

## Emergency Response Modeling under Seismic Conditions in Level 3 PSA

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### 1. Introduction

From the perspective of radiological risk, a hazard can be defined as a condition or event that may cause harm during facility operation. Hazards are broadly classified into external and internal hazards. External hazards are associated with natural phenomena or other events originating outside the site, whereas internal hazards are related to failures or abnormal conditions of facilities, systems, and operational activities within the site. Therefore, the characteristics of each hazard should be appropriately considered throughout Level 1, Level 2, and Level 3 PSAs to comprehensively assess the risk of nuclear facilities.

This study focuses on external hazards, particularly seismic events, which are considered a major external hazard for nuclear power plants in Korea. While some external hazards may be screened out based on site-specific characteristics and occurrence frequencies, seismic events remain subject to detailed evaluation. Accordingly, Level 1 and Level 2 Seismic PSAs evaluate core damage frequency (CDF), containment behavior, and radioactive material release characteristics associated with seismic events.

In Level 3 PSA, seismic events may also affect emergency response because public evacuation and radiological impacts are evaluated following an accident. In particular, seismic damage to roads and infrastructure may change evacuation routes and travel times, affecting public radiation exposure. However, studies linking seismic impacts with emergency response and dose assessment in Level 3 PSA remain limited.

Therefore, this study evaluates seismic impacts by integrating them into the emergency response and dose assessment processes of Level 3 PSA. Probabilistic Seismic Hazard Analysis (PSHA) and Monte Carlo Simulation (MCS) for different levels of seismic intensity were performed to generate various scenarios. Based on these scenarios, the fragility of buildings and roads was evaluated, and public evacuation routes were analyzed. Finally, dose analysis was performed using the MACCS code by incorporating the resulting evacuation characteristics.

### 2. Methodology

#### 2.1 Probabilistic Seismic Hazard Analysis (PSHA)

In Seismic PSA, Probabilistic Seismic Hazard Analysis (PSHA) is performed to quantitatively evaluate seismic hazard. Seismic hazard assessment accounts for uncertainties in earthquake magnitude, location, and ground motion at the site. It probabilistically combines models of potential future earthquakes with models that predict the corresponding ground motion [1]. PSHA estimates the annual frequency of exceedance for different ground motion levels at the site.

In this study, PSHA was performed for the Hanul Nuclear Power Plant site in Korea. Fig. 1 shows the distribution of historical earthquakes with magnitudes greater than 2.0 within 100 km of the Hanul site. The completeness magnitude ( $M_c$ ) of the collected earthquake catalog was evaluated as 2.5. Accordingly, earthquake data with magnitudes of 2.5 or greater were used to derive the Gutenberg–Richter relationship in Eq. (1). Here,  $\lambda_m$  is the rate of earthquakes with magnitudes greater than  $m$ ,  $a$  represents seismic activity,  $b$  characterizes the magnitude distribution, and  $m$  denotes earthquake magnitude.

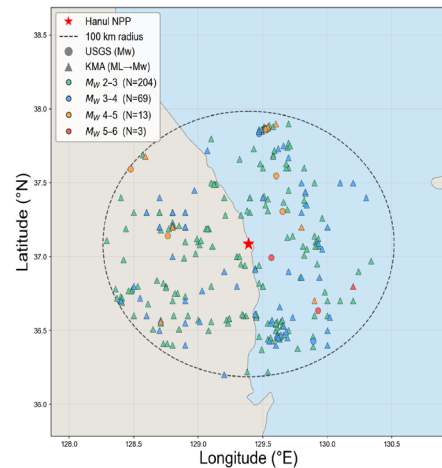


Fig. 1. Historical Seismic event around the Hanul NPP.

$$\log (\lambda_m) = a - bm \quad (1)$$

Ground motion simulation was performed to evaluate the ground motion intensity. Ground motion is commonly estimated using Ground Motion Prediction Equations (GMPEs). However, the limited strong-motion records available in Korea make it difficult to

develop reliable GMPEs. Therefore, this study applied the Stochastic Source Model [2] in Eq. (2) to simulate Peak Ground Acceleration (PGA) for each magnitude–distance combination and calculate the logarithmic mean( $\ln IM$ ) and standard deviation( $\sigma_{\ln}$ ) of PGA. The model parameters were adopted from previous studies in Korea, as listed in Table I, and equal weights were assigned to each parameter set.

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

Table I. Parameters of the Stochastic Model in Korea

| 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                |
| $\rho$                           | 2.7 g/cm <sup>3</sup>  | 2.7 g/cm <sup>3</sup> | 2.7 g/cm <sup>3</sup> | 2.7 g/cm <sup>3</sup> |
| $\beta$                          | 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<br>+0.0001634R | 0.00112<br>+0.000224R | 0.00516<br>+0.000147R | 0.016<br>+0.000157R   |

Eq. (3) represents the probability that PGA exceeds a specified value for an earthquake with a given magnitude ( $m_j$ ) and distance ( $r_k$ ). Based on this probability, Eq. (4) calculates the annual exceedance rate of PGA above a specified value  $x$ , where  $m_{min}$  was set to 5.0. The resulting seismic hazard curve is shown in Fig. 2.

In addition, a Vs30-based site amplification model was applied to account for the site conditions at Hanul. The final seismic hazard curve was then obtained by incorporating the site amplification effect.

$$P(IM > x | m_j, r_k) = 1 - \Phi\left(\frac{\ln x - \ln IM}{\sigma_{\ln}}\right) \quad (3)$$

$$\lambda(IM > x) = \lambda(M > m_{min}) \times \sum_{j=1}^{n_M} \sum_{k=1}^{n_R} P(IM > x | m_j, r_k) P(M = m_j) P(R = r_k) \quad (4)$$

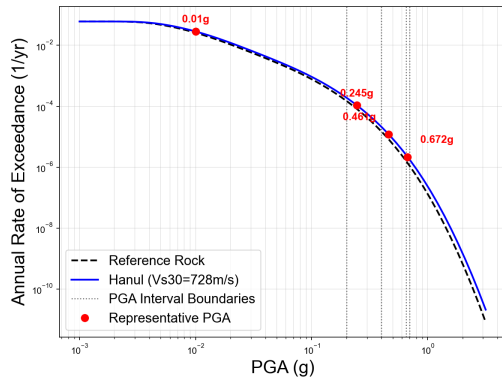


Fig. 2. Seismic Hazard Curve

## 2.2 Development of Representative Seismic Scenarios

To evaluate the impact of seismic events on the evacuation of residents near the site, this study developed representative seismic scenarios reflecting realistic earthquake characteristics. Because seismic damage may vary with seismic intensity level, the PGA levels were divided into four intervals, as shown in Table II [3]. These intervals were defined to be consistent with the PGA ranges used for seismic fragility assessment in Level 1 and Level 2 Seismic PSAs.

Table II. PGA-Based Hazard Classification Criteria in PSHA

| Bin | Criteria                                                                                                                                                          | PGA (g)              |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| 1   | Hazard < SSE                                                                                                                                                      | 0—0.2<br>(0.01)      |
| 2   | SSE ≤ Hazard < HCLPF of most fragile safety-related SSC                                                                                                           | 0.2—0.4<br>(0.245)   |
| 3   | HCLPF of most fragile safety-related SSC ≤ Hazard < HCLPF of critical instrumentation or HCLPF level of 25 <sup>th</sup> percentile component, whichever is lower | 0.4—0.65<br>(0.461)  |
| 4   | Wide-spread damage to critical instrumentation                                                                                                                    | 0.65—0.70<br>(0.672) |

The representative PGA for each interval was selected as the PGA corresponding to the median hazard contribution within the interval, based on the Hanul seismic hazard curve in Fig. 2. Deaggregation was then performed using Eq. (5) to identify the magnitude–distance scenarios contributing to each representative PGA and to quantify the hazard contribution of each magnitude–distance combination.

$$P(M = m, R = r | IM > x) = \frac{\lambda(IM > x, M = m, R = r)}{\lambda(IM > x)} \quad (5)$$

Seismic damage may also vary with source azimuth and hypocentral depth, in addition to ground motion intensity. To account for these characteristics, 50 seismic scenarios were generated for each PGA interval in proportion to the hazard contribution of each magnitude–distance combination. The source azimuth and hypocentral depth of each scenario were then sampled using Monte Carlo Simulation (MCS).

## 2.3 Fragility Evaluation of Buildings and Roads

One of the main factors that can hinder evacuation during a seismic event is restricted road access caused by road damage and building collapse. Therefore, this study evaluated road accessibility by considering both building and road damage. For building damage, low-rise reinforced concrete (RC) buildings and masonry buildings, which are common near the Hanul site, were selected as representative building types and evaluated using Eq. (6) and the parameters in Table III. In addition, the evacuation travel time of road segments located

within 50 m of buildings with a damage probability greater than 0.8 was doubled to reflect evacuation delays caused by building damage.

$$P_{\text{damage}} = \Phi \left[ \frac{\ln(PGA) - \ln(m)}{\beta} \right] \quad (6)$$

Table III. Building Fragility Parameters [4]

| Building Type        | $m$  | $\beta$ |
|----------------------|------|---------|
| Low-rise RC Building | 0.21 | 0.64    |
| Masonry Building     | 0.26 | 0.64    |

Road damage was evaluated by calculating the Permanent Ground Deformation (PGD) of each road segment using Eqs. (7)–(9) and applying the parameters in Table IV according to the Damage State. Road damage was classified into four Damage States. The original evacuation travel time was multiplied by 1.5 and 3.0 for DS1 and DS2, respectively, while road segments in DS3 and DS4 were assumed to be impassable.

$$P(DS|S_a) = \Phi \left[ \frac{\ln(PGD) - \ln(m_{ds})}{\beta_{ds}} \right] \quad (7)$$

$$PGD = 0.0254 \times LSI \quad (8)$$

$$\log LSI = -3.49 - 1.86 \log R + 0.98 M_w \quad (9)$$

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

| Damage State | $m$  | $\beta$ |
|--------------|------|---------|
| DS 1         | 0.15 | 0.55    |
| DS 2         | 0.30 | 0.55    |
| DS 3         | 0.61 | 0.50    |
| DS 4         | 0.61 | 0.50    |

#### 2.4 MACCS Emergency Response Input Definition

This study used the MACCS code to perform dose analysis considering evacuation characteristics during seismic events. Evacuation routes were developed based on OpenStreetMap, and four directions with relatively dense residential areas were selected for analysis, as shown in Fig. 3. The analysis domain from 0 to 30 km was divided into radial intervals with boundaries at 0.70, 0.95, 1.28, 1.72, 2.31, 3.03, 3.92, 5.00, 6.36, 8.06, 10.00, 12.81, 16.09, 19.98, 24.57, and 30.00 km. The main emergency response parameters were DLTSHL (Delay to Sheltering), DLTEVA (Delay to Evacuation), ESPEED (Evacuation Speed), DURBEG (Duration of Beginning Phase), and DURMID (Duration of Middle Phase), as defined in MACCS, and were set as summarized in Table V. In MACCS, DLTSHL and DLTEVA are defined for each ring, whereas ESPEED,

DURBEG, and DURMID are defined as representative values for each direction.

DLTSHL was divided into household departure time and travel time to the shelter. Household departure time was sampled from a uniform distribution based on a previous study reporting that approximately 90% of residents departed their residences within 30 min after the Gyeongju earthquake. DLTEVA was defined using a uniform distribution based on existing evacuation initiation delay data for the Hanul site, with additional delays due to seismic events. When PGA exceeded 0.2 g, vehicle use was assumed to be restricted and evacuation was conducted on foot. The sheltering duration was also increased with the likelihood of aftershocks.

ESPEED was divided into early, middle, and late phases of evacuation, with 0.6, 0.3, and 1.0 times the reference speed applied, respectively, to account for traffic congestion. The reference speed was determined as either vehicle or walking speed based on the PGA of the nearest road at each distance point in a given direction. These speeds were then averaged using area-proportional population weighting to obtain a representative speed for each direction.

To determine DURBEG and DURMID, the evacuation start time for each ring was defined as the sum of DLTSHL and DLTEVA, and the subsequent evacuation travel time to the EPZ boundary was calculated using the actual road network. A population-weighted cumulative evacuation completion curve was then constructed across all rings. The earliest evacuation start time among the rings was used as the reference time ( $t_0$ ). DURBEG and DURMID were calculated as  $t_{20} - t_0$  and  $t_{80} - t_{20}$  respectively, where  $t_{20}$  and  $t_{80}$  represent the times at which cumulative evacuation completion reached 20% and 80%.

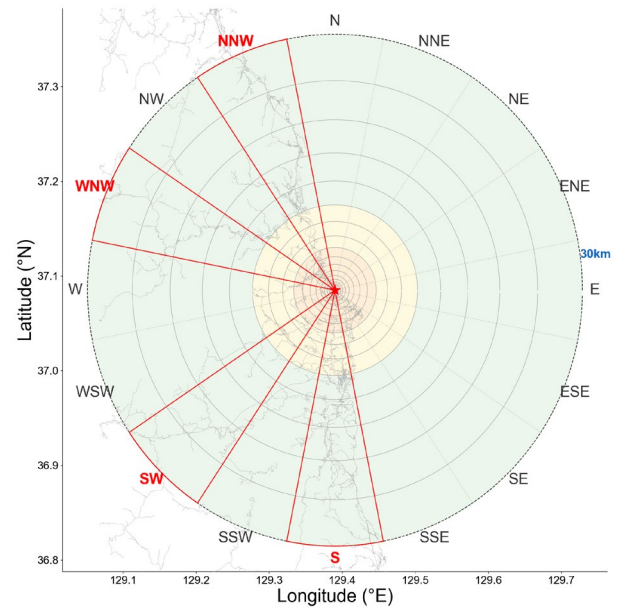


Fig. 3. Sector-Based Evacuation Planning

Table V. Definition of MACCS Emergency Response Parameters

| Parameters | Definition / Setting                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| DLTSHL     | $T_{exit} + T_{shelter\ travel}$<br>$T_{exit} \sim \text{Uniform}(0 \sim 30) \text{ min}$ , $T_{shelter\ travel} = \frac{D_{shelter}}{V_{PGA}}$ ,<br>$V_{PGA} = \begin{cases} 4.6 \text{ km/h (for walking, } PGA \geq 0.2g) \\ 54 \text{ km/h (for vehicle, } PGA < 0.2g) \end{cases}$                                                                                                                                                                                                                                                                                                                                                                                                |
| DLTEVA     | $T_{base} \times \text{multiplier}_{PGA} + T_{aftershock}$<br>$T_{base} = \begin{cases} \text{Uniform}(15 \sim 120) \text{ min} & (d < 2 \text{ km}) \\ \text{Uniform}(15 \sim 120) \text{ min} & (2 \leq d < 5 \text{ km}) \\ \text{Uniform}(15 \sim 120) \text{ min} & (5 \leq d < 30 \text{ km}) \end{cases}$ ,<br>$\text{multiplier}_{PGA} = \begin{cases} 1.0 & (x < 0.20g) \\ 1.3 & (0.20 \leq x < 0.4g) \\ 1.6 & (0.4 \leq x < 0.65g) \\ 2.0 & (x \geq 0.65g) \end{cases}$ ,<br>$T_{aftershock} = \begin{cases} +1.0 \text{ hr} & P(M \geq 4.0, 24 \text{ hr}) \geq 0.50 \\ +0.5 \text{ hr} & P(M \geq 4.0, 24 \text{ hr}) \geq 0.20 \\ 0 \text{ hr} & \text{else} \end{cases}$ |
| ESPEED     | <p><b>In general, ESPEED 1 &gt; ESPEED 2</b></p> <p>ESPEED 1: base speed * 0.6, ESPEED 2: base speed * 0.3, ESPEED 3: base speed * 1</p> <p>Base speed:</p> $V_{PGA} = \begin{cases} 4.6 \text{ km/h (for walking, } PGA \geq 0.2g) \\ 54 \text{ km/h (for vehicle, } PGA < 0.2g) \end{cases}$                                                                                                                                                                                                                                                                                                                                                                                         |

### 3. Results

#### 3.1 Analysis of Evacuation Delay Characteristics

To evaluate the impact of seismic events on evacuation, a representative scenario was selected for each PGA range. The representative PGA values for the four ranges defined in Table II were 0.01, 0.245, 0.461, and 0.672 g. For the seismic scenarios generated using Eq. (5) and MCS, the maximum evacuation delay factor among the four directions (NNW, WNW, SW, and S) was calculated. The scenario corresponding to the 95th percentile of this distribution was selected as the representative scenario for each PGA range. This represents a conservative scenario with an evacuation delay in the upper 5% of each range. Table VI summarizes the main seismic characteristics of the selected scenarios, including earthquake magnitude, hypocentral depth, and hypocentral distance.

Here, PGA represents the ground motion intensity at the NPP site. For example, the earthquake magnitude of the 0.461 g scenario is larger than that of the 0.672 g scenario, while the latter produces a higher site PGA because its hypocenter is closer to the site. Therefore, evaluating evacuation impacts based only on site PGA may not fully capture the effects of seismic events. The spatial distribution of building and road damage can vary with earthquake magnitude and hypocentral location, which may also change the location and extent of evacuation delays. This study therefore considered these spatial differences in the evacuation delay and dose assessments.

Table VI. Seismic Characteristics of Representative Scenarios

| Representative PGA (g) | $M_w$ | Hypocentral Depth (km) | Hypocentral Distance (km) |
|------------------------|-------|------------------------|---------------------------|
| 0.01                   | 5.17  | 10.74                  | 48.97                     |
| 0.245                  | 5.32  | 7.95                   | 9.70                      |
| 0.461                  | 6.22  | 9.25                   | 12.08                     |
| 0.672                  | 6.14  | 6.57                   | 7.37                      |

Fig. 4 shows the distribution of delayed and blocked roads caused by building and road damage for each representative PGA scenario. The blue triangles indicate the epicentral projections of the hypocenters for each scenario. For the 0.010 g scenario, the hypocenter, located 48.97 km from the site in the W direction, falls outside the area shown in the figure. The distribution varied depending on the hypocentral location and earthquake magnitude of each scenario. No delayed or blocked roads were observed in the 0.01 g scenario. In the 0.245 g scenario, 20 roads were delayed, with no blocked roads. For the 0.461 g scenario, 19,464 roads were delayed and 38 were blocked, while these numbers increased to 40,270 and 804, respectively, in the 0.672 g scenario. Overall, road delays and blockages increased with PGA and were more pronounced near the hypocenter. These results show that the proposed method appropriately reflects the spatial variation in road damage associated with PGA level and hypocentral location.

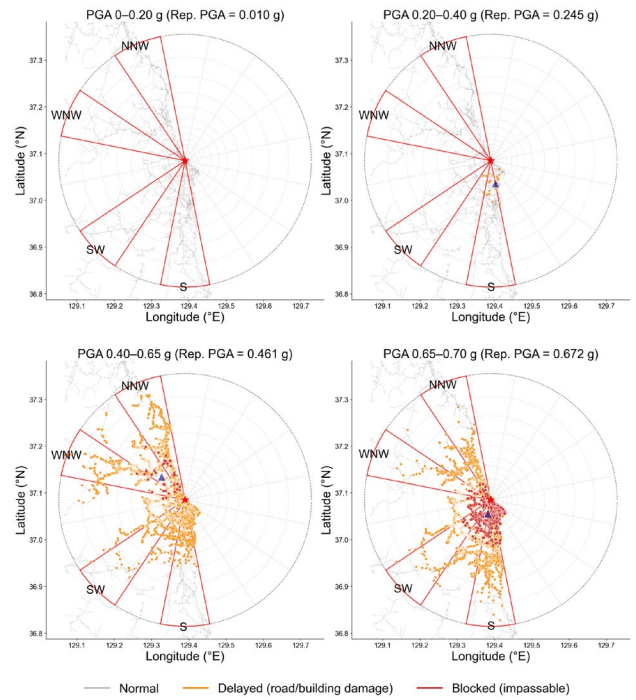


Fig. 4. Road Accessibility Considering Building and Road Damage within 30 km for Representative PGA Scenarios

Fig. 5 shows the relative change in total evacuation time from each ring to the EPZ boundary (30 km)

compared with the undamaged scenario. The total evacuation time includes DLTSHL, DLTEVA, and evacuation travel time. Evacuation delays were generally larger near the hypocenter, and the affected area expanded as PGA increased. DLTSHL and DLTEVA were sampled from uniform distributions within specified time ranges to account for uncertainties in human behavior. therefore, they showed relatively small changes with site PGA and hypocentral location. In contrast, evacuation travel time was more sensitive to earthquake magnitude and hypocentral location because it was directly affected by road damage. Accordingly, the spatial pattern of total evacuation time in Fig. 5 was similar to that observed when only evacuation travel time was considered.

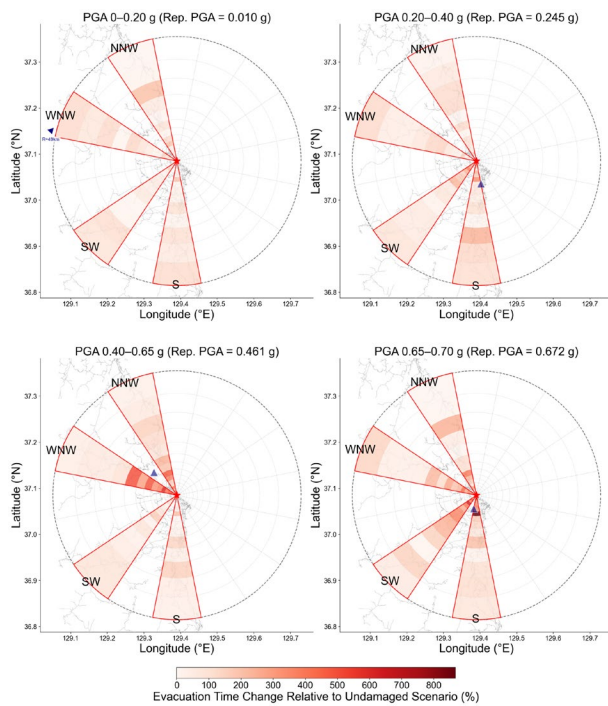


Fig. 5. Change in Evacuation Time Relative to the Undamaged Scenario within 30 km for Representative PGA Scenarios

### 3.2 Assessment of Radiological Dose Impacts

Fig. 6 presents the difference in population-weighted cancer fatality risk relative to the undamaged scenario. The calculation used the source term data for the Short-Term Station Blackout (STSBO) accident from the SOARCA Surry report to represent more realistic accident conditions. The population-weighted health effect risk is calculated by estimating the expected number of health effect cases in each area and dividing it by the total population of that area. This metric accounts for both the population distribution and the wind rose. The risk difference was zero in areas with no population, including the 0–1.7 km range in most directions and the 2.3–5 km range in the SW direction. In addition, some spatial variability may arise from the wind direction frequency reflected in the wind rose. Therefore, the

results were interpreted primarily based on trends that consistently appeared with increasing PGA rather than changes at individual locations.

Overall, the cancer fatality risk tended to increase relative to the undamaged scenario particularly in sectors toward the epicenter. The enlarged results within 5 km in Fig. 7 further show that the increase was greatest near the epicenter direction and generally decreased with increasing angular distance from it. To further examine this trend, the three directions were compared in order of increasing angular difference from the hypocentral direction (the PGA = 0.010g scenario was excluded because the effect of hypocentral location was limited, and the SW direction was excluded because both the population and risk within 5 km were very low). The magnitude of the risk increase followed the same order. For PGA = 0.245g, the directions were S, WNW, and NNW in order of increasing angular difference from the hypocentral direction, with corresponding risk increases of 35.8%, 34.9%, and 13.8%, respectively. For PGA = 0.461g, the directions were WNW, NNW, and S in order of increasing angular difference, with corresponding risk increases of 71.9%, 17.6%, and 13.4%, respectively. For PGA = 0.672g, the corresponding order was S, WNW, and NNW, with risk increases of 66.7%, 61.9%, and 22.5%, respectively.

Compared with the undamaged scenario, the PGA = 0.010g scenario showed a decrease in risk in some regions. Because PGA = 0.010 g represents a very low level of ground motion, the seismic impact is limited compared with the undamaged scenario. Therefore, random variations associated with the uniform distributions of DLTSHL and DLTEVA may have a relatively large influence on the results. In contrast, as PGA increases, the seismic impact becomes more dominant, reducing the relative influence of these random variations.

In addition, comparison with Fig. 5 showed a similar spatial pattern, with higher risks generally observed in areas with greater evacuation time delays. To quantify this relationship, correlations between risk and DLTSHL, DLTEVA, and evacuation travel time were analyzed for each PGA range and direction, and the Pearson correlation coefficients are presented in Table VII. The Pearson correlation coefficient ranges from  $-1$  to  $+1$ , with values closer to  $+1$  indicating a stronger positive linear relationship and values closer to  $0$  indicating a weaker relationship.

Overall, the risk showed relatively strong positive correlations with DLTSHL and DLTEVA, while the correlations with evacuation travel time were generally lower. In the NNW direction, the highest correlation was observed with DLTEVA, with a coefficient of 0.86. In the WNW direction, DLTSHL and DLTEVA showed relatively high correlations of 0.73 and 0.69, respectively. Similarly, in the S direction, the corresponding coefficients were 0.73 and 0.86. In contrast, the SW direction showed a low correlation with DLTSHL of 0.17, while the correlations with DLTEVA and

evacuation travel time were 0.48 and 0.49, respectively, indicating no clear relationship compared with the other directions. This may be partly attributed to the relatively small population in the SW direction, which was the lowest among the four directions and approximately 1/34 of that in the S direction, where the population was the largest. As a result, a consistent relationship between risk and the evacuation time-related variables may have been less apparent in the SW direction. evacuation travel time showed correlation coefficients of 0.31–0.49 across all directions, suggesting that changes in risk were more closely associated with DLTSHL and DLTEVA than with evacuation travel time itself.

Table VII. Pearson Correlation Coefficients between Evacuation Time-Related Variables and Risk by Direction

| Direction | DLTSHL | DLTEVA | Evacuation Travel Time |
|-----------|--------|--------|------------------------|
| NNW       | 0.38   | 0.86   | 0.34                   |
| WNW       | 0.73   | 0.69   | 0.31                   |
| SW        | 0.17   | 0.48   | 0.49                   |
| S         | 0.73   | 0.86   | 0.43                   |

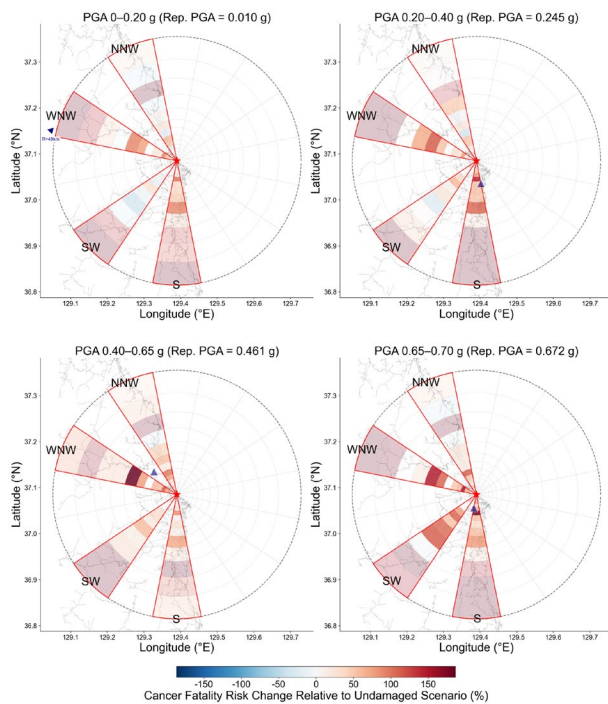


Fig. 6. Cancer Fatality Risk Change Relative to the Undamaged Scenario within 30 km for Representative PGA Scenarios

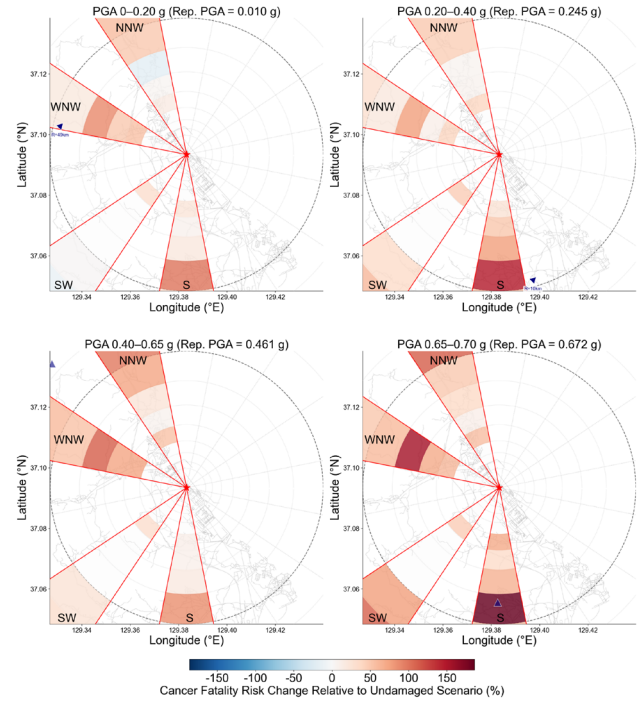


Fig. 7. Cancer Fatality Risk Change Relative to the Undamaged Scenario within 5 km for Representative PGA Scenarios

#### 4. Conclusion

This study proposed a Level 3 PSA emergency response assessment methodology that more realistically reflects seismic conditions. To this end, PSHA used in Level 1 and Level 2 Seismic PSA was combined with MCS to generate various seismic scenarios and simulate evacuation processes considering earthquake magnitude and hypocentral location. The results showed that the spatial distribution of building and road damage varied with earthquake magnitude and hypocentral location, and these differences affected both evacuation delays and dose results. Therefore, a simplified evacuation model based only on site seismic intensity and a uniform increase in evacuation time may not adequately reflect the spatial effects of seismic events. Future work will incorporate the shielding factor and perform sensitivity analyses to identify challenging evacuation conditions and vulnerable areas.

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