

Probabilistic tsunami risk assessment based on submarine active faults in the Sea of Japan for a thermal power plant

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Abstract

The Sea of Japan coastal areas have experienced tsunami damage caused by submarine active seismic faults. Large uncertainties remain regarding seismic activity of these faults and the following tsunami. Probabilistic tsunami risk assessment (PTRA) enables the evaluation of tsunami risk accounting for such uncertainties. In this study, the tsunami risks of a thermal power plant located on the Sea of Japan coast were evaluated using the PTRA based on submarine active faults, including coupled faults, across the Sea of Japan. The results indicate that coupled fault models had large impacts on risk levels, especially for severe damage states. In addition, the risk levels varied depending on the structures, even within the same sites. The spatial distribution of tsunami risk revealed that structures with high risk levels existed not only along the coast but also inland. The findings in this study provide practical insights for robust tsunami risk assessment, which are useful for the development of disaster resilience measures, especially for infrastructure.

1. Introduction

The 2024 Noto Peninsula Earthquake once again demonstrated the existence of tsunami hazards along the Sea of Japan coast. A post-event survey revealed that the inundation height exceeded 5 m [1]. Before this event, the Sea of Japan coast had been hit by several earthquakes and following tsunamis, such as the 1983 Mw 7.8 the Sea of Japan Earthquake and the 1993 Mw7.7 Hokkaido Nansei-oki Earthquake. Notably, the tsunamis of 1983 and 1993 were huge, with maximum run-up heights exceeding 14 m and 31 m, respectively [2, 3]. Regarding the possibility of future tsunamis, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and Headquarters for Earthquake Research Promotion (HERP) of Japan published the Sea of Japan submarine active fault models, part of which is shown in Fig. 1(a) [4, 5]. These faults have the potential to generate tsunamis that could cause damage along the Sea of Japan; thus, the Sea of Japan coastal region faces tsunami risks.

The Sea of Japan coastline is complex coastline and has a complex bathymetric feature that contributes to unique tsunami propagation characteristics in this region [6]. For example, the 2024 Noto Peninsula earthquake tsunamis generated on the continental shelf were trapped along the coastal areas, resulting in local wave amplification [7, 8]. This trapped tsunami propagated as an edge wave [9], which is characterized by long duration and amplification in subsequent waves, and can cause damage[10–13]. Submarine active fault models are the primary cause of tsunamis in the Sea of Japan; however, they are associated with uncertainties. In the 2024 Noto Peninsula earthquake, faults with different plane orientations were linked together [14]. This type of fault model was not considered in the published fault models [4, 5]. Regarding the tsunami triggered by these submarine active faults, Satake et al. [15] demonstrated that the tsunami heights generated by these submarine active faults can vary by a factor of approximately two, depending on the scaling law. Therefore, it is necessary to consider both the unique characteristics of tsunami propagation and the associated uncertainties when assessing tsunami risks along the Sea of Japan coast.

Risk assessment is essential for disaster risk reduction in addition to hazard assessment. Probabilistic tsunami hazard assessment (PTHA) is an approach that accounts for uncertainties associated with earthquakes and tsunamis [16, 17]. Based on PTHA, a probabilistic tsunami risk assessment (PTRA) was proposed to quantify tsunami-induced damages and losses. A PTRA method that applies to specific structures, such as nuclear power plants [18] and to multiple structures [19, 20], was proposed. Mulia et al. [21] conducted a PTHA based on submarine active faults in the entire the Sea of Japan and clarified the characteristics of tsunami hazards in each region. However, in this study, coastal tsunami heights were estimated by applying an empirical law to offshore tsunami heights calculated using large grid sizes to achieve large-domain calculations. This method potentially underestimates tsunami heights because it fails to fully capture local amplification. In addition, the fault model considered uncertainties related to slip distribution and magnitude; however, the coupling of faults was not examined.

In this study, the tsunami risks in the coastal area along the Sea of Japan were revealed by conducting PTRA based on submarine active faults, including coupled faults, located across the Sea of Japan. Furthermore, the assessments considered local propagation characteristics by employing tsunami simulations with detailed bathymetry. This study presents the first PTRA for the Sea of Japan that explicitly considers the complex tsunami propagation characteristics and coupled fault models. To apply the proposed methodology in practice, this study focused on a thermal power plant in Joetsu city, Niigata Prefecture, as shown in Fig. 1. During the 2024 Noto Peninsula Earthquake tsunami, the maximum tsunami height was instrumentally observed at the Joetsu offshore wave gauge [22]. A post-disaster survey revealed that the tsunami run-up height exceeded 3 m, exceeding the predicted by the tsunami warning system [1, 23]. This showed that Joetsu faces a huge tsunami hazard. Additionally, a thermal power plant is located on the coast and is essential to the social and economic activities of the surrounding areas because thermal power generation is a major source of electricity in Japan. On the other hand, thermal power plants must be constructed in coastal lowlands owing to their dependence on fuel imports and cooling needs; however, the tsunami risk is high in these areas. In addition, large fuel tanks store fuel for the power plant, and any damage caused by a tsunami has the potential to trigger secondary disasters such as fires. Therefore, by conducting a PTRA, it is possible to identify the probability of damage to each structure and establish effective countermeasures. Furthermore, even for extremely rare massive tsunamis that are difficult to prevent completely, PTRA is helpful for developing recovery plans by identifying structures that are vulnerable to damage. This study provides a PTRA framework based on submarine active fault models and contributes to the development of tsunami countermeasures for infrastructure.

2. Results

2.1. Tsunami hazard and source characteristics of Joetsu

To investigate the characteristics of local tsunami hazard in Joetsu and incorporate them into the assessment, tsunami simulations were conducted. The thermal power plant was inundated by tsunamis triggered by fault models shown in Fig. 1(b). Twelve faults models are distributed across four fault

domains. It should be noted that a fault domain refers to a group of faults that have the potential to interact, and a fault model refers to an individual fault or a combination of faults. These fault domains are mainly located around the offshore of Joetsu, but some are also distributed around the offshore of the Noto Peninsula and northern Japan. Tsunamis generated by fault models around Joetsu arrive in a very short time. In a scenario with the shortest observation time for maximum tsunami height, a 6.2 m tsunami reached the coast 13.5 min after the earthquake occurred. This is a specific characteristic of submarine active faults where the rupture zone is close to land. In addition to this characteristic, another notable feature is the delayed arrival of maximum tsunami waves. Figure 2 shows the relationship between the duration to the maximum tsunami wave and the amplification ratio in comparison to the first-arrived wave. The duration to the maximum wave is defined as the time duration from the tsunami arrival to the maximum wave observation. The maximum tsunami waves were amplified to over five times those of first arrived waves, as measured in the scenario of the fault model located around Sado Island. Scenarios with an amplification ratio of 2 times or more accounted for 23%. Across these, four-fifths had a duration exceeding. Scenarios with these characteristics tend to have lower scenario numbers, meaning they tend to be located on the northern side. Thus, the Joetsu coastal area is characterized by a contrasting tsunami hazard: short arrival time and long duration.

Besides the characteristics of the tsunami hazard, the characteristics of submarine active seismic faults also need to be considered in the assessment. Since the detailed slip distribution of these faults are difficult to estimate, there is a major uncertainty regarding their asperities. To investigate the impact of this uncertainty on tsunami heights, tsunami heights were compared in scenarios with uniform and heterogeneous slips. Four large slip locations were set for each fault model. Figure 3 shows the variation in maximum tsunami heights due to the locations of large slips. As the magnitudes (M_w) increased, the variation of the maximum tsunami heights increased. For scenarios with the largest variation, the variation in tsunami height was 2.8 m, with a standard deviation of 1.0. Therefore, submarine active faults and the following tsunamis are variable and uncertain, and risk assessment must take these factors into account.

2.2 Tsunami risk at the power plant in Joetsu

PTRA was performed to quantitatively evaluate tsunami risk under various uncertainties, and the results are shown in Fig. 4. The relationship between the damage probability and annual exceedance probability was calculated at each damage level for all structures in the power plant. Four damage levels (DL) were examined in this study were DL2 (moderate damage), DL3 (major damage), DL4 (complete damage), and DL5 (collapsed). Further details regarding damage levels are described in Suppasri et al.[24]. The risk level was defined as the expected probability of each DL, which is equal to the area enclosed by the axes and the risk curve. Scenarios where coupled fault models considered or excluded are shown in Fig. 4 (a) and (b), respectively. The median expected probabilities of each DL, considering coupled faults, were 2.0×10^{-4} for DL2, 1.1×10^{-4} for DL3, 5.5×10^{-5} for DL4, and 2.1×10^{-5} for DL5. In contrast, without considering the coupled faults, the median expected probabilities of each DL were 2.4×10^{-4} for DL2, 9.2×10^{-5} for DL3, 2.9×10^{-5} for DL4, and 8.2×10^{-5} for DL5. It

became clear that, the risk increases when coupled faults are considered, except for DL2. Furthermore, as DL increase, the rate of change resulting from the consideration of coupled fault models relative to the median value increased. Especially, the median values increased by 154% in DL5.

The variation in risk level across the structures on the site was reduced by considering the coupled fault models because the number of scenarios in which inundation occurred increased when coupled faults were considered. Consequently, the expected probability of each DL rose, and this increase was particularly marked at facilities that originally had low risk levels. In addition, owing to the increased number of fault models considered, the relative contribution of existing fault models decreased. The existing fault models were relatively small-scale. As a result, the risk levels decreased, especially at facilities where the expected probability of each DL was originally high. In fact, the maximum expected probability of the structures of each DL decreased when coupled faults were considered, except for DL5. The rate of decrease was greater for smaller DLs. These findings demonstrated that evaluations that consider coupled fault models enable a robust risk assessment that reflects realistic conditions.

The spatial distribution of risk levels across the structures on the site was also examined. The thermal power plant site has many structures, including boiler houses, fuel tanks, and control structures. Figure 5 shows the spatial distribution of the damage probability of each DL for a 10^{-4} annual exceedance probability. For all DLs, the structure with the highest risk level was the structure located in the northeast, indicated by the blue circle in Fig. 5. Based on satellite imagery, this structure likely represents a fuel tank. The maximum risk level was approximately twice the median for all DLs. This structure is located near the sea and tends to be inundated frequently, with inundation depth reaching significant heights. Additionally, structures with high risk levels were observed not only in coastal areas but also in inland locations, such as those located on the southern side of the site. These structures are inundated with large depths, even though they are located inland. To compare the variability in risk levels across structures within each DL, the coefficient of variation (CV) was calculated. The CV was highest at 0.37 in DL5, but it was around 0.35 in other DLs as well. Therefore, assessing each structure is essential, even within the same site.

3. Discussion

In this study, two tsunami propagation characteristics were observed: rapid arrival and amplification in subsequent waves. Although a short arrival time is caused by the location of the fault rupture zone, the causes of amplification are not clear. To investigate this, the influences of bathymetry was examined by applying manipulated bathymetry, as shown in Fig. 6(a). The manipulated bathymetry was created by replacing the Torigakubi Cape with a 10 m deep sea to flatten the coastline. Tsunamis were simulated using the manipulated bathymetry were performed for the 17 scenarios in which both amplification in subsequent waves and long duration were observed. The results with the original and modified bathymetry are shown in Fig. 6(b) and 6(c), respectively. In most scenarios, the amplification ratio decreased by approximately 34% on average, when manipulated bathymetry was applied. These results show that the cape influences the amplification in subsequent waves. The generation of edge waves

likely contributes to this amplification. Previous studies have reported that edge waves are often observed in coastal areas situated between capes [9, 25, 26]. This spatial tendency suggests that capes contribute to the generation of edge waves.

This study examined the impact of considering coupled fault models on risk assessment. The median and maximum risk levels increased only in DL5, which is the most severely affected. This implies that coupled fault models contribute more greatly to the more severe states DL. Infrastructure such as power plants must be prepared for infrequent but severe disasters. Therefore, robust assessment that considers coupled fault models are essential for such infrastructures. Furthermore, risk assessments were conducted not on individual structures identifiable in satellite images, and not on representative sites, and risk levels varied across the structures; the maximum value was approximately twice the median. Therefore, results evaluating the site as a single point potentially leads to an underestimation. Structures with high risk levels were also located in inland areas. Thus, evaluating spatial risk distribution is necessary to determine disaster prevention measures.

However, this study has certain limitations. First, fault models have limitations. Estimating slip rates of active faults difficult owing to their low activity frequency, although the recurrence period of seismic events depends on slip rates [27, 28]. For the fault models [4, 5] applied in this study, the activity level was not estimated in the reports. Thus, activity level and recurrence periods were determined based on previous studies [29]. Besides the lack of knowledge about identified faults, some active faults in the Sea of Japan may still be unidentified. A more accurate assessment becomes possible if detailed information about seismic activity can be obtained. Additionally, limitations regarding ground shaking also exist. The fragility curve used in this study was constructed for tsunami damage; however, it implicitly incorporates the effects of ground shaking as well. This risk assessment only considered tsunamis as the target hazard, and ground shaking is not evaluated. Crustal deformation associated with fault movement was also not considered. Considering hazards associated with seismic events other than tsunamis, such as ground motion, enable a more robust assessment. Multi hazard risk assessment studies, including tsunamis, have been conducted [30]. These approaches are expected to be applied to the coastal areas along the Sea of Japan in the future. Lastly, there are uncertainties to ideally be considered. In the hazard assessment, a probabilistic approach that considered both aleatoric and epistemic uncertainties was employed. However, this study did not consider the uncertainty associated with the fragility curve. Uncertainty should be considered when converting a hazard curve into a risk curve using the fragility curve. Future research will examine the impact of these uncertainties to achieve more accurate risk assessments.

4. Conclusion

This study investigated the tsunami propagation characteristics in Joetsu and conducted PTRAs for the thermal power plant. The main findings are summarized as follows:

1. The tsunami propagation characteristics observed in Joetsu included a short arrival time and amplification in subsequent waves. It revealed that amplification was influenced by a nearby cape.
2. Coupled fault models had large impacts on the risk levels of the thermal power plant in Joetsu. For sever DL, considering coupled fault models resulted in an increased risk level.
3. Risk levels varied depending on the structures. The spatial distribution of tsunami risk indicated that high-risk level buildings existed not only along the coast but also inland.

This study attempted to assessment tsunami risk based on submarine active faults in the Sea of Japan, including coupled fault models. Practical insights into infrastructure risk assessment, including the impact on tsunami risk by considering coupled fault models and variations in risk levels across structures. The findings of this study will contribute to the advancement of risk assessment of structures at risk of tsunamis caused by submarine active seismic faults.

5. Method

In this study, PTRa was conducted to quantitatively evaluate tsunami risk using the evaluation method shown in Fig. 7. The details of the evaluation process are follows.

5.1 Fault model setting

In this analysis, 11 fault domains were considered based on the published fault model[4, 5]. These submarine active faults are located from the western offshore of Hokkaido to the offshore around the Noto Peninsula, as shown in Fig. 1(a). The proposed fault model was used as it is in eight fault domains; in the remaining three fault domains, fault models, including newly coupled fault models were used. These coupled fault models are a combination of different fault-plane directions of overlapping fault planes. The faults that triggered the Noto Peninsula Earthquake consisted of multiple faults with differing plane orientations [14].

The submarine active faults located north of Joetsu, were estimated by MLIT [4], and the submarine active faults models located south of Joetsu were established by HERP [5]. Since these fault models were estimated using different methods, the magnitude, average slip amount, and recurrence period were calculated using a different method for each fault model. For the detailed procedure, refer to the supplementary notes. Pre-calculations were performed using Eq. (1) to identify the seismic fault models that influence the tsunami hazard on the power plant:

$$X > H\kappa^{2.3} \# (1)$$

where X is the reference water level, H is the maximum tsunami height, and κ is the logarithmic standard deviation of Aida [31]. The reference water level was set at 2 m based on the site elevation. The logarithmic standard deviation was applied at 1.55 to account for high variability [29]. Fault domains with fault models that exceeded the threshold were selected for analysis.

Recurrence periods were also calculated using different methods for MLIT and HERP model, respectively. Regarding the MLIT model, the occurrence frequency was assumed to be uniformly distributed, as shown in Supplementary Table 1 [29]. For the HERP model, the recurrence period was determined using the following equation [32].

$$T = \frac{M_o}{\bar{M}_o} \# (2)$$

$$\bar{M}_o = \mu S \nu \# (3)$$

where M_o is the seismic moment, $\bar{M}_o$ is the long-term accumulated seismic moment, μ is the rigidity, S is the fault area, ν is the average displacement velocity. The average displacement velocity was assumed to follow a uniform distribution from 10 m / 1000 years to 1 m / 1000 years. The recurrence periods of the coupled fault models were calculated using Eqs. (6) and (7) from the assumed slip amount and average displacement velocity as an independent individual fault model.

Multiple magnitudes and large slip areas were considered for each fault model to account for uncertainty, as shown in Supplementary Fig. 1. Regarding magnitude, three scenarios were set up: one calculated using published fault parameters, and two others with the magnitude adjusted by ± 0.1 . In addition, four large slip areas were set for each fault model. The fault plane was divided along its length into four segments, establishing four large slip locations. The large slip was set to twice the average slip [29]. The slips of background zones, outside of large slip zones, were set to two-thirds of the average amount to conserve the seismic moment [29].

5.2 Tsunami numerical simulation

To estimate the tsunami height along Joetsu Coast, this study used a tsunami numerical simulation. The initial water level was calculated using the theory proposed by Okada [33]. TUNAMI-N2 was used for tsunami simulation; it solves the nonlinear long-wave equation in a Cartesian coordinate system based on a leap-frog scheme[34] as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \# (4)$$

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q_x Q_y}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{\frac{7}{3}}} Q_x \sqrt{Q_x^2 + Q_y^2} = 0 \# (5)$$

$$\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x Q_y}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q_y^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{\frac{7}{3}}} Q_y \sqrt{Q_x^2 + Q_y^2} = 0 \# (6)$$

where Q_x and Q_y are the discharge fluxes in the x and y directions, respectively, η is the water level, g is the gravitational acceleration (9.81 ms^{-2}), D is the total water depth, and n is the Manning's

roughness coefficient, which was set to a uniform value of $0.025 \text{ m}^{-1/3} \text{ s}$ for all computational grids [35–38]. The time step was 0.1 s, which satisfies the CFL condition. The total simulation time was 8 h.

The calculation domain is shown in Fig. 1. The tsunami simulation was conducted on a six-layer nested grid system with spatial resolutions of 1215 m, 405 m, 135 m, 45 m, 15 m, and 5 m. The 1215 m and 405 m mesh data were obtained from the General Bathymetric Chart of the Oceans (GEBCO) [39] and resampled by ArcGIS Pro software. The 135 m mesh data were obtained from MLIT [4]. The 45 m, 15 m, and 5 m data were developed using a digital bathymetric chart (M7011 Sado) published by the Japan Hydrographic Association, and a digital elevation model, with a horizontal resolution of 50 m, provided by the Geospatial Information Authority (GSI).

The uncertainty caused by such incompleteness of numerical simulation models was considered by treating tsunami heights as random variables following a truncated log-normal distribution [16, 29]. The log-normal standard deviation β considered four values, shown in Supplementary Fig. 1. Truncation limits were set at $\pm 3\beta$. The values and its branch weights were based on Japan Society of Civil Engineering (JSCE) [29].

5.3 Construction of hazard curves

Firstly, the hazard curves of each scenario were calculated. To consider multiple uncertainties, total 1824 scenarios were set. The hazard curve for each fault model was obtained by calculating the weighted average of these scenarios using the following equation [40].

$$F_m(x) = \sum_{i=1}^n w_i \int_x^{\infty} f_i(x) dx \quad \# (7)$$

where, F_m is the hazard curve of the fault model, w_i is the weight defined in the logic tree, f_i is the probability density function of the tsunami inundation depth for each scenario, x is the inundation depth, and n is the number of scenarios for each fault model. These hazard curves represent the calculated average each scenario of each fault model. Similarly, the hazard curves for each fault domain were calculated by averaging the hazard curve of the fault models located within the same domain. Thus, the hazard curve of the Joetsu Coast was obtained. This hazard curve considers all fault domains and is calculated using the following equation [40].

$$F(x) = 1 - \prod_{j=1}^{11} (1 - F_{d-j}(x)) \quad \# (8)$$

where, F is the hazard curve of Joetsu Coast, and F_d is the hazard curve of the fault domain.

5.4 Probabilistic tsunami risk assessment

To estimate the tsunami risk at Joetsu Thermal Power Plant, building data was extracted from satellite imagery using ArcGIS Pro, and 35 buildings were extracted. Polygon data was created for each building to identify its center points, being the representative points for each building. The seawalls on the north side of the site, which were included in the bathymetry data.

As methods for assessing vulnerabilities, approaches exist that evaluate damage and loss, respectively. In this study, the damage probability was evaluated as a risk assessment for infrastructure. Infrastructure must continue to operate after a disaster, making damage probability assessment necessary for disaster prevention. The Suppasri et al. [24] fragility curve was used in this study, showing the relationship between inundation depth and damage probability for each damage level. The fragility curve was developed from 251,301 building damage data counts from the Great East Japan Earthquake. MLIT categorized these damage data into six damage levels [41]; however, this study used four levels: Damage Level 2 to 5, which were considered to make it difficult for the facility to continue operationing. Details of these damage levels are in Suppasri et al.[24].

The risk curve was obtained by transforming the fragility curve to transform the hazard curve as follows [42].

$$f_D(p_d) = f_H\left(f_v^{-1}(p_d)\right) \bullet \left|\frac{d}{dp_d}f_v^{-1}(p_d)\right| \# (9)$$

where, f_D is the damage density function, p_d is the probability of damage, f_H is the inundation depth density function, and f_v is the fragility curve. For each damage level, risk curves were derived using f_D , following the same methodology as that used for hazard curves.

Declarations

Competing interests

The authors state that there are no competing interests to declare.

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Author Contribution

H.K.: conceptualization, analysis, writing- original draft, Y.M.: analysis, writing- original draft, A.C.: writing-review & editing, A.S. and F.I.: supervision, writing – review & editing. All authors reviewed the manuscript.

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Data Availability

Data used in this study will be made available on request.

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Figures

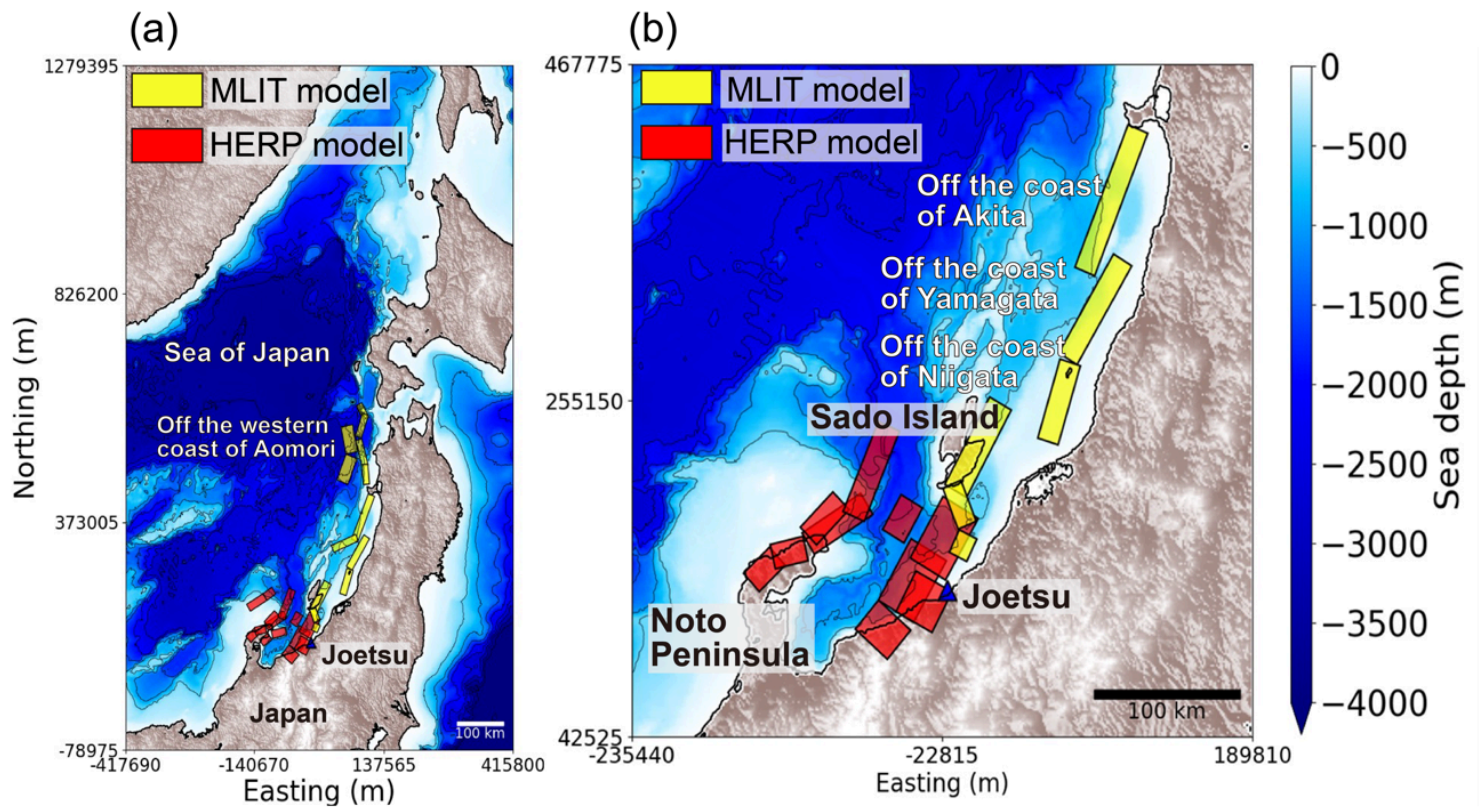


Figure 1

(a) Submarine active fault models across the Sea of Japan. (b) Submarine active fault models causing inundation at Joetsu Thermal Power Plant. The blue triangle indicates the location of Joetsu. Yellow and red rectangles are the fault models published by MLIT [4] and HERP [5], respectively. Black contour lines represent the water depth every 500 m.

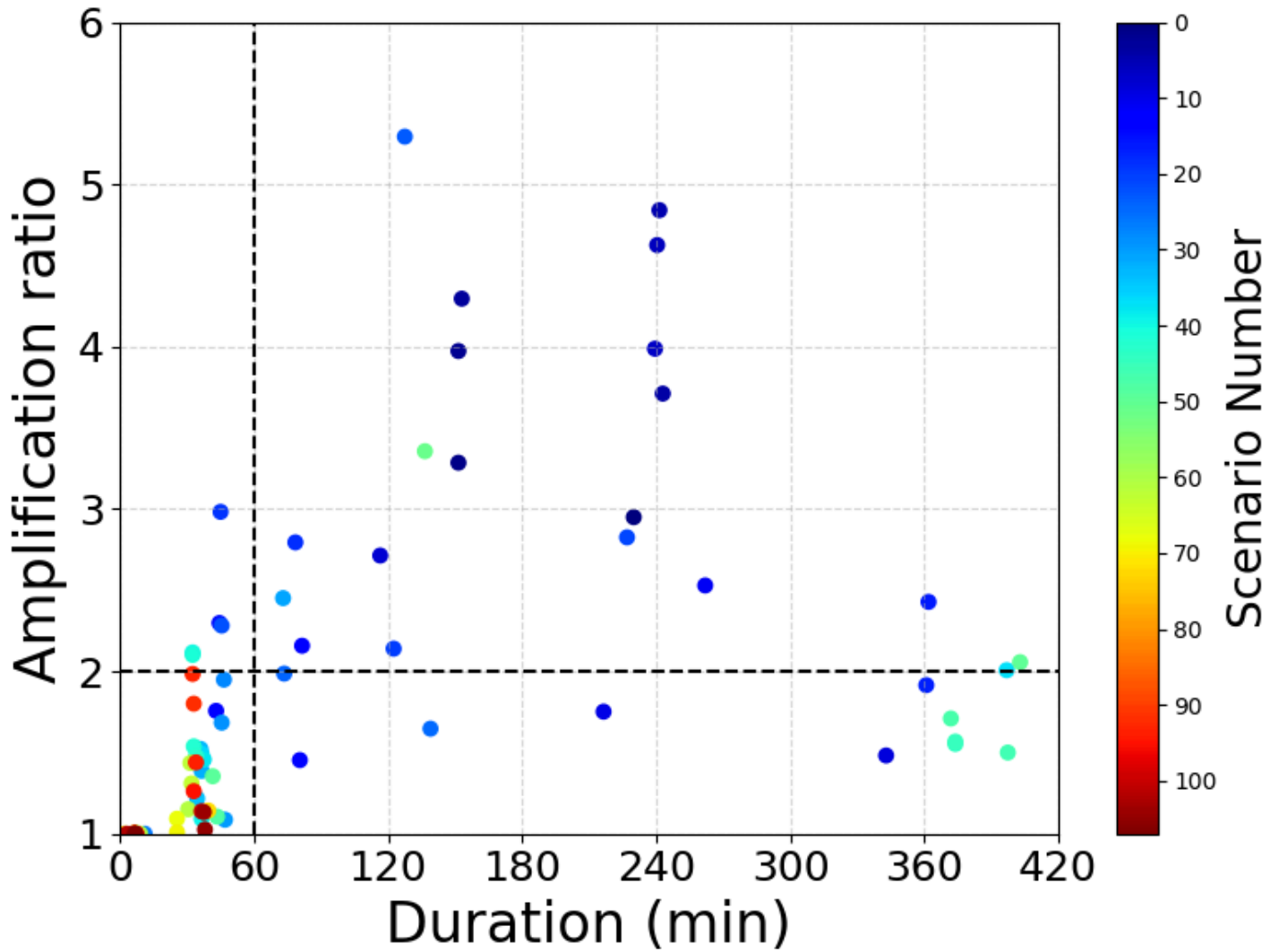


Figure 2

Relationship between the tsunami duration and subsequent tsunami amplification ratio. The vertical axis represents the ratio of maximum tsunami and first tsunami height. The horizontal axis represents the duration from arrival time to the observation of the maximum tsunami height. Coloring is by scenario number, with scenario numbers assigned from the north.

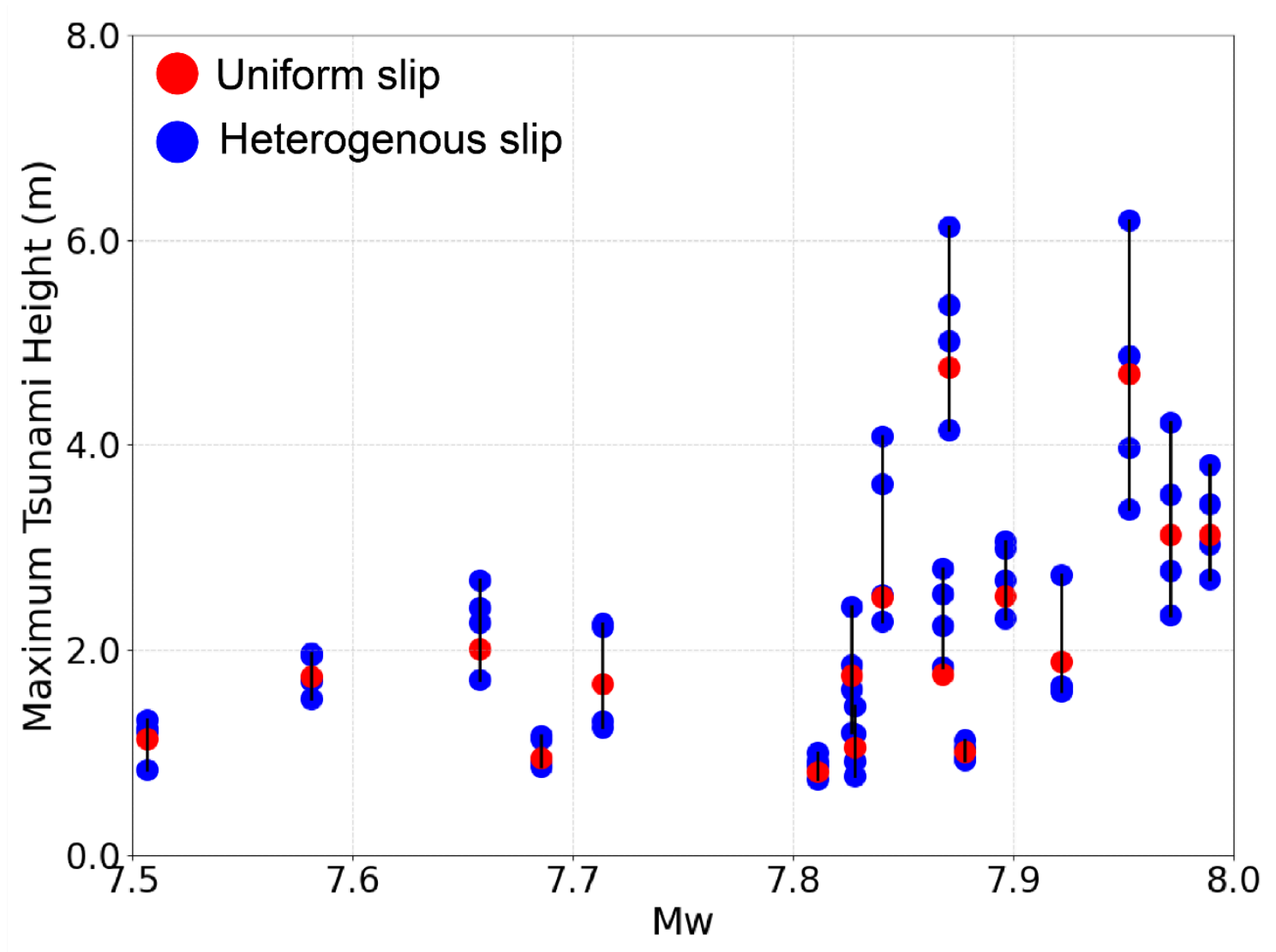


Figure 3

Variation in maximum tsunami height caused by asperities. The red and blue plots indicate the maximum tsunami height applied uniform and heterogenous slip, respectively.

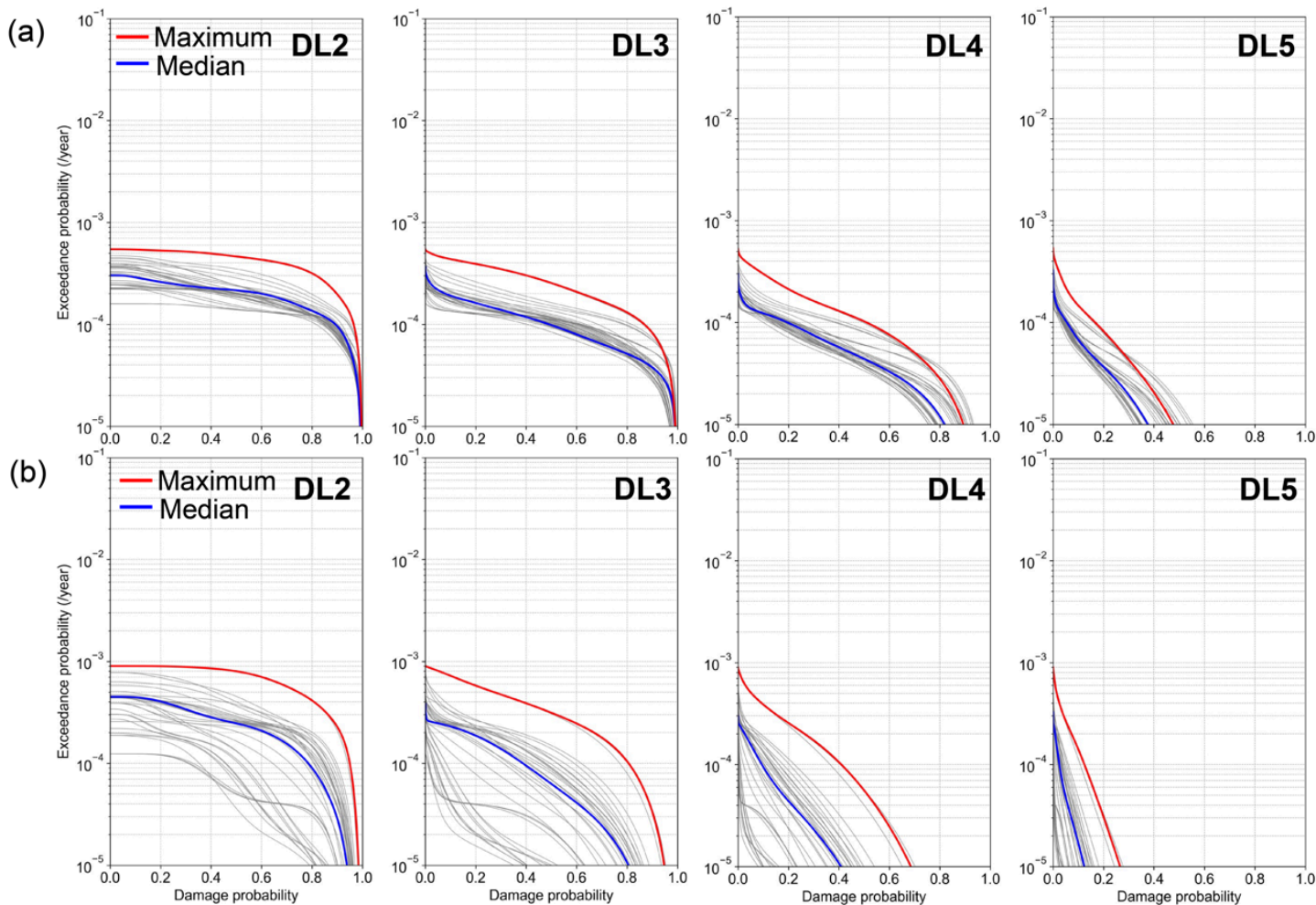


Figure 4

(a) Risk curve considering coupled faults models and (b) risk curve excluding coupled faults models at Joetsu Thermal Power Plant. The black lines represent the risk curve for each structure. The red and blue lines indicate the maximum and median risk levels.

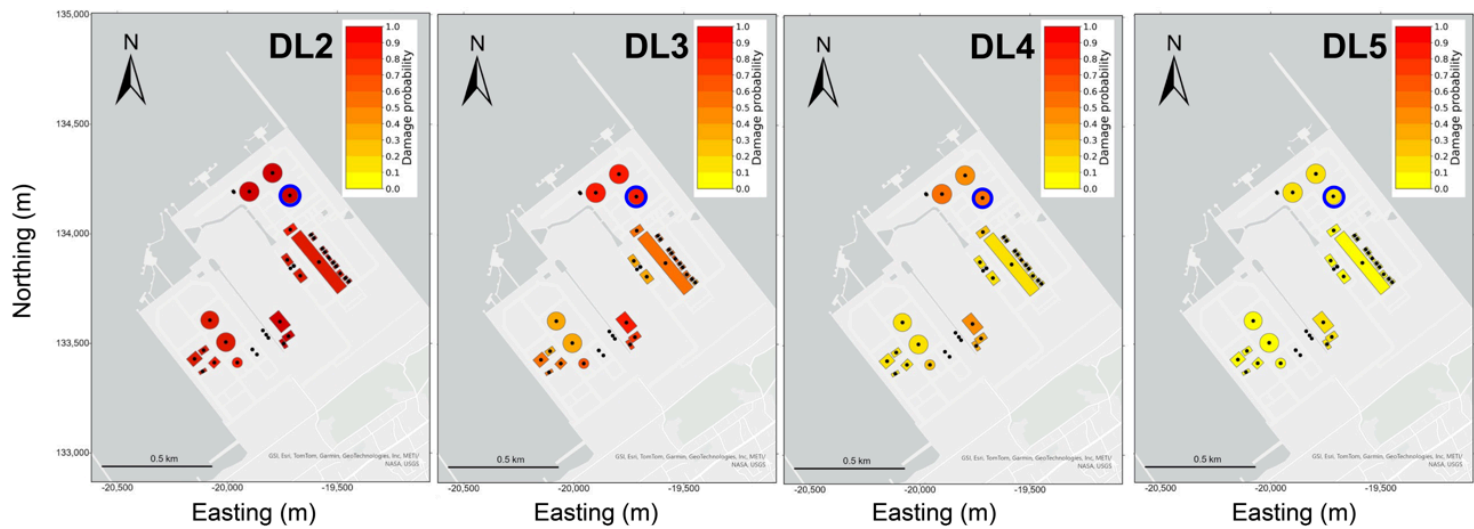


Figure 5

Spatial distribution of damage probabilities for a 10^{-4} annual exceedance probability. The blue circle indicates the building with the highest risk level. The dots indicate the centers of buildings.

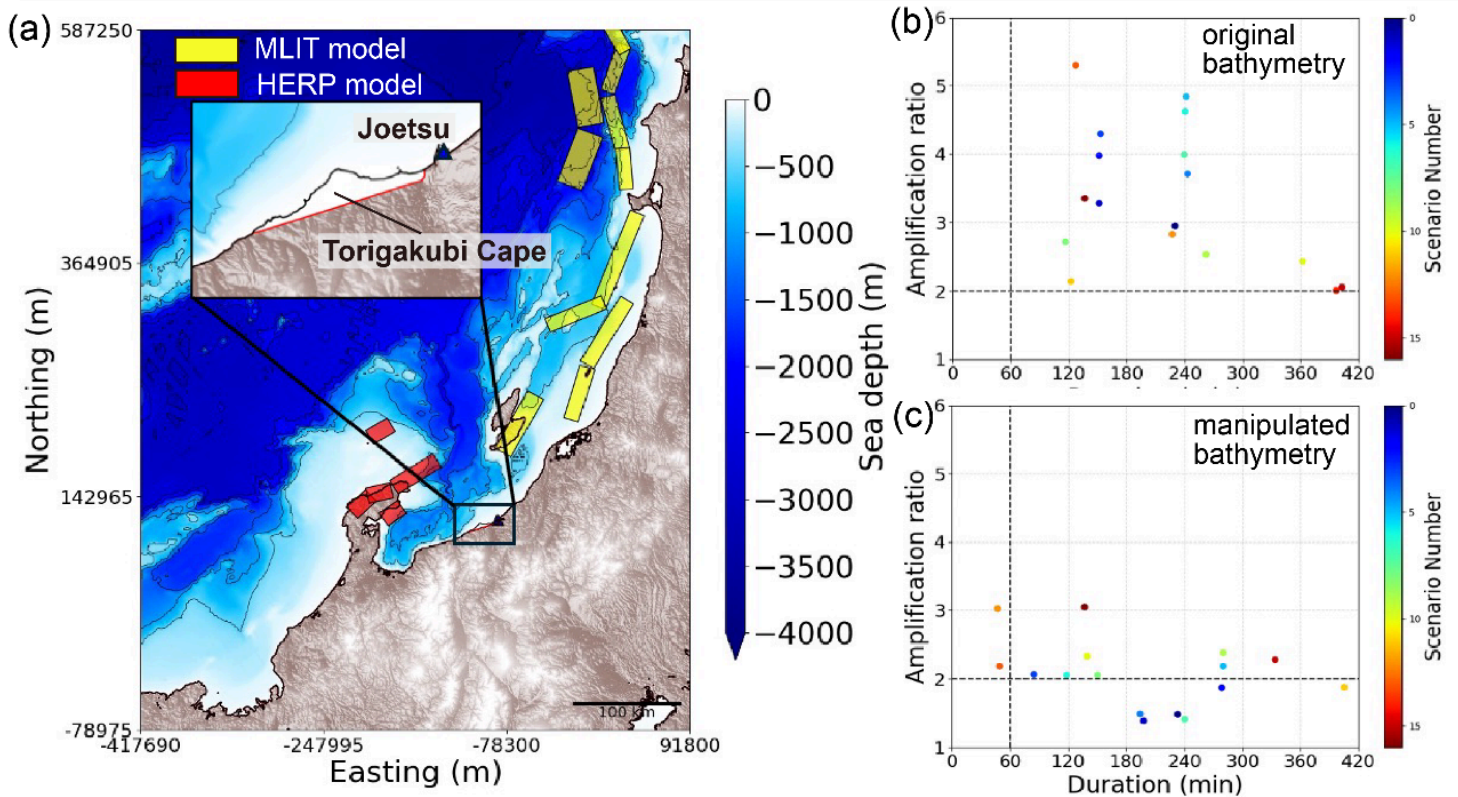
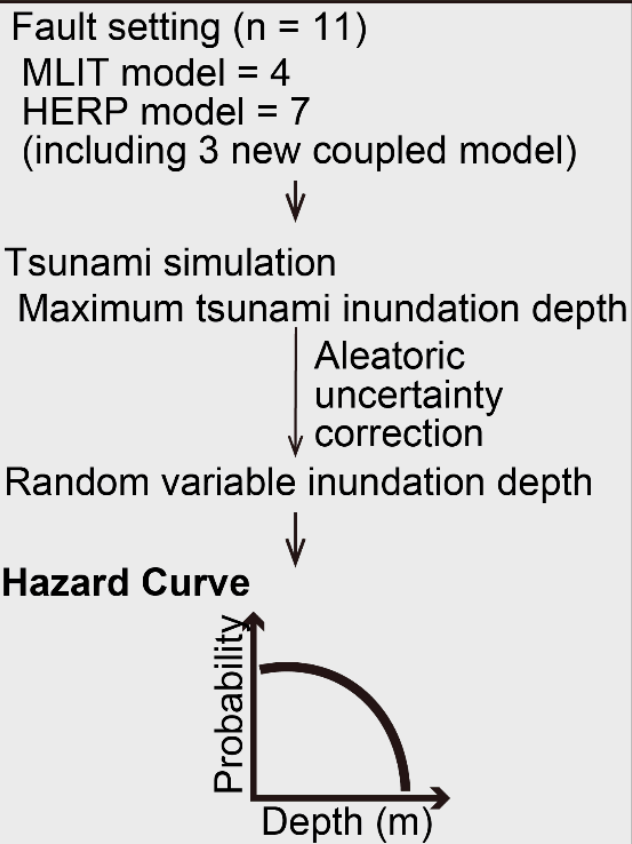


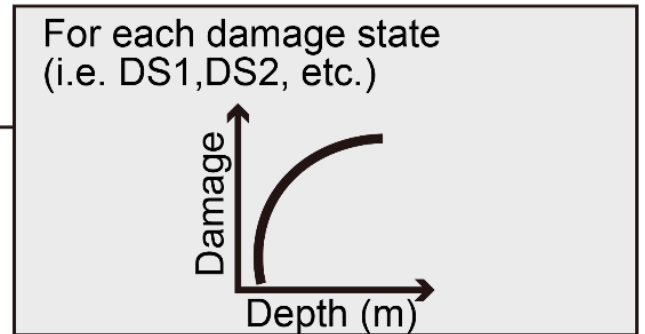
Figure 6

Manipulated bathymetry and location of target fault models. The upper map is enlarged around Torigakubi Cape. The black and red lines represent original and manipulated coastlines. The blue triangle indicates the location of Joetsu. (b, c) Relationship between the duration and subsequent tsunami amplification ratio applied (b) original bathymetry and (c) manipulated bathymetry.

Hazard Analysis



Fragility Curve



Risk Curve

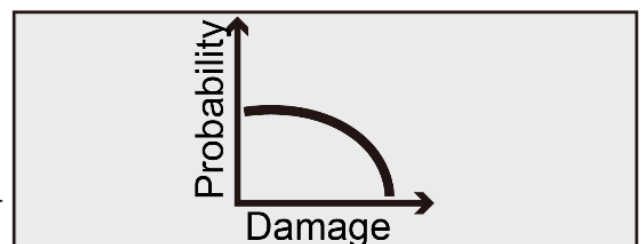


Figure 7

The PTRa framework applied in this study.

Supplementary Files

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