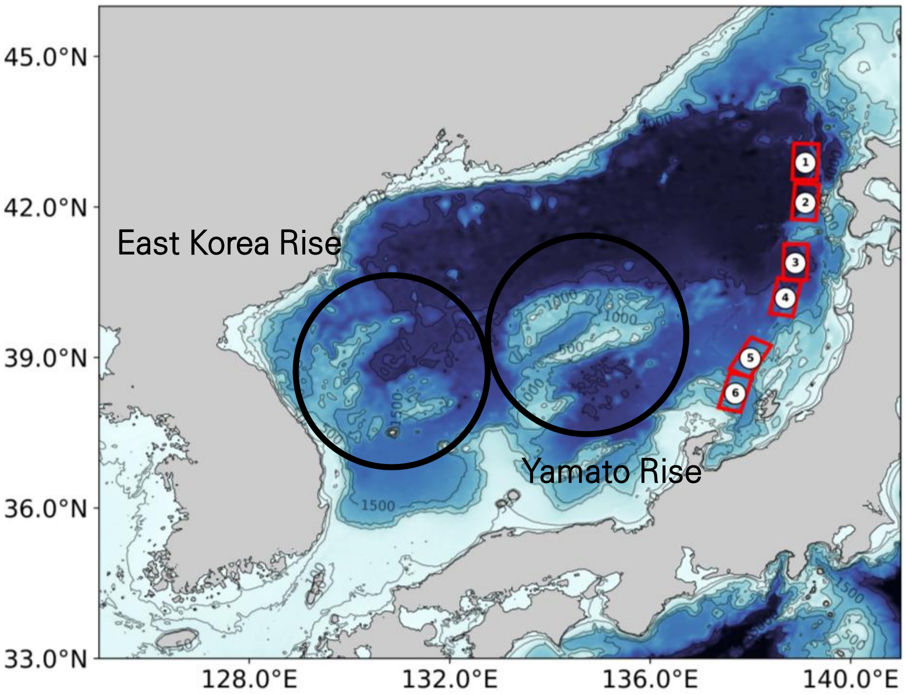
	M1	M2	M3	M4
case1	0.04	0.54	2.83	6.70
case2	0.13	1.81	6.69	8.51
case3	1.08	3.72	6.97	8.40
case4	0.26	2.21	5.96	8.40
case5	0.46	2.25	5.98	8.61
case6	0.44	3.20	6.53	8.30

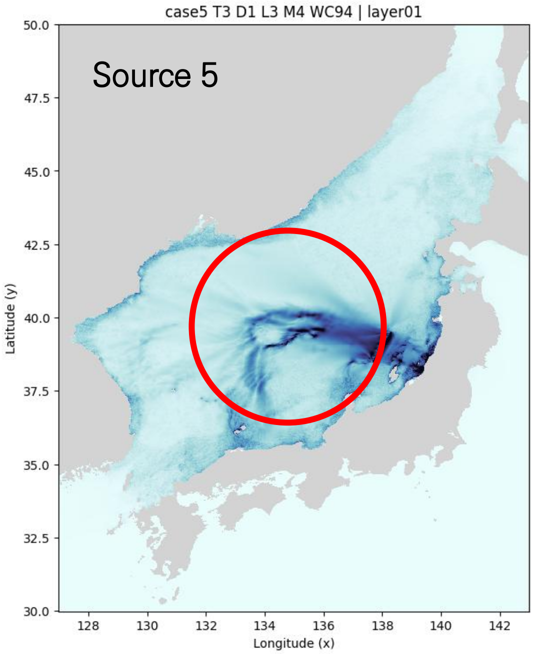
	T1	T2	T3	T4	T5
case1	2.40	1.82	2.02	1.94	1.93
case2	3.44	3.52	3.22	3.32	3.63
case3	4.03	4.16	4.20	4.04	3.75
case4	3.47	3.16	3.45	3.44	3.31
case5	4.02	3.87	3.19	3.06	3.15
case6	3.79	3.81	3.81	3.61	3.45

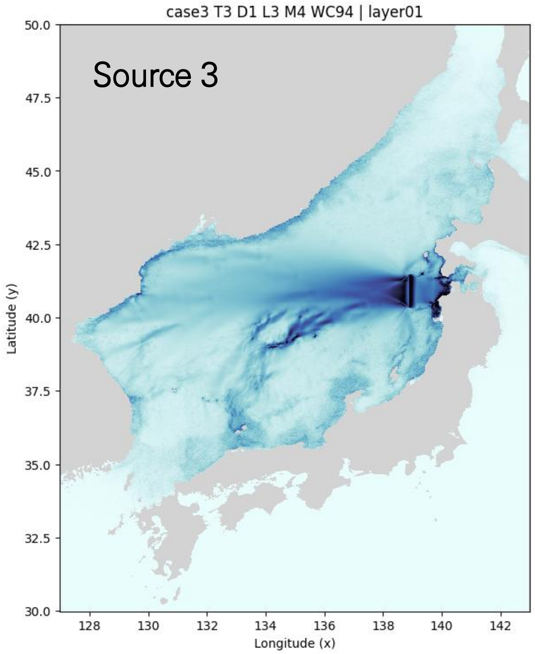
	D1	D2	D3
case1	2.38	3.57	4.16
case2	4.82	5.79	6.52
case3	5.45	6.81	7.91
case4	4.59	5.71	6.54
case5	4.56	5.90	6.82
case6	5.81	6.26	6.40

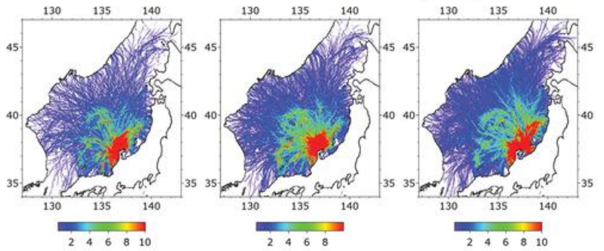
	L1	L2	L3
case1	3.60	3.44	3.07
case2	5.70	5.79	5.64
case3	6.80	6.84	6.54
case4	5.45	5.63	5.75
case5	5.62	5.85	5.82
case6	6.14	6.22	6.11

Hazard Variability and Bathymetric Amplification

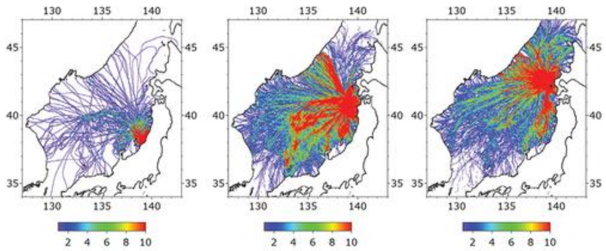








(a) nt24 west (n11-n13) tp=10min (b) nt24 center (n07-n10) tp=10min (c) nt24 east (n01-n06) tp=10min



(d) ni64 (nii) tp=10min (e) nc83 (chn, chu) tp=10min (f) hn93 (hok, hos) tp=10min

- ✓ Physical amplification effects due to bathymetric features
- ✓ Yamaguchi & Uehara (2026) confirmed refraction and interference of waves passing through the East Korea Rise and Yamato Rise.
- ✓ The amplification of wave heights at specific sites is closely related to bathymetric factors

Conclusion

✓ Quantitative Hazard Assessment via PTHA

- Expected wave heights for each return period derived from the eastern margin fault zone scenario DB
- Probabilistic hazard curves derived for 4 major port and High-hazard zone identified through hazard map

✓ Dominant source zone identification

- Source 5 dominates hazard at Sokcho, Donghae, and Imwon – attributed to a favorable combination of fault strike orientation and propagation pathway via the Yamato Rise
- Source 6, despite closer proximity, shows lower contributions → fault orientation and bathymetric effects outweigh source proximity alone
- Pohang exhibits a distinctly different multi-source pattern, highlighting the need for site-specific disaster mitigation strategies

✓ Parameter Sensitivity Analysis

- M4 (Mw 8.0): Largest wave heights — greater rupture area and slip magnitude
- D3 (δ = 60°): Steeper dip → greater vertical seafloor displacement
- L2 (λ = 90°): Pure reverse faulting → maximum vertical displacement efficiency
- Strike angle (θ): Site-dependent directional sensitivity → requires further analysis

Thank you !