# 論文の内容の要旨

論文題目　Numerical Assessment of Multi-hazard Vulnerability in Tokyo Bay Using an Integrated Coastal Ocean and Drainage Pipe Model
（沿岸海洋・排水管統合モデルを用いた沿岸複合災害による東京湾沿岸の脆弱性評価）

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## 1. Introduction

Since joint impacts of the three hazards (storm surge, tsunami, and river flood) have not been investigated, in this study, the assessment of inundation vulnerability caused by them is the research target. Inundation simulation is a widely used and straightforward way in coastal vulnerability assessments. However, it is computationally expensive, and considering an increase in the number of cases in the multiple hazard analysis, it is necessary to develop an efficient method to identify overall vulnerability and to screen representative scenarios for detailed analysis. For this purpose, an efficient method was proposed using an estimated overflow volume without computing inundation, which was validated by comparing with inundation simulation. In addition, although inundation period is one of the most important parameters for the vulnerability assessment, drainage through drainage pipes has often been ignored. To consider this drainage, a drainage pipe model was implemented in FVCOM for the first time. The efficient method was then applied to multi-hazard vulnerability assessment. The worst multi-hazard case and the resultant vulnerability was identified. The difference between single hazard and multi-hazard vulnerabilities including moderate multiple hazards and worst single hazard was also discussed. The role of drainage system in local coastal flood was investigated using the integrated model. Finally, some lessons for better disaster prevention and prediction were extracted.

## 2. Methods and Data

Considering the advantages and limitations among different coastal ocean models, FVCOM is adopted as the coastal ocean model. Several reanalysis datasets are for wind and pressure fields, including the ERA-Interim (ERA-I), NCEP-DOE reanalysis II, and parametric typhoon models. ERA-I and Mitsuta–Fujii formula (M–F model) were used because both of them were more consistent with the measured data in Tokyo Bay. By introducing the radius of $R_\mathrm{b}$ and the transition bandwidth of $W_\mathrm{b}$, a generalized hybrid method is proposed where the M–F model is applied in the $0 \leq \mathrm{r} \leq R_\mathrm{b}$ region and switching to ERA-I in the $r \geq R_\mathrm{b} + W_\mathrm{b}$ region (outer region of the transition band) while interpolating the two models in the transition band of $R_\mathrm{b} < r < R_\mathrm{b} + W_\mathrm{b}$. The tsunami initial water surface condition is calculated using Okada model.

The mixed flow drainage pipe model is based on the Saint-Venant equations. The four-point weighted implicit finite difference scheme (Preissmann, 1961) is used as the numerical method. Newton-Raphson method provides a means for correcting the trial values until the residuals are reduced to a suitable tolerance level, which is used to solve the discretized equations. The information exchange between FVCOM program and drainage pipe model is based on the original groundwater function. At every drainage pipe model running step, the "groundwater" flux ($\mathrm{m}^3/\mathrm{s}$) is updated by the drainage pipe program depending on the flow condition in the drainage pipes.

A simple approach using overflow volume to measure coastal vulnerability is introduced. By applying Bernoulli energy equation and critical flow condition between the coastal area and dike, the overflow depth, and the overflow velocity could be solved, and then, by integration in total time steps, the overflow volume can be estimated.

## 3. Model Validation

Owing to the substantial effect on Tokyo Bay, especially the coastal areas in Chiba prefecture, storm surges caused by Typhoon 8506 and Typhoon 1115 are selected as the validation study cases for the storm surge model. Results show that hybrid method II can be easily tuned for each storm surge cases using only ERA-I and M–F data with high accuracy.

A commonly used Storm Water Management Model (SWMM) is adopted to demonstrate the model capability. The model comparison contains two parts, the first one is for single pipe scenarios, including the circular cross-section pipe and trapezoidal shape pipe, the second part is for a drainage pipe network, including surcharged flow condition and open channel flow state. Results show that the developed model is consistent with SWMM. The overflow inundation in Kisarazu Port during the 2011 Tohoku earthquake tsunami is used as the validation case to demonstrate the reliability of the modified FVCOM and drainage pipe model. According to the previous study made by Sasaki et al. 2012, in Kisarazu Port, the inundation was not attributed to overflowing the parapet of the seawalls but rather flooding through the side ditch when the water level rose. It can be concluded that the integrated model could reproduce the pipe-induced overflow well.

The vulnerability measurement method using overflow volume is validated by comparing with inundation computation through a series of numerical experiments using different dike heights. Results show that the overflow volume estimated by the adopted approach is consistent with inundation simulation method when free overflow type is dominant.

## 4. Multi-hazard Vulnerability Assessment

### 4.1 Multi-hazard scenarios

The typhoon cases prepared by Chiba Prefecture Storm Surge Committee (2018) are adopted. The earthquake fault area is calculated in Okada (1985) model using a combination of the fixed rupture length and width of 50 km × 25 km rectangular sub-faults. The discharge, salinity and temperature of three rivers (Arakawa River, Nakagawa River, Edogawa River) are given as constant values. The discharge value is about 50 years return period.

### 4.2 Vulnerability of Tokyo Bay

The levels of the vulnerability have been determined as seven classes: “I” (grey), “II” (purple), “III” (blue), “IV” (green), “V” (olive), “VI” (orange), “VII” (red), which are divided according to the overflow volume. Level “VII” (red) represents that the part of coastline under the hazard scenario is the most vulnerable, and Level “I” (grey) represents that it is the least vulnerable.

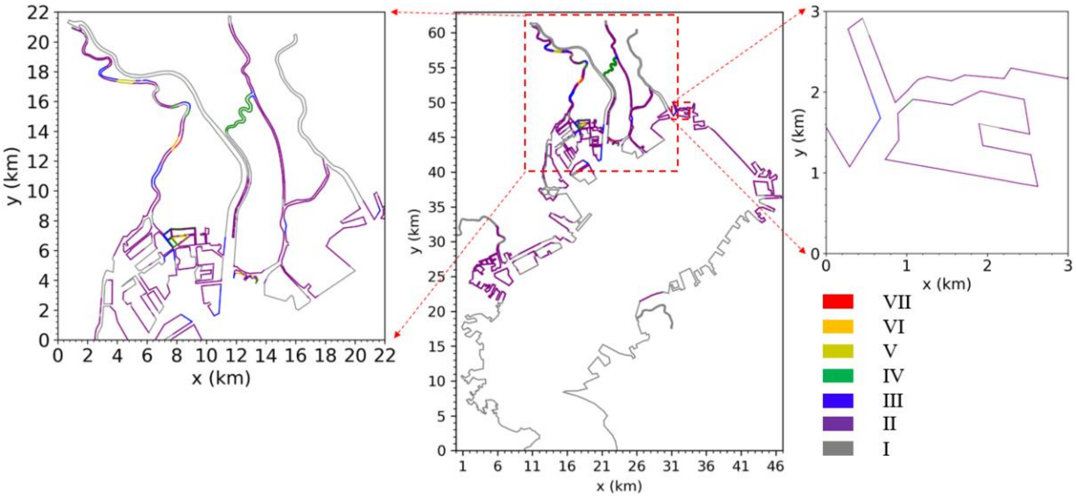

Figure 1. Vulnerability map of overflow volume for worst storm surge, ToKai-ToNankai earthquake tsunami and river flood cases

### 4.3 Effect of drainage pipe system

The integrated FVCOM and drainage pipe model is applied to a local region for detailed inundation simulation combining the drainage pipe system. Funabashi Sanbanze Seashore Park is selected as the study area. Results show that the drainage system could contribute to the decrease of inundation period under normal conditions. However, whether the drainage system could still work well under accident conditions, e.g., garbage accumulation, needs more investigations.

## 5. Discussion

A comparison between a multi-hazard case and a case linearly superposing each single hazard case extracted from the multi-hazard case was conducted. It could be found that the difference varies spatially significantly and it is larger in ports and river channels than in other coastal areas. In most coastal areas, the anomaly of superposing case is greater than that of concurrent case, but in some places, concurrent case results in larger anomalies than superposing case. The comparison of the multi-hazard case (moderate storm surge and moderate tsunami) and the single hazard case (worst storm surge) is also conducted. The return period of the storm surge and tsunami is around 5 years and 200 years, respectively, while the return period of the worst storm surge is more than 1000 years. It could be found that in the worst storm surge case, anomalies are larger than those of moderate multi-hazard case.

Based on the research, consideration of upgrading the dike heights in areas where superposing method underestimates the multi-hazard anomalies may need to be considered. Incorporation of drainage system in the current early-warning system is also needed.

## 6. Conclusions

The method without computing inundation is demonstrated to be applicable for measuring inundation vulnerability when free overflow happens. The performance of the implementation of drainage pipe model in FVCOM is found to be superior to the original FVCOM regarding the reproducibility of pipe overflow. The drainage system is important in local coastal flood for reducing the inundation volume and water logging period. The hybrid method combining reanalysis meteorological data and a parametric typhoon model is found to be more accurate than each of them for reproducing wind and atmospheric pressure field, and for storm surge hindcasting.

Compared to single hazard like only tsunami, in multi-hazard case, e.g., concurrent tsunami and storm surge, the tsunami shoaling process is changed because the anomaly difference of superposing case and concurrent case varies. In most coastal areas, the anomaly of superposing case is greater than that of concurrent case, but in some places, concurrent case results in larger anomalies than superposing case, which demonstrates the interaction between storm surge and tsunami. The anomaly difference of superposing case and concurrent case is basically larger in ports and river channels than in other coastal areas. Worst storm surge would cause larger anomalies than moderate multiple hazards, in which the return period of these two types of hazards is basically identical.

## References

Sasaki, J. *et al.* Behavior of the 2011 Tohoku earthquake tsunami and resultant damage in Tokyo Bay. *Coast. Eng. J.*, **54**(1), 2012.

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