Development of Emergency Response Models for Seismic and High-wind Events in Level 3 PSA

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Dakyoung Lee
Ph.D. Student, Seoul National University
Research Student, KAERI

Why Consider External Hazards in Level 3 PSA?

✓ **Level 3 PSA (Probabilistic Safety Assessment)**

- Evaluates radiological consequences to the public and the environment following radioactive release
- Emergency response models are key inputs to offsite consequence assessment

✓ **Emergency Response Model**

- Defines protective actions (e.g., sheltering, evacuation)
- Should reflect realistic accident scenarios and site characteristics

[Fig. 1. Emergency Phase in Level 3 PSA]

✓ **External hazards**

- External hazards depend on site-specific characteristics and include **seismic events, high winds, external flooding, and tsunamis**
- External hazards can affect emergency response by disrupting road networks, evacuation conditions, and protective actions
- However, current Level 3 PSA emergency response models do not explicitly account for the detailed impacts of external hazards (e.g., simplified assumptions in U.S. NRC Level 3 PRA Project, Volume 4e [1])

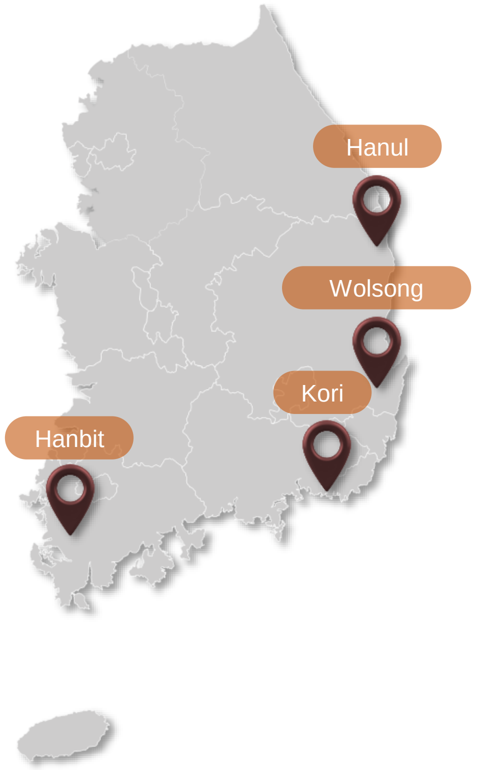
Selection of External Hazards Relevant to Korea

✓ **Seismic Events**

- **Increased significance in nuclear safety**: Following the March 2011 Fukushima Daiichi accident
- **Seismic characteristics of Korea**
  - Relatively low seismicity, but low seismic-wave attenuation
  - Potential wide-area impacts from moderate-to-large earthquakes
- Sep. 2016 | M5.1 Gyeongju Earthquake → Shutdowns: Wolsong Units 1–4

✓ **High Wind Events – Typhoons**

- **High typhoon exposure**: Coastal location of most Korean nuclear power plants, 3–4 typhoons affecting the Korean Peninsula annually
- Sep. 2003 | Typhoon Maemi → Shutdowns: Kori Units 1–4, Wolsong Unit 2
- Sep. 2020 | Typhoon Maysak → Shutdowns: Kori Units 3–4, Shin-Kori Units 1–2
- Sep. 2020 | Typhoon Haishen → Shutdowns: Wolsong Units 2–3
- **Recent climate-related trend: Increasing typhoon intensity reported in recent studies**



[Fig. 2. Locations of NPP Sites in Korea]

Category	SST [$°C\ decade^{-1}$]	OHC [K $cm^2\ decade^{-1}$]	D26 [m $decade^{-1}$]	VWS [$ms^{-1} decade^{-1}$]
Trend	0.2	4.7	2.1	-0.02

[Table. 1. Changes in Typhoon-Related Parameters over the North Pacific Ocean from 1980 to 2020 [2]]

SST: Sea Surface Temperature
OHC: Ocean Heat Content
D26: 26° isothermal depth
VWS: Vertical wind shear

Framework for External Hazard Modeling

Develop an emergency response model applicable to seismic events and typhoons for the Hanul site

Seismic Event

Probabilistic Seismic Hazard Analysis
↓
Monte Carlo Simulation
↓
Representative Seismic Scenario

Typhoon

Probabilistic Typhoon Hazard Analysis
↓
Monte Carlo Simulation
↓
Representative Typhoon Scenario

Emergency Response Modeling

Selection of Temporary and Final Shelters by Sector
↓
Hazard Impact Assessment (Building Damage, Road Accessibility, and Shelter Availability)
↓
Evacuation Route Generation (Based on Minimum Travel Time)
↓
Sheltering Duration Estimation (by Hazard Severity)

Generation of MACCS Input Data

Probabilistic Seismic Event Modeling

✓ **Seismic Event Data Collection**

- Historical earthquake catalog (1978–2025) from USGS and KMA
- Earthquakes with moment magnitude $M_w \geq 2.0$ within 100 km of the Hanul NPP

✓ **Probabilistic Seismic Modeling [3]**

- Estimate conditional exceedance probability for each M, R combination

$$P\left(IM > x | m_j, r_k\right) = 1 - \Phi\left(\frac{lnx - \overline{lnIM}}{\sigma_{ln}}\right)$$

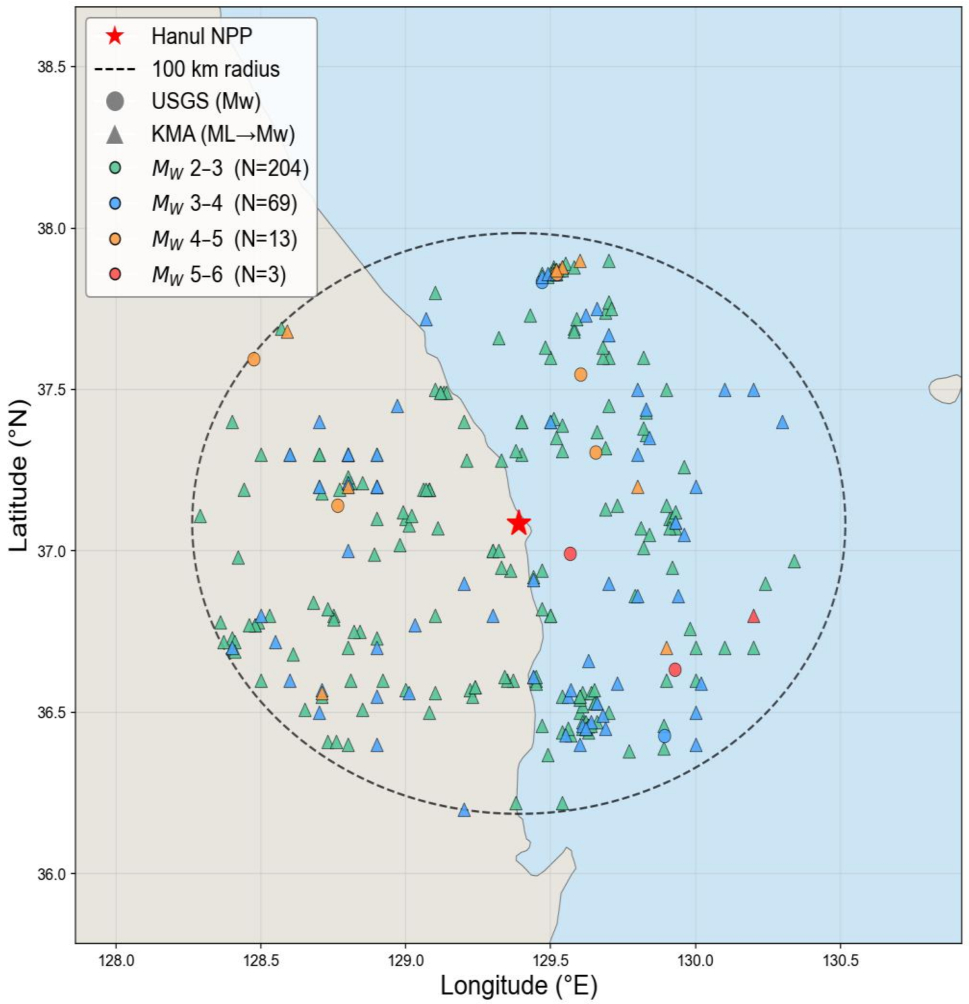
[Eq. 1. Probability that PGA exceeds x for an earthquake with magnitude m_j and r_k]

IM: Ground − motion intensity measure, m_j: j − th Moment magnitude, r_k: k-th epicentral distance,
$\overline{lnIM}$: Mean of lnIM for the corresponding m_j, r_k combination, Φ: Culmulative standard normal distribution,
σ_{ln}: Standard deviation of residuals (predicted vs. observed IM)

- Estimate the total annual exceedance rate ($m_{min} = 5.0$)

$$\lambda(IM > x) = \lambda(M > m_{min}) \times \sum_{j=1}^{n_M} \sum_{k=1}^{n_R} P\left(IM > x | m_j, r_k\right) P\left(M = m_j\right) P\left(R = r_k\right)$$

[Eq. 2. Annual exceedance rate of PGA above x]



[Fig. 3. Historical Seismic event around the Hanul NPP]

Probabilistic Seismic Event Modeling

✓ **Ground Motion Simulation**

- PGA(Peak Ground Acceleration) is estimated using a stochastic source model
- Insufficient strong-motion data limit GMPE development in Korea
- A stochastic source model validated for Korea is therefore adopted
- Estimation of PGA statistics for each (M,R) combination ($\overline{lnIM}$, σ_{ln})

$$A(M_o, \gamma, f) = \frac{\langle R_{\theta\phi} \rangle \times F \times V}{4\pi\rho\beta^3} \times \frac{(2\pi f)^2 M_o}{1 + \left(\frac{f}{f_c}\right)^2} \times \frac{e^{-\pi k f}}{\gamma}$$

[Eq. 3. Stochastic Source Model (Brune ω^2 Source Model) [4][5]]

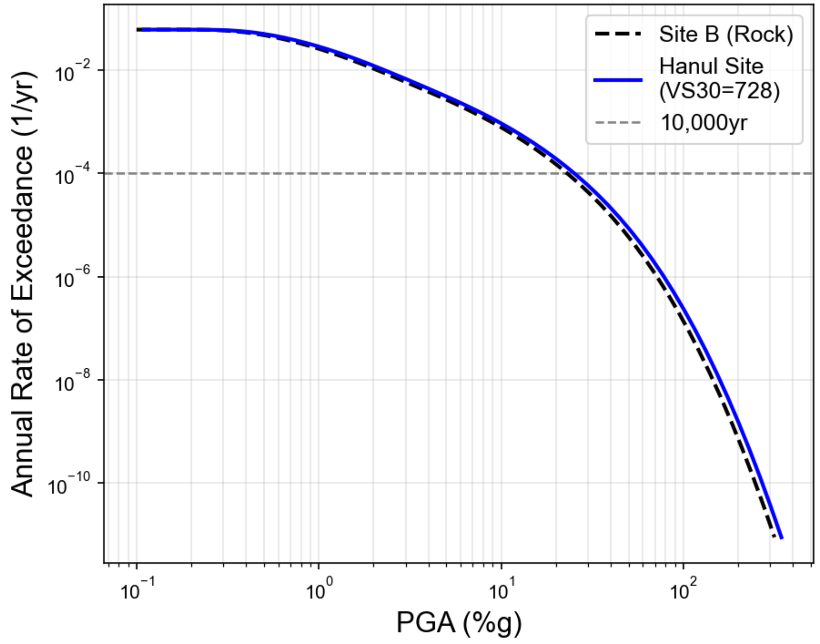
$R_{\theta\varphi}$: *Radiation Pattern Coefficient*, F: *Free − Surface Amplification Factor*, V: *Partition Factor*,
ρ: *Density*, β: *Shear − Wave Velocity*, M_o: *Seismic Moment*, f: Frequency, f_c: *Corner Frequency*,
k: *Attenuation Parameter*, $e^{-\pi k f}$: *Anelastic Attenuation*, γ: *Geometrical Spreading*

✓ **Generation of Seismic Hazard Curve**

- For each M–R combination, 100 simulations from four equally weighted models were combined to estimate median lnPGA.
- Apply a V_{S30}-based site amplification model (Hanul site V_{S30}: $728 m/s$)
- Total uncertainty: $\sigma_{Total} = \sqrt{\sigma_{ln}^2 + \sigma_{ln,site}^2}$
- Final site PGA: $\overline{lnIM_{site}} = \overline{lnIM} + \overline{f_{mod,site}(IM_r, V_{S30})}$

[Table. 2. Parameters of the Stochastic Model in Korea [6]]

Earthquake parameters	Parameter values			
	Noh and Lee	Jo and Baag	Junn et al	Jo and Baag
$\langle R_{\theta\phi} \rangle$	0.63	0.63	0.63	0.63
F	2.0	2.0	2.0	2.0
V	0.7071	0.7071	0.7071	0.7071
ρ	$2.7\ g/cm^3$	$2.7\ g/cm^3$	$2.7\ g/cm^3$	$2.7\ g/cm^3$
β	$3.5\ km/s$	$3.5\ km/s$	$3.5\ km/s$	$3.5\ km/s$
$\Delta\sigma$	$50\ bar$	$100\ bar$	$65\ bar$	$92\ bar$
k	$0.01397 + 0.0001634R$	$0.00112 + 0.000224R$	$0.00516 + 0.000147R$	$0.016 + 0.000157R$



[Fig. 4. Seismic Hazard Curve]

Probabilistic Seismic Hazard Modeling

✓ **Deaggregation**

- Identify representative M–R scenarios contributing to each target PGA level
- Select four target PGA levels based on Table 3 and the median Hanul site hazard curve
- Estimate the contribution of each M–R combination

$$P(M = m, R = r | IM > x) = \frac{\lambda(IM > x, M = m, R = r)}{\lambda(IM > x)}$$

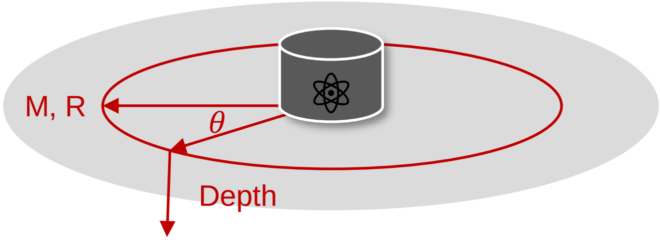
Occurrence rate of earthquakes with magnitude m and distance r contributing to $IM > x$

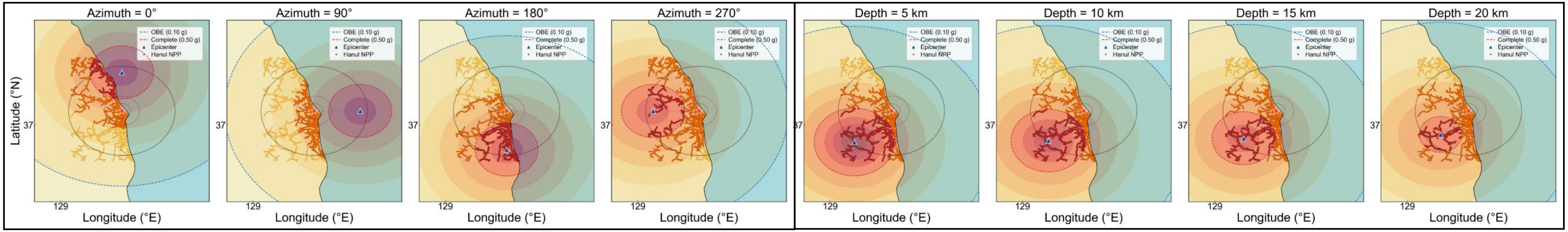
[Table. 3. PGA-Based Hazard Classification Criteria in PSHA [7]]

Bin	Criteria	PGA (g)
1	Hazard < SSE	0.2
2	SSE ≤ Hazard < HCLPF of most fragile safety-related SSC	0.2—0.4
3	HCLPF of most fragile safety-related SSC ≤ Hazard < HCLPF of critical instrumentation or HCLPF level of 25^{th} percentile component, whichever is lower	0.4—0.65
4	Wide-spread damage to critical instrumentation	0.65~

✓ **Monte Carlo Simulation (MCS)**

- Allocate 50 scenarios across the M–R combinations for each PGA range based on their contribution distribution
- Sample the source azimuth and focal depth for each scenario using MCS





[Fig. 5. Representative Seismic Scenarios by Azimuth and Depth]

Seismic-Based Emergency Response Modeling

✓ **Structural Damage Assessment**

- Estimate damage probabilities for representative building types (Table 4)

$$P_{damage} = \Phi\left[\frac{\ln(PGA) - \ln(m)}{\beta}\right]$$

- Determine m, β based on the HAZUS Pre-Code design level:

  Low-rise RC ≈ C1L,   Masonry ≈ URML

✓ **Road Damage and Accessibility Assessment**

- Estimate PGD(Permanent Ground Deformation) for each road segment

$$logLSI = -3.49 - 1.86logR + 0.98M_w$$

$$PGD = 0.0254 \times LSI$$

- Calculate the probabilities of road damage states DS1–DS4 (Table 5)

$$P(DS|S_a) = \Phi\left[\frac{\ln(PGD) - \ln(m_{ds})}{\beta_{ds}}\right]$$

- Apply damage-state-specific travel-time multipliers or road closures
- Apply an additional delay to road segments within 50 m of damaged buildings

[Table. 4. Building Fragility Parameters [8]]

Building Type	m	β
Low-rise RC Building	0.21	0.64
Masonry Building	0.26	0.64

[Table. 5. Road Fragility Parameters by Damage State [9]]

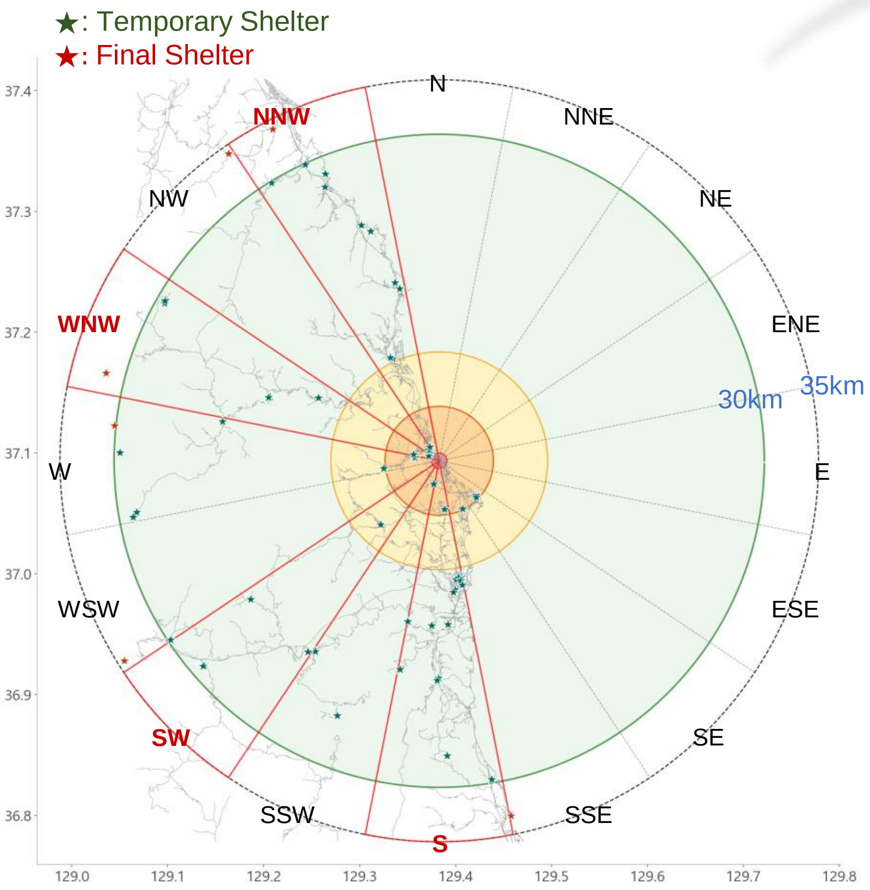
Damage State	m	β
DS 1	0.15	0.55
DS 2	0.30	0.55
DS 3	0.61	0.50
DS 4	0.61	0.50

[Table. 6. Travel-Time Factors by Damage State]

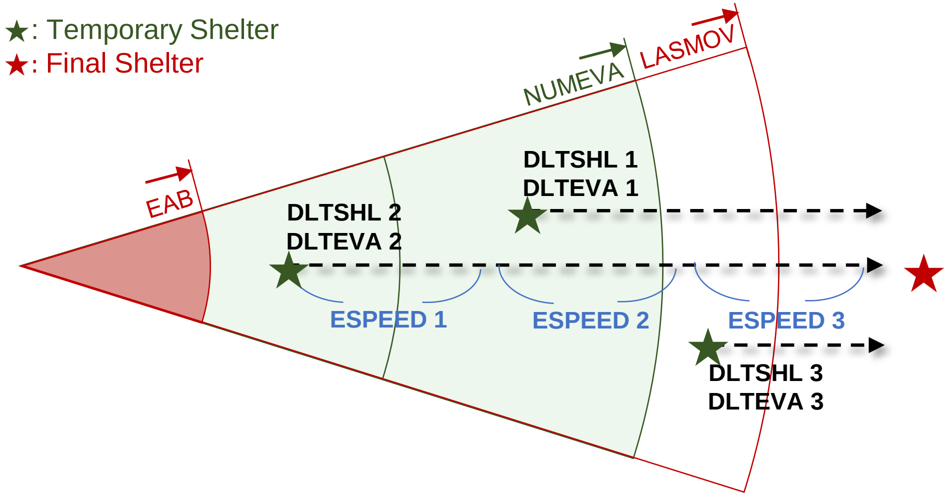
Damage State	**Road Accessibility**
DS 1	Travel time × 1.5
DS 2	Travel time × 3.0
DS 3	Road closed
DS 4	Road closed

Seismic-Based Emergency Response Modeling

✓ **Evacuation Route Generation**



[Fig. 6. Sector-Based Evacuation Planning]



[Table. 7. Definition of MACCS Emergency Response Parameters]

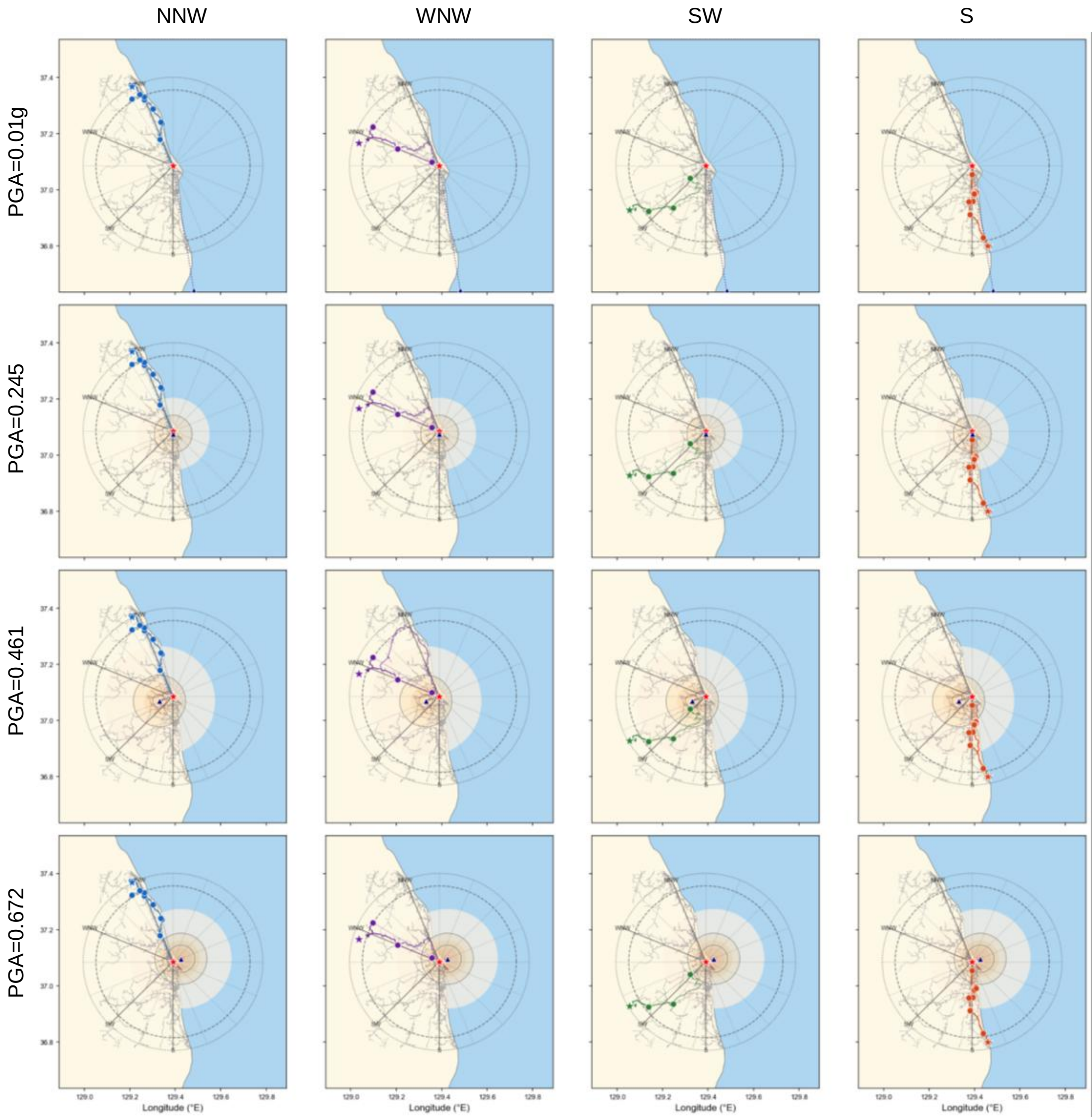
Parameters	Definition / Setting
DLTSHL [10][11][12]	$\boldsymbol{T_{exit} + T_{travle}}$ $T_{exit} \sim \text{Uniform}(0\sim30)min, \quad T_{travle} = \frac{D_{road}}{V_{PGA}}, \quad V_{PGA} = \begin{cases} 4.6km/h(for\ walking, PGA \geq 0.2g) \\ 54km/h(\ for\ vehicle, PGA < 0.2g\ ) \end{cases}$
DLTEVA [12][13]	$\boldsymbol{T_{base} \times multiplier_{PGA} + T_{aftershock}}$ $T_{base} = \begin{cases} \text{Uniform}(15\sim120)min & (d < 2km) \\ \text{Uniform}(15\sim120)min & (2 \leq d < 5km) \\ \text{Uniform}(15\sim120)min & (5 \leq d < 30km) \end{cases}, multiplier_{PGA} = \begin{cases} 1.0 & (x < 0.20g) \\ 1.3 & (0.20 \leq x < 0.4g) \\ 1.6 & (0.4 \leq x < 0.65g) \\ 2.0 & (x \geq 0.65g) \end{cases}, T_{aftershock} = \begin{cases} +1.0\ hr & P(M \geq 4.0, 24hr) \geq 0.50 \\ +0.5\ hr & P(M \geq 4.0, 24hr) \geq 0.20 \\ 0\ hr & else \end{cases}$
ESPEED [11][12]	**In general, ESPEED 1 > ESPEED 2** ESPEED 1: base speed * 0.6, ESPEED 2: base speed * 0.3, ESPEED 3: base speed * 1 Base speed: $V_{PGA} = \begin{cases} 4.6km/h(for\ walking, PGA \geq 0.2g) \\ 54km/h(\ for\ vehicle, PGA < 0.2g\ ) \end{cases}$

* DLTSHL: Delay to Shelter, DLTEVA: Delay to Evacuation, ESPEED: Evacuation Speed

Seismic-Based Emergency Response Modeling

✓ **Representative Seismic Scenario Results**

[Fig. 7. Sector-Based Evacuation Routes for the Representative Scenario]



[Table. 8. Results for the 95th Percentile Scenario]

PGA(g)	Sector	Shelter	DLTSHL(hr)	DLTEVA(hr)	ESPEED1 (km/h)	ESPEED2 (km/h)	ESPEED3 (km/h)	Travel Time (hr)
0.01	NNW	호산초등학교	0.24	1.67	32.4	16.2	54.0	0.54
0.01	WNW	한울스포츠센터	0.17	2.12	32.4	16.2	54.0	0.77
0.01	SW	부구초등학교	0.48	1.36	32.4	16.2	54.0	0.77
0.01	S	구 죽변초등학교 화성분교 터	0.21	2.33	32.4	16.2	54.0	0.61
0.245	NNW	호산초등학교	0.25	1.54	32.4	16.2	54.0	0.54
0.245	WNW	한울스포츠센터	0.52	1.99	32.4	16.2	54.0	0.78
0.245	SW	부구초등학교	0.53	1.42	32.4	16.2	54.0	0.77
0.245	S	구 죽변초등학교 화성분교 터	0.28	2.33	32.4	16.2	54.0	0.62
0.461	NNW	호산초등학교	0.14	2.67	32.4	16.2	54.0	0.55
0.461	WNW	한울스포츠센터	0.90	3.25	2.8	1.4	4.6	15.62
0.461	SW	부구초등학교	1.08	2.40	2.8	1.4	4.6	5.83
0.461	S	구 죽변초등학교 화성분교 터	1.16	1.91	2.8	1.4	4.6	9.42
0.672	NNW	호산초등학교	0.85	2.10	2.8	1.4	4.6	6.46
0.672	WNW	한울스포츠센터	0.64	2.94	2.8	1.4	4.6	10.60
0.672	SW	부구초등학교	0.90	3.38	2.8	1.4	4.6	9.26
0.672	S	구 죽변초등학교 화성분교 터	0.86	1.87	2.8	1.4	4.6	7.71

Probabilistic Typhoon Hazard Modeling

✓ **Typhoon Data Collection**

- Historical best-track data (1951–2025) from RSMC Tokyo and JTWC
- Typhoons passing within 300 km of the Hanul NPP
- Only typhoons with wind speeds ≥ 25 m/s (STS or higher) were considered

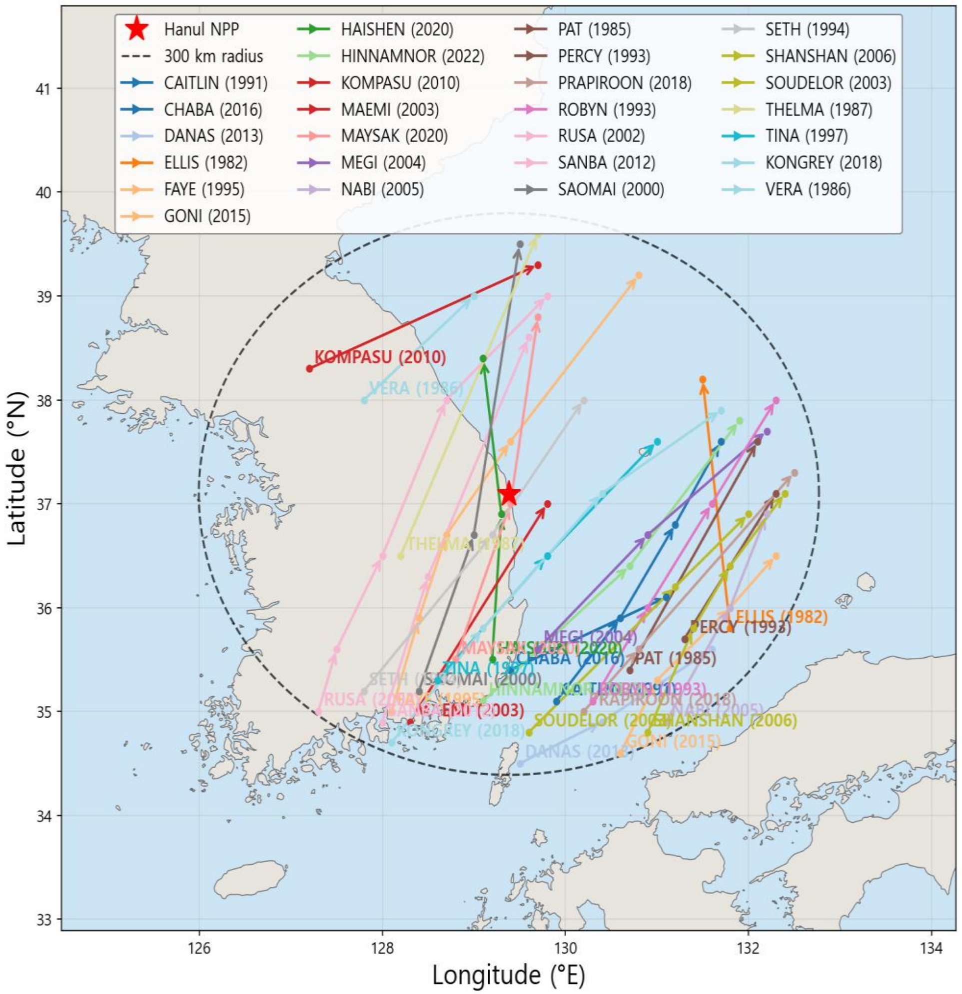
✓ **Probabilistic Typhoon Modeling**

- Estimate probability distributions of key typhoon parameters
- Generate synthetic typhoon scenarios using Monte Carlo Simulation
- Evaluate site-specific wind hazards around the Hanul NPP

$$V_g(r,\theta) = \frac{V_r \sin\theta - f_r}{2} + \sqrt{\frac{(V_T \sin\theta - f_r)^2}{4} + \frac{B\Delta p}{\rho}\left(\frac{r_{mw}}{r}\right)^B exp\left[-\left(\frac{r_{mw}}{r}\right)^B\right]}$$

[Eq. 4. Modified Holland Wind Field Model (Georgiou et al.) [14][15]]

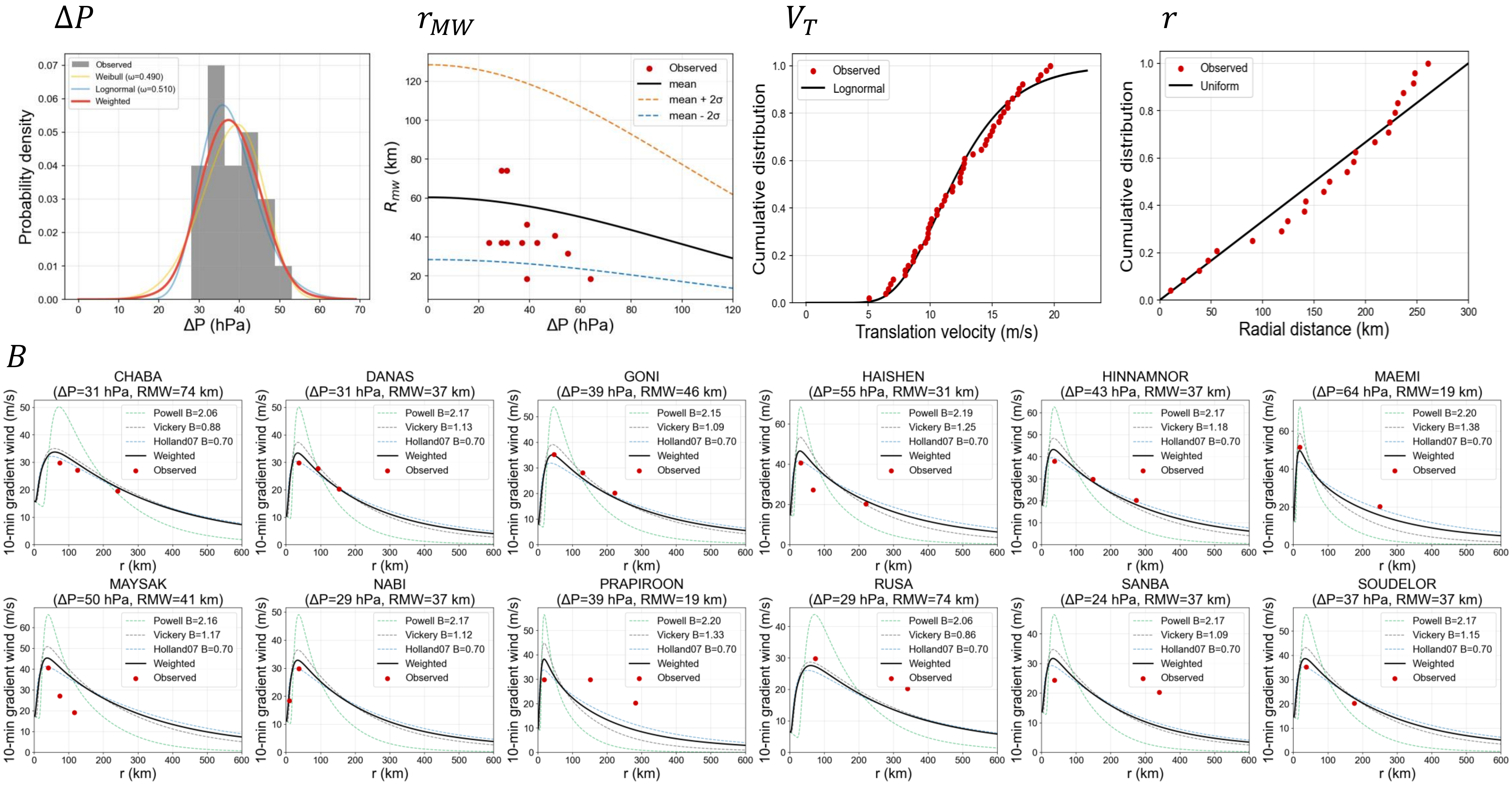
$f = 2\Omega \sin\psi$: *Coriolis parameter*, $\Omega = 7.929 \times 10^{-5}$: *Angular velocity of the rotation of the earth*,
ψ: *Latitude of interest site (degree)*, $\rho = 1.15 kg/m^3$: *Air density*, ΔP: *Central pressure difference (hPa)*,
r_{MW}: *Radius to the maximum wind speed (km)*, B: *Pressure profile parameter*, r: *Radial distance to the typhoon*,
V_T: *storm's translation velocity*, θ : *approach angle of a storm*



[Fig. 8. Historical Typhoon Tracks around the Hanul NPP]

Probabilistic Typhoon Hazard Modeling

✓ **Estimate probability distributions of key typhoon parameters**



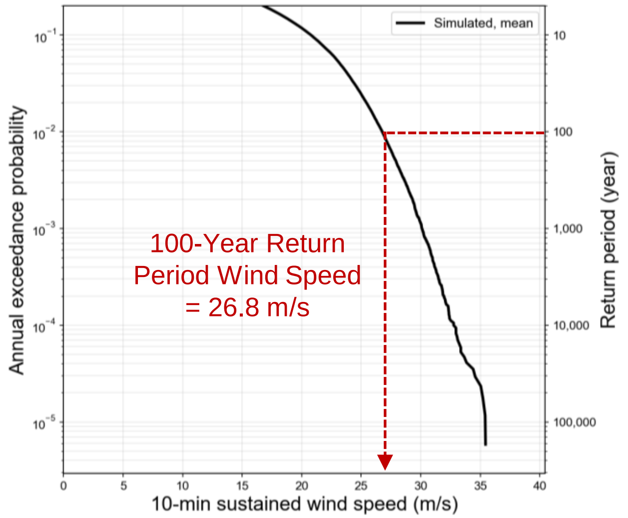
[Fig. 9. Probabilistic Modeling of Typhoon Parameters]

Probabilistic Typhoon Hazard Modeling

✓ **Generation of Typhoon Hazard Curve**

- Generate **100,000** synthetic typhoon scenarios using Monte Carlo Simulation
- Calculate site wind speeds using the **Georgiou (1985) wind field model**
- Construct the **site-specific wind hazard curve**

100-Year Return Period Wind Speed = 26.8 m/s



[Fig. 10. Typhoon Hazard Curve]

✓ **Representative Typhoon Scenario (100-year return period data)**

- Straight-line track assumption

$$s(t) = V_T \cdot t, \qquad r(t) = \sqrt{d_{min}^2 + s(t)^2}, \qquad \theta(t) = \arctan 2(d_{min}, -s(t))$$

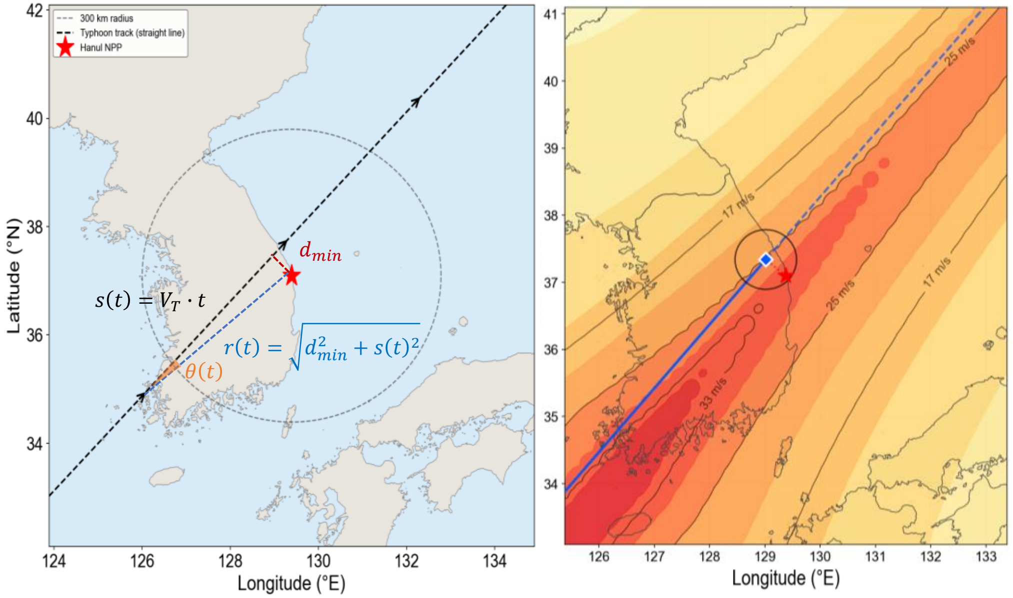
- Wind decay model [16])

$$V_{max} = V_b + (V_{max0} - V_b)\exp(-\alpha T)$$

V_b: *background wind*, V_{max0}: TC maximum wind speed at landfall,
α: *fitting parameter*, T: *elapsed time after landfall*

* Initial intensity back-calculation to reproduce the target wind speed at the CPA

- Consideration of heading variations across eight cases (0°–315°)



[Fig. 11. Straight-Line Typhoon Model]

Typhoon-Based Emergency Response Modeling

✓ **Structural Damage Assessment**

- Structural failure occurs when the wind load exceeds the structural resistance

$$G(R, W) = R - W$$

- Building damage probability is estimated using fragility curves

$$Fragility = Fr(y) = \phi\left[\frac{\ln(y) - m_R}{\zeta_R}\right]$$

- Building damage states are assigned according to building type
- Assumption: Buildings near the Hanul NPP are predominantly low-rise RC and masonry buildings

[Table. 9. Fragility Parameters by Damage State [17]]

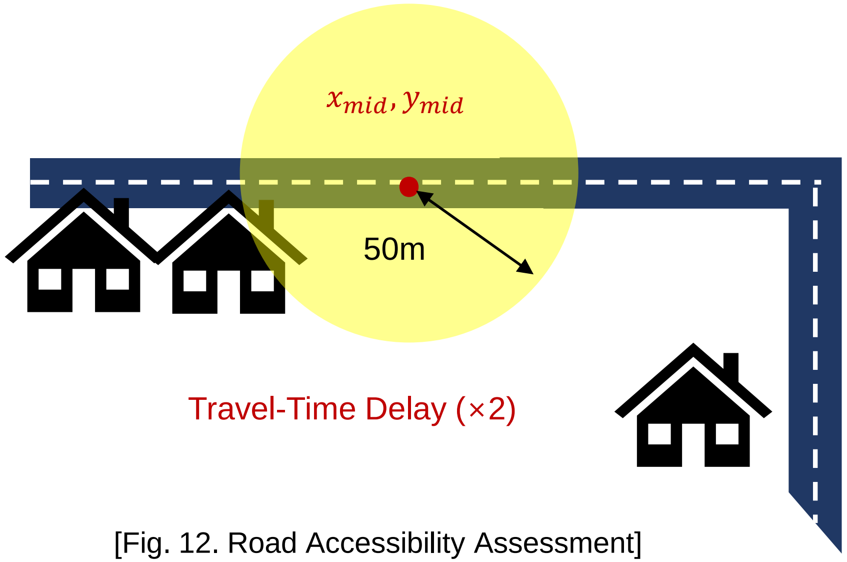
Damage State	Best-Fit Lognormal Parameters	
	m_R	ζ_R
DS 1	3.382	0.125
DS 2	3.535	0.092
DS 3	3.606	0.093
DS 4	3.675	0.096

✓ **Road Accessibility Assessment**

- Maximum wind speed for each road segment

Wind Speed (m/s)	Road Accessibility
$V < 17$	Normal travel
$17 \leq V < 21$	Travel time × 1.5 (vehicle only)
$21 \leq V < 25$	Travel time × 3.0 (severely restricted)
$V \geq 25$	Road closed (no access)

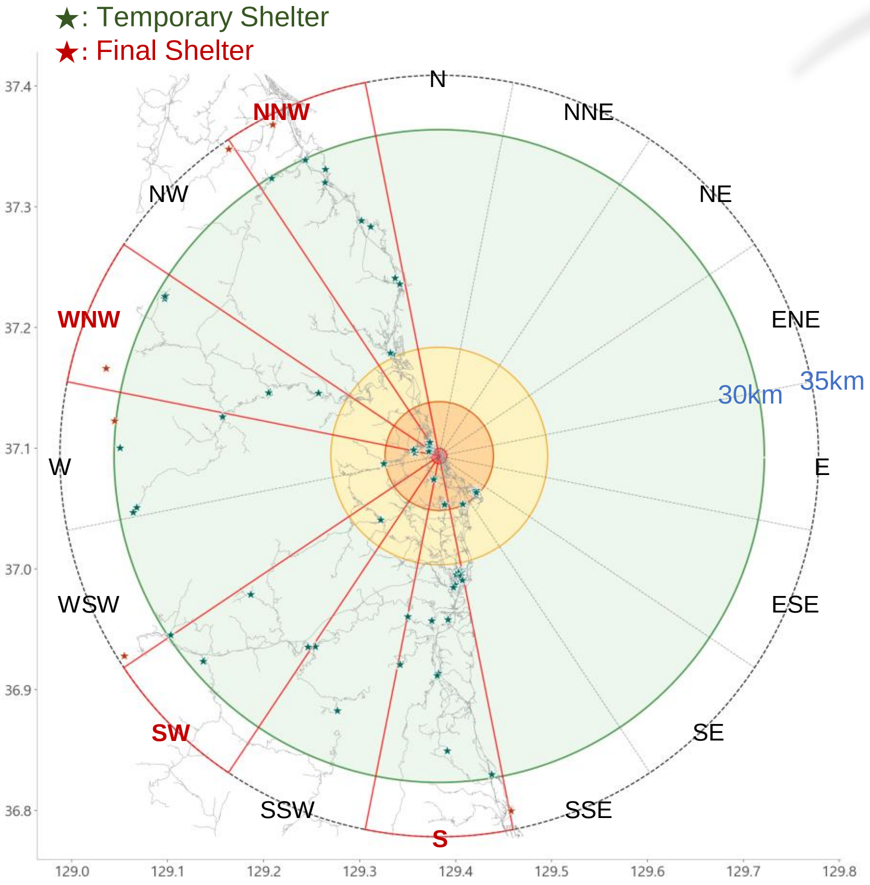
- Building damage assessment within a 50 m buffer
- Apply a travel-time delay factor (×2) when the damage threshold is exceeded



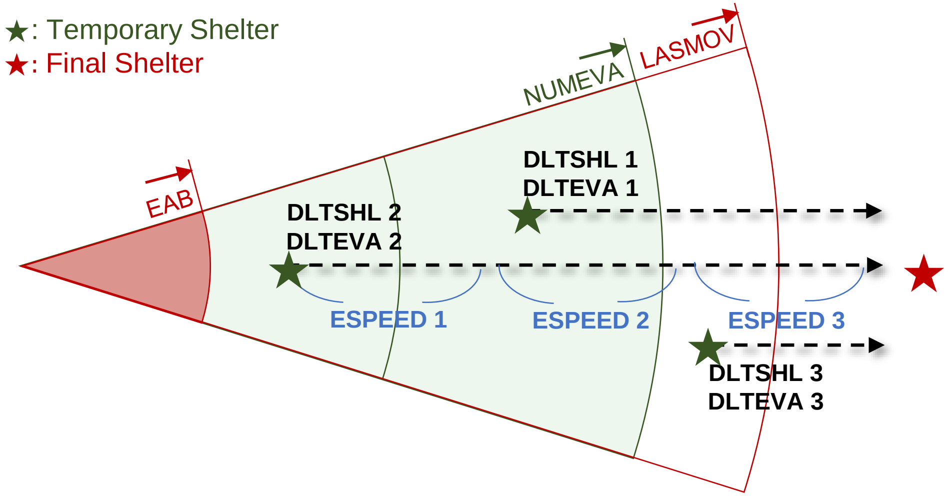
[Fig. 12. Road Accessibility Assessment]

Typhoon-Based Emergency Response Modeling

✓ **Evacuation Route Generation**



[Fig. 13. Sector-Based Evacuation Planning]



[Table. 10. Definition of MACCS Emergency Response Parameters]

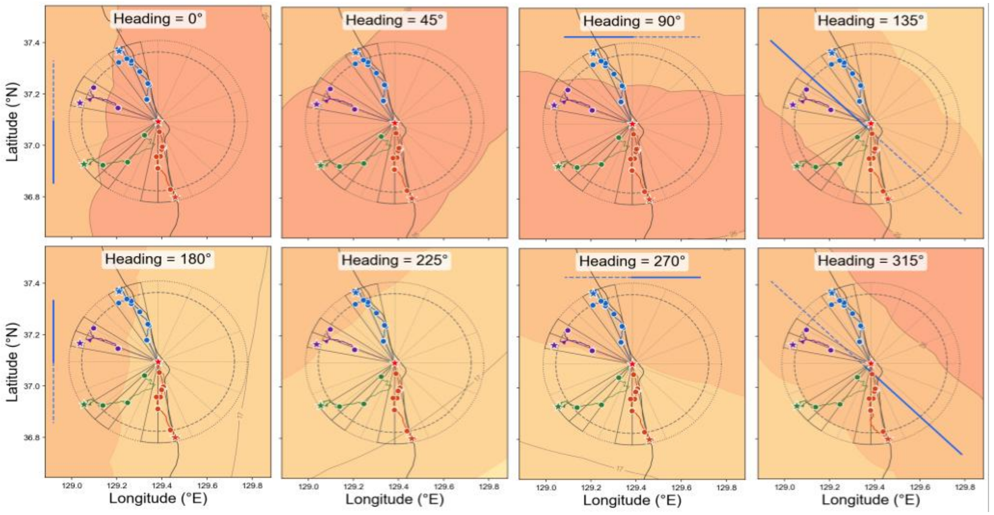
Parameters	Definition / Setting
DLTSHL [18]	$\boldsymbol{T_{base} \times multiplier_{PGA}}$ $T_{base} = \begin{cases} 10 & (d < 2km) \\ \text{Uniform}(30\sim60)min & (2 \le d < 5km) \\ \text{Uniform}(30\sim60)min & (5 \le d < 8km) \\ \text{Uniform}(30\sim60)min & (8km \le d < 30km) \end{cases}$, $multiplier_{PGA} = \begin{cases} 1.0 & (v < 14m/s) \\ 1.3 & (14m/s \le v < 17m/s) \\ 1.6 & (17m/s \le v < 21m/s) \\ 2.0 & (v \ge 21m/s) \end{cases}$
DLTEVA [12]	$\boldsymbol{T_{base} + T_{17m/s}}$ $T_{base} = \begin{cases} \text{Uniform}(15\sim120)min & (d < 2km) \\ \text{Uniform}(15\sim120)min & (2 \le d < 5km) \\ \text{Uniform}(15\sim120)min & (5 \le d < 30km) \end{cases}$, $T_{17m/s}$=waiting time until wind speed decreases to $\le 17m/s$
ESPEED [12]	**In general, ESPEED 1 > ESPEED 2** ESPEED 1: base speed * 0.6, ESPEED 2: base speed * 0.3, ESPEED 3: base speed * 1 Base speed: 48 km/h (free-flow speed under adverse summer weather conditions near the Hanul site)

* DLTSHL: Delay to Shelter, DLTEVA: Delay to Evacuation, ESPEED: Evacuation Speed

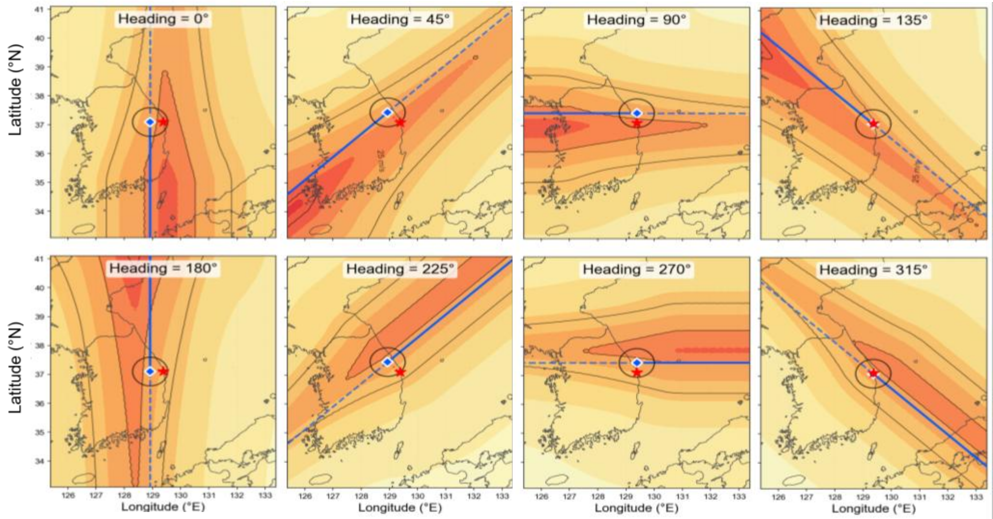
Typhoon-Based Emergency Response Modeling

✓ Representative Typhoon Scenario Results

[Fig. 14. Sector-Based Evacuation Routes by Heading Angle]



[Fig. 15. Wind Fields by Heading Angle]



[Table. 11. Representative Results for the NNW and S Sectors under Different Headings]

Heading(°)	Sector	Shelter	Travel Distance (km)	DLTSHL(hr)	DLTEVA (hr)	Travel Time (hr)
0	NNW	호산초등학교	29.3	1.77	1.95	1.3
45	NNW	호산초등학교	29.3	1.77	1.95	1.3
90	NNW	호산초등학교	29.3	1.77	1.65	1.3
135	NNW	호산초등학교	29.3	1.77	1.02	1.3
180	NNW	호산초등학교	29.3	1.42	2.3	0.6
225	NNW	호산초등학교	29.3	1.42	1.6	0.6
270	NNW	호산초등학교	29.3	1.42	1.02	1.2
315	NNW	호산초등학교	29.3	1.77	1.02	1.3
0	S	구 죽변초등학교 화성분교 터	32.8	1.68	1.21	1.9
45	S	구 죽변초등학교 화성분교 터	32.8	1.68	1.41	1.9
90	S	구 죽변초등학교 화성분교 터	32.8	1.68	1.41	1.9
135	S	구 죽변초등학교 화성분교 터	32.8	1.68	0.49	1.9
180	S	구 죽변초등학교 화성분교 터	32.8	1.35	2.04	1.0
225	S	구 죽변초등학교 화성분교 터	32.8	1.35	0.64	0.9
270	S	구 죽변초등학교 화성분교 터	32.8	1.35	1.74	1.0
315	S	구 죽변초등학교 화성분교 터	32.8	1.68	0.49	1.5

Evacuation-Speed Parameters
ESPEED1 (Early): 28.8 km/h | ESPEED2 (Middle): 14.4 km/h | ESPEED3 (Late): 48.0 km/h

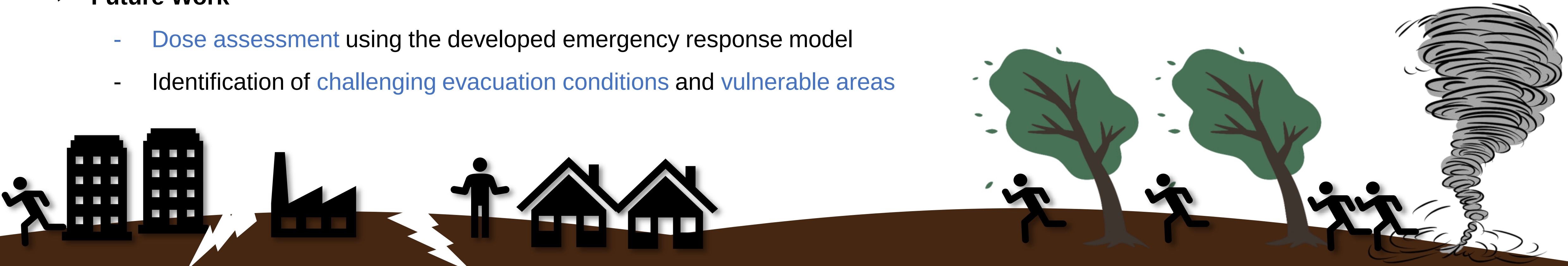
Conclusions & Future Work

- ✓ **Research Objective**
  - Develop an emergency response model applicable to seismic events and typhoons for the Hanul site

- ✓ **Key Results**
  - Generated MACCS input parameters reflecting road and building damage and changes in evacuation conditions caused by seismic events and typhoons
  - Derived evacuation routes and travel times for each hazard scenario and selected representative scenarios

- ✓ **Limitations**
  - Limited domestic fragility data
  - Validation of assumptions underlying the factors used to derive the MACCS inputs

- ✓ **Future Work**
  - Dose assessment using the developed emergency response model
  - Identification of challenging evacuation conditions and vulnerable areas



Thank you for your kind attention!

Presenter Information
Dakyoung Lee
Seoul National University & Korea Atomic Energy Research Institute
🖂 dkyoun.g@snu.ac.kr

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