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Numerical Study on Spatial Correlation Characteristics of Tsunami Inundation Depth

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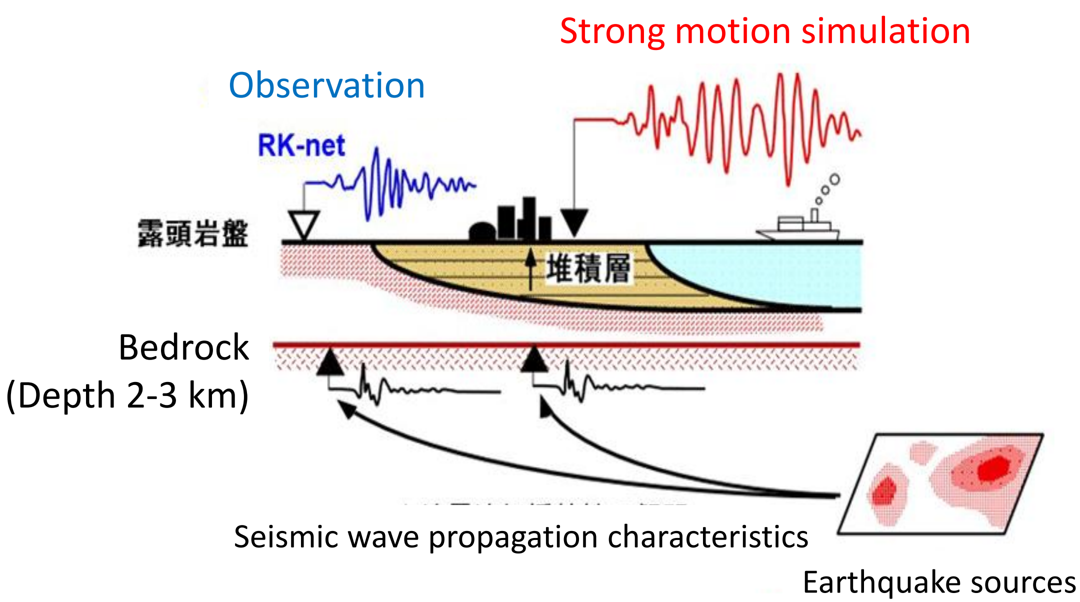
Background

- In a probabilistic disaster risk assessment for multiple buildings, we need to consider hazard correlation among site locations and damage correlation among multiple buildings because the probability distribution of aggregate damage for multiple buildings is affected.
- Analyses that consider the spatial correlation of hazards have been relatively advanced in the fields of probabilistic seismic hazard assessment and probabilistic seismic risk assessment (PSHA and PSRA, respectively) (e.g. [1]-[3]).



Prediction of Strong Motion

（Reference:CRIEPI HP/https://criepi.denken.or.jp/jp/civil/intro/earthquake.html

Purpose of this study

- On the other hand, in the cases of probabilistic tsunami hazard assessment and probabilistic tsunami risk assessment (PTHA and PTRA, respectively), we also need to consider the spatial correlation characteristics of tsunami hazard and damage, but there have been no studies that evaluate these correlation.

The purpose of this study is to evaluate the spatial correlation coefficients of tsunami inundation depth according to the relative distance by using the results of tsunami numerical simulations with nonlinear long-wave equations.

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The results of this study, the correlation coefficients of tsunami inundation depth is assumed to be applied to the tsunami damage assessment of the building portfolio.

An evaluation method for the macrospatial correlation coefficient of tsunami hazards

- Based on past studies (e.g. [4]-[7]) that evaluated the spatial correlation coefficients of seismic ground motions, we evaluated the spatial correlation coefficients of tsunami phenomena.
- Now we define $H_{sim}(r_i)$ as the maximum tsunami wave heights obtained by numerical simulations on a grid i and $H_{pre}(r_i)$ as the predicted wave heights obtained by an evaluation formula on a grid i. Here, r_i is the shortest distance between each grid and the fault end point, or the coastline. The residual $\varepsilon(r_i)$ between the numerical simulation result and the predicted value is evaluated as follows:

$$\varepsilon(r_i) = \log\left(\frac{H_{sim}(r_i)}{H_{pre}(r_i)}\right) \qquad (1)$$

- Using this residual $\varepsilon(r_i)$, we evaluate the variance in the residual (σ^2) as follows:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(\varepsilon(r_i))^2 \qquad (2)$$

Here, n is the number of target grids.

An evaluation method for the macrospatial correlation coefficient of tsunami hazards

- Next, we evaluate the macrospatial correlation characteristics.
- The covariance of the i-th observation point 1 and observation point 2 can be written as follows from the definition of covariance:

$$\mathrm{cov}(r_{i1}, r_{i2}) = \rho(r_{i1}, r_{i2})\, \sigma(r_{i1})\, \sigma(r_{i2}) \tag{3}$$

Here, $\rho(r_{i1}, r_{i2})$ is a correlation coefficient between two points, and σ is a standard deviation in each grid. Assuming that the distance x between the two observation points 1 and 2 and the standard deviation σ are constant regardless of the point, we can reconstruct Eq. (3) to the Eq. (4):

$$\mathrm{cov}(r_{i1}, r_{i2}) = \rho(x)\, \left(\sigma(r_i)\right)^2 \tag{4}$$

- $\mathrm{cov}(r_{i1}, r_{i2})$ can also be written as follows by using the residual $\varepsilon(r_i)$ between the numerical simulation result and the predicted value:

$$\mathrm{cov}(r_{i1}, r_{i2}) = \frac{1}{N(x)} \sum_{i=1}^{N(x)} \varepsilon(r_{i1})\, \varepsilon(r_{i2}) \tag{5}$$

Here, $N(x)$ is the number of pairs in which the distance between the two points satisfies the following formula:

An evaluation method for the macrospatial correlation coefficient of tsunami hazards

$$x - \frac{\Delta x}{2} \leq |r_{i1} - r_{i2}| \leq x + \frac{\Delta x}{2} \tag{6}$$

Here, Δx was set to 500 m for a numerical simulation of tsunami wave height and 10 m for a numerical simulation of tsunami inundation depth.

- We can derive the following formula from Eq. (4) and Eq. (5):

$$\rho(x)\left(\sigma(r_i)\right)^2 = \frac{1}{N(x)} \sum_{i=1}^{N(x)} \varepsilon(r_{i1})\varepsilon(r_{i2}) \tag{7}$$

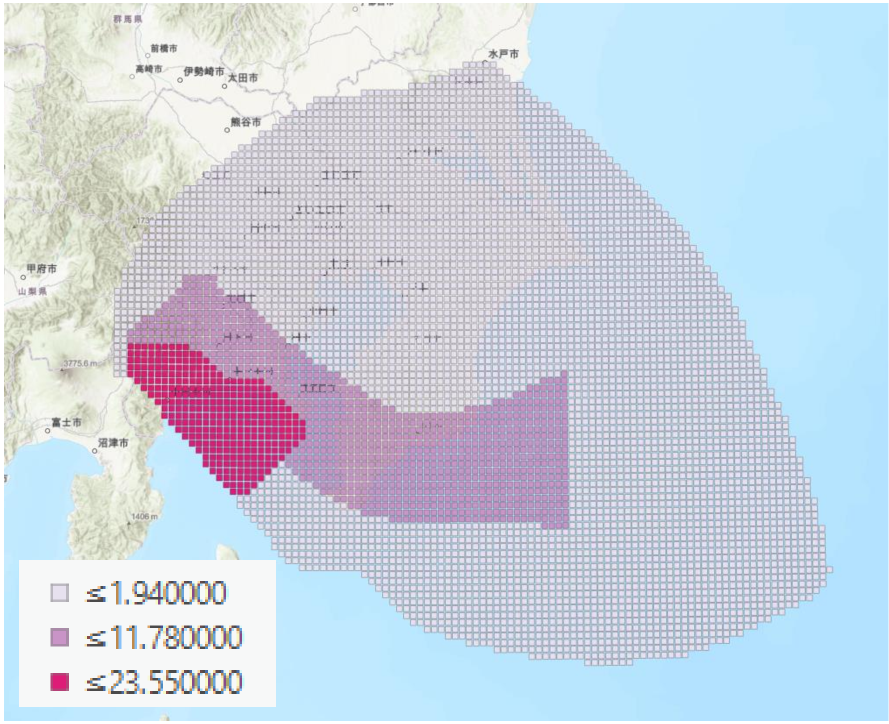
- Finally, the correlation coefficient $\rho(x)$ with respect to the distance x between points 1 and 2 can be evaluated as follows:

$$\rho(x) = \frac{1}{\left(\sigma(r_i)\right)^2 N(x)} \sum_{i=1}^{N(x)} \varepsilon(r_{i1})\varepsilon(r_{i2}) \tag{8}$$

We can evaluate the spatial correlation coefficient $\rho(x)$ of tsunami inundation depth by calculating each variable on the right side of the formula. If we know the spatial correlation coefficient of the tsunami hazard, we can evaluate the spatial correlation coefficient of damage among multiple buildings using the relationship in the next paragraph and perform a stochastic damage evaluation for the building portfolio.

Numerical study of the macrospatial correlation of tsunami inundation depth

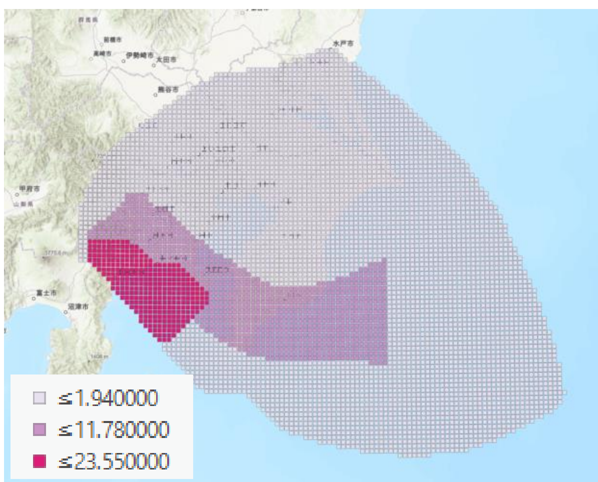
- We first constructed the fault parameters of the earthquake of the Sagami trough, which has a large slip off the Kanto area in Japan, with reference to the earthquake parameter published by the Japan Seismic Hazard Information.
- The moment magnitude (Mw) of the earthquake is 8.7, and there are 6,149 small faults. The slip distribution of the earthquake was set to three levels for the super large slip region (23.5 m), large slip region (11.7 m), and background slip region (1.94 m) to satisfy the Mw 8.7 of the earthquake [8].



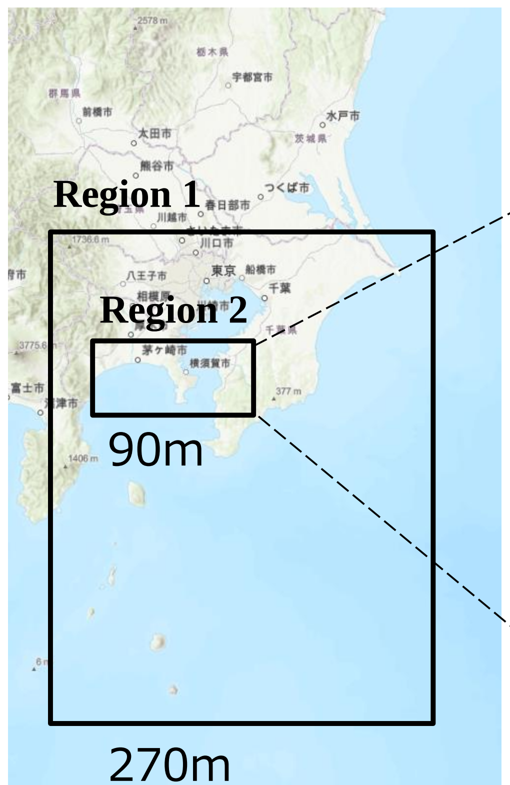
Slip distribution of the Sagami trough（Mw 8.7）

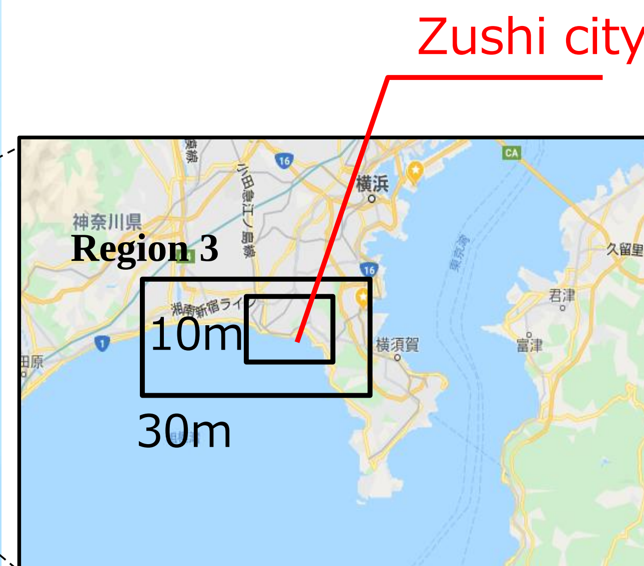
Numerical study of the macrospatial correlation of tsunami inundation depth

- Using the initial water displacement calculated from the earthquake parameters as input data [9], we solved the continuous equation and nonlinear long-wave equations by using the staggered leapfrog method and plane rectangular coordinates.
- We nested the four grid data with mesh lengths of 270 m, 90 m, 30 m and 10 m. We used the topography and roughness data published by the Cabinet Office in Japan and conducted the tsunami numerical simulation for 3 hours after the earthquake occurrence.



Slip distribution of the Sagami trough (Mw 8.7)





Target region of numerical simulation

Numerical study of the macrospatial correlation of tsunami inundation depth

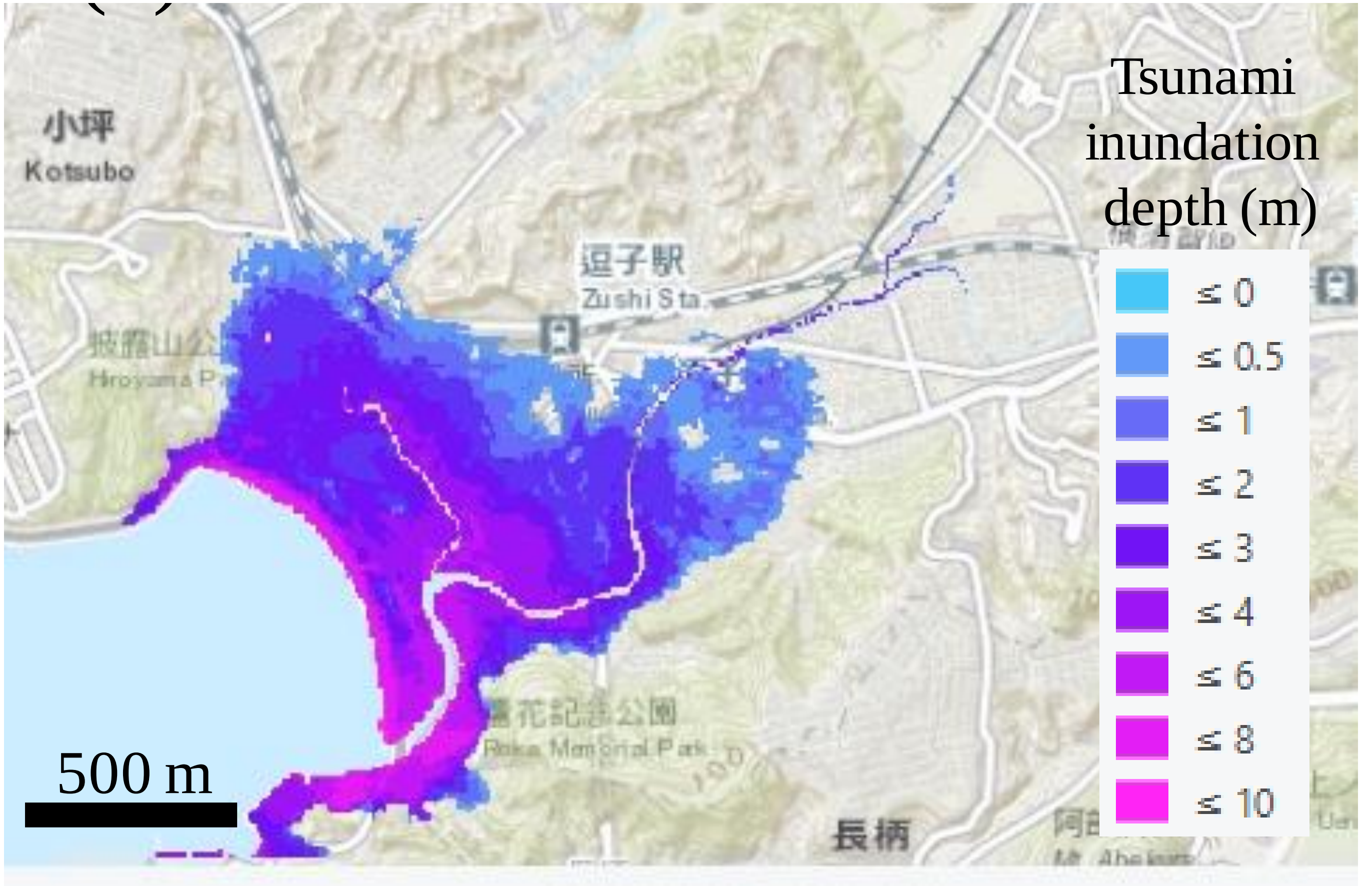
- We used the two-dimensional continuous equation and nonlinear long-wave equations are as follows:

Calculation condition of the numerical simulation

Governing equation	The continuous equation and nonlinear long-wave equations $\begin{cases} \frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \\ \frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left[\frac{M^2}{D}\right] + \frac{\partial}{\partial y}\left[\frac{MN}{D}\right] + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M\sqrt{M^2+N^2} = 0 \\ \frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left[\frac{MN}{D}\right] + \frac{\partial}{\partial y}\left[\frac{N^2}{D}\right] + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}} N\sqrt{M^2+N^2} = 0 \end{cases}$ where η is the water level, *D* is the total water depth, g is the gravitational acceleration, n is Manning's roughness coefficient and *M* and *N* are the flow fluxes in the x and y directions.
numerical integration method	Staggered-leap frog method
Initial condition	Initial water level as evaluated from fault parameters by Okada's (1985) [9] formula
Boundary condition	Open boundry
Coordinate system	Plane rectangler coordinate system
Tide level	T.P. +0.9 m
Mesh size (ΔxΔy)	270 m → 90 m → 30 m → 10 m
Calculation time	3 hours

Numerical study of the macrospatial correlation of tsunami inundation depth

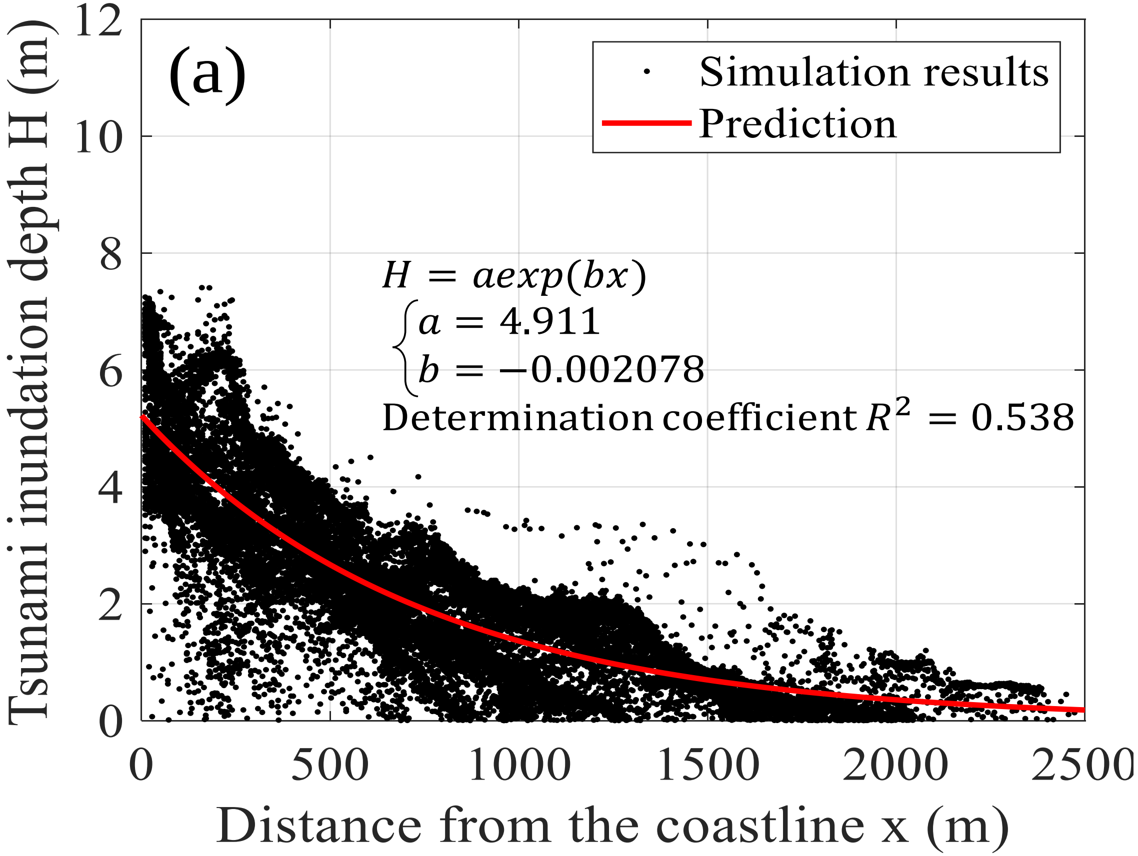
- Below figure shows the results of the tsunami inundation simulation in Zushi city, Kanagawa Prefecture. The maximum tsunami inundation depth was 8.71 m. The results are almost consistent with the inundation area and depth of the tsunami hazard map published by Zushi city.



Tsunami inundation depth distribution in Zushi city, Kanagawa Prefecture

Numerical study of the macrospatial correlation of tsunami inundation depth

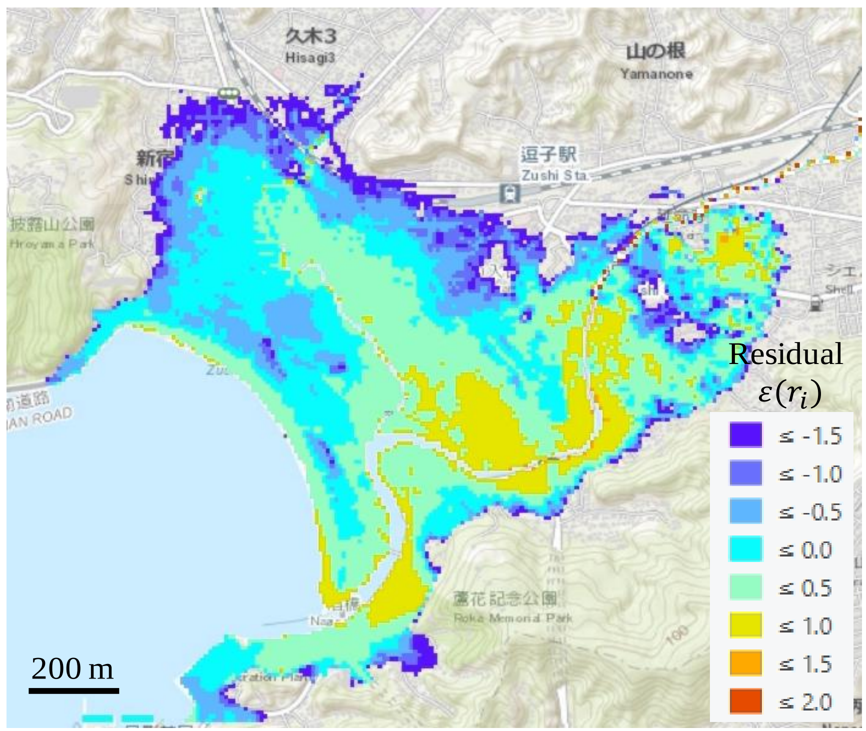
- Below figure shows the relationship between the shortest distance from the coastline and the tsunami inundation depth.
- We regressed the exponential function $H = \mathrm{aexp}(\mathrm{b}x)$ using the least squares method to determine the median values. The regression coefficients were a = 4.911 and b = -0.002078, and the determination coefficient was 0.538.



Tsunami inundation depth attenuation

Numerical study of the macrospatial correlation of tsunami inundation depth

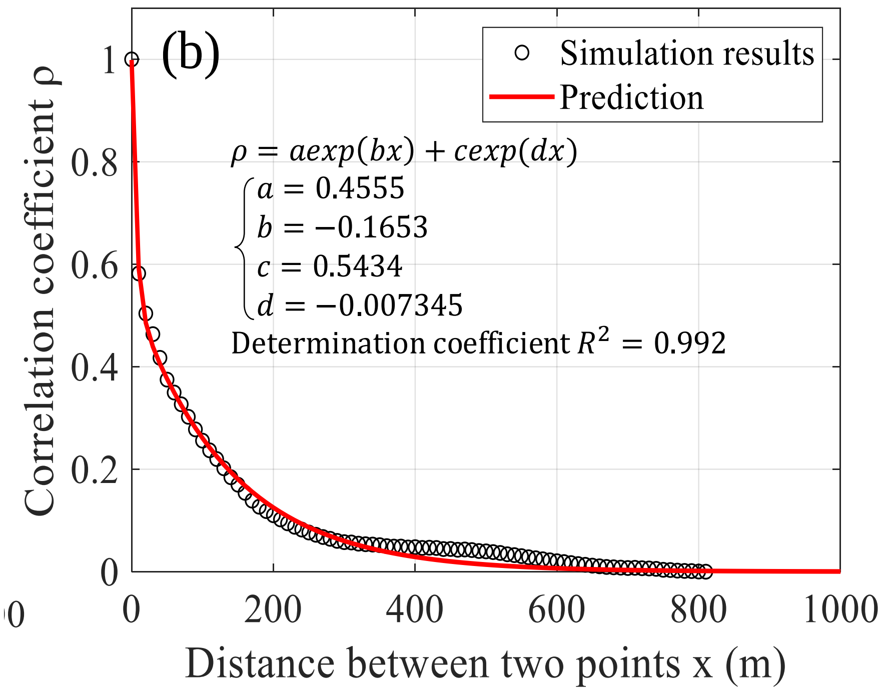
- The standard deviation of the residual $\varepsilon(r_i)$ between the numerical simulation results and the predicted values from the exponential function is $\sigma^2 = 0.794$.
- Below figure shows the spatial distribution of the residual $\varepsilon(r_i)$ between the numerical simulation results and the predicted values. There is an area where the numerical calculation is overestimated along the river; in addition, there is an area where the estimation by the evaluation formula is overestimated at the tip of the run-up.



Spatial distribution of the residual $\varepsilon(r_i)$ between the numerical simulation results and the predicted values

Numerical study of the macrospatial correlation of tsunami inundation depth

- Below figure shows the result of the correlation coefficients between two points. The correlation coefficient decreased by approximately 0.78 at a distance of 1 mesh (10 m), indicating a low correlation of tsunami inundation depth.
- This result occurs because the run-up tsunamis were greatly affected by the bottom friction on the land and attenuated the inundation depth faster compared to the offshore area.
- We regressed the following exponential function using the least squares method:



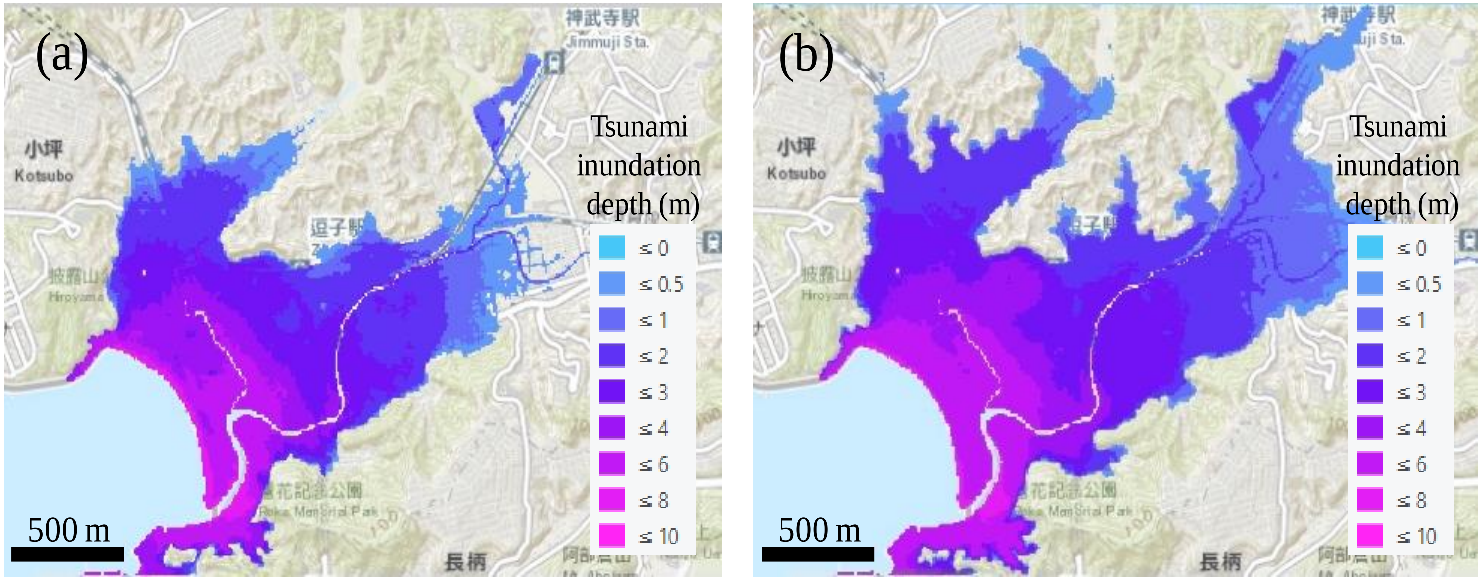
Correlation coefficient of the tsunami inundation depth

$$\rho(x) = a\exp(bx) + c\exp(dx) \tag{9}$$

- As a result, we obtained an evaluation formula with relatively high accuracy. The regression coefficients were a = 0.4555, b = -0.1653, c = 0.5434, and d = -0.007345, and the determination coefficient was 0.992.
- The correlation length was 53.2 m, and the correlation coefficient was equal to 1/e.

Numerical study of the macrospatial correlation of tsunami inundation depth

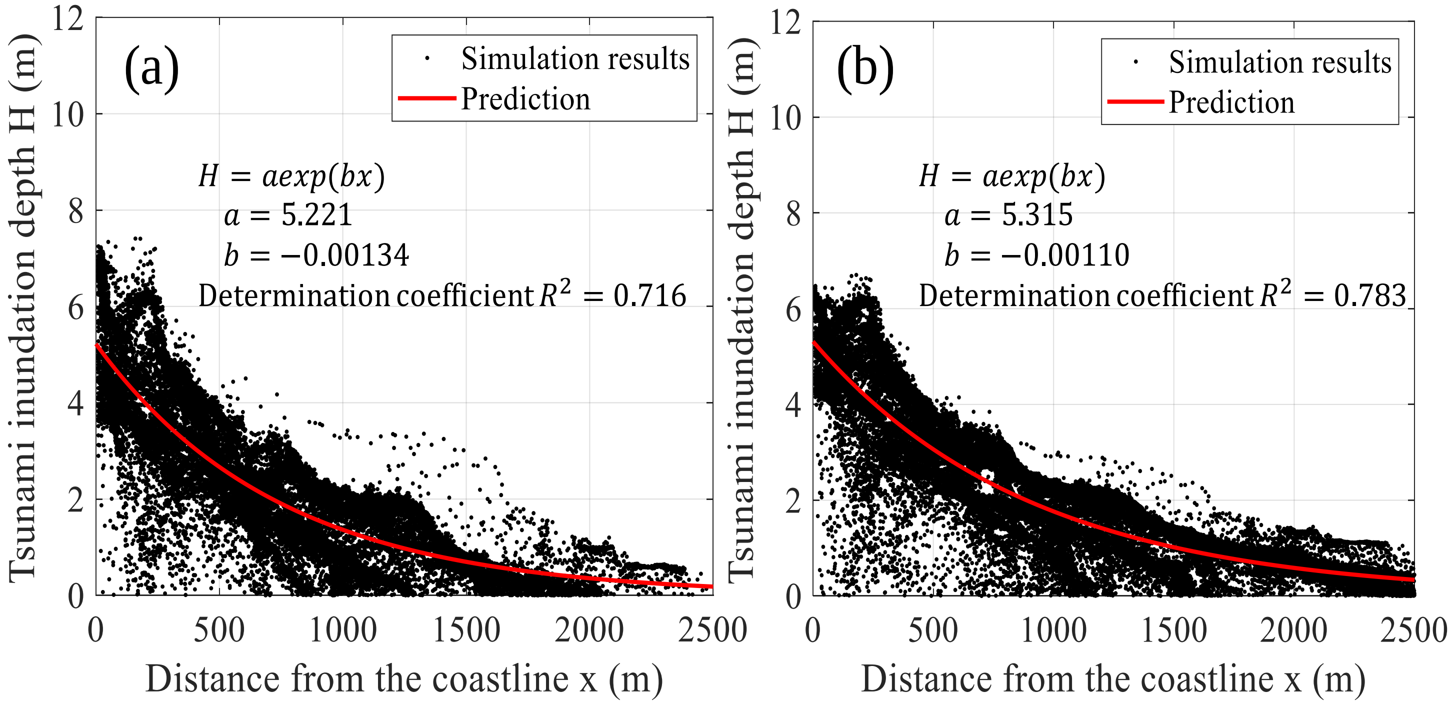
- However, the values of the spatial correlation coefficient could exhibit various fluctuations due to changes in the assumed faults, seabed and land topography.
- In the following, we set the slope of the land to 1/2 or 1/4, we re-evaluated the spatial correlation coefficient without changing the other conditions, and we determined how the values change.
- Below Figs. (a) and (b) show the simulation results of the tsunami inundation depth. When the slope of the land is set to 1/2 or 1/4, the tsunami penetrates and floods into the inland area where the terrain is more complicated. For this reason, the maximum tsunami wave height along the coastline is reduced by approximately 1-2 m.



(a) – Tsunami inundation depth in the case of a 1/2 gradient (b) – 1/4 gradient

Numerical study of the macrospatial correlation of tsunami inundation depth

- Below Figs. 8 (a) and (b) show the results of the relationship between the shortest distance from the coastline and the tsunami inundation depth.
- We regressed the exponential function $H = \mathrm{a}\exp(\mathrm{b}x)$ using the least squares method to determine the median values.
- The standard deviation of the residual $\varepsilon(r_i)$ between the numerical simulation results and the predicted values from the exponential function is $\sigma^2 = 1.309$ in the case with a 1/2 gradient and is $\sigma^2 = 0.825$ in the case with a 1/4 gradient.



(a) – Tsunami inundation depth attenuation in the case of changes with a 1/2 gradient, (b) – 1/4 gradient

Numerical study of the macrospatial correlation of tsunami inundation depth

- Below Fig. (a) shows the result of the correlation coefficients between two points, and Fig. (b) shows the difference in the correlation coefficient from the results of the control simulation without changing the gradient.
- From these figures, the fluctuation of ± 0.05 can be confirmed up to the distance of approximately 400 m between the two points; however, the spatial correlation coefficient hardly changes even if the topographic gradient is changed. This result indicates that we can evaluate the macrospatial correlation coefficient of tsunami inundation depth regardless of the land gradient by using Eq. (9).

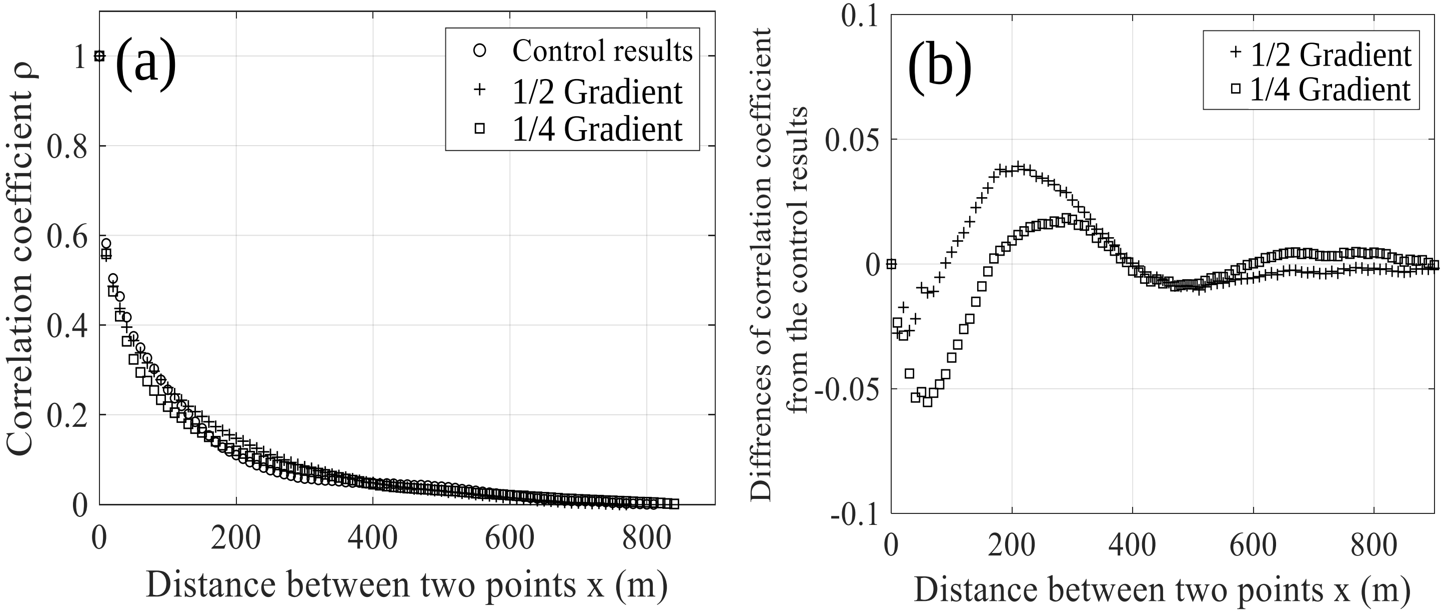


Fig. (a) – Correlation coefficients of the tsunami inundation depth in the case of the control results, 1/2 gradient and 1/4 gradient, (b) – Differences in correlation coefficients from the control results

Conclusions

We determined the following spatial correlation features of tsunami inundation depth as the results of the tsunami numerical experiments using nonlinear long-wave equations:

- The macrospatial correlation coefficients of the tsunami inundation depth in the tsunami run-up region have a tendency to decrease as the distance increases.
- The correlation coefficient decreases by approximately 0.78 at a distance of 10 m, indicating a low correlation of the tsunami inundation depth. This result occurs because the run-up tsunamis on the land are affected in various ways by the bottom friction and attenuate faster compared to those in the offshore region.
- The macrospatial correlation coefficient of the tsunami inundation depth can be evaluated by the exponential function (Eq. (9): $\rho(x) = aexp(bx) + cexp(dx)$) regardless of the land gradient.

The results of this study can be used for a probabilistic tsunami risk assessment of real estate building portfolios by parties such as large companies, insurance companies, reinsurance companies, and real estate agencies.

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