

QUANTITATIVE EVALUATION OF DISASTER VULNERABILITY AND RISK BASED ON PREDICTED EVACUATION TIME

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BASED ON PREDICTED EVACUATION TIME
(避難所要時間に基づいた災害脆弱性とリスクの定量的評価)

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論 文 内 容 の 要 旨

Over the past decades, the intensity and frequency of natural disasters have increased. Globally, natural disasters have dramatic implications for human lives lost, well-being damaged, and economic costs. Even though these disasters cannot be prevented entirely, many disasters are predictable to some extent. In this sense, an appropriate and effective evacuation can help minimize the disaster's impact and mitigate human casualties. Local municipalities are thus expected to issue the appropriate evacuation notifications to the appropriate region at the appropriate time. However, there were cases where some residents did not evacuate promptly due to improper evacuation notifications and the lack of trust in the issued notifications. Therefore, providing quantitative disaster vulnerability and risk assessment oriented to the evacuation process is essential to supporting appropriate and trustworthy evacuation decisions. For this reason, the approaches to answering the following important issues are studied in this thesis:

- 1) How much time does it take to reach evacuation shelters?
- 2) When and where more evacuation preparation is needed?
- 3) When and who needs to evacuate as soon as possible?

The primary objective of this study is to provide quantitative and visualized evacuation information for individuals and authorities. Regarding vulnerability assessment oriented to evacuation preparation, this study aims to help individuals and authorities make targeted planning and preparedness before disasters occur, so as to be ready to evacuate when necessary, and ultimately improve evacuation efficiency. Regarding risk assessment oriented to evacuation decision-making during a disaster, this study aims to facilitate individuals' awareness to understand their situation, as well as provide authorities with a basis to make quick and right evacuation decisions, and ultimately mitigate the impact of the disasters to protect lives and property.

The thesis consists of the following chapters.

Chapter 1 introduces the background of disaster vulnerability and risk assessment from an evacuation perspective, highlights the key issues and existing problems, and presents the scope and objectives of this study. Then, the overview and framework of this thesis are given.

Chapter 2 gives an overview of existing evacuation and related research. The following three issues are emphasized: 1) Situation of evacuation decision-making for authorities and individuals, 2) Research on evaluation of disaster vulnerability and risk, and 3) Research on travel time estimation on evacuation route.

Chapter 3 develops the models to estimate the required travel time on evacuation routes during normal times. Estimating the required travel time is crucial for evacuation preparation and management, considering factors such as the occurrence of congestion, road width, and intersection turns. In many previous studies, travel time estimation just applied a mean speed based on road grade. However, the driving speed could vary

significantly among different driving conditions. Even during peak hours, the travel speed on roads prone to congestion could be much lower than the mean value. Thus, it would be inaccurate and dangerous if the required evacuation time was based on the mean speed. In this chapter, both region-specific models with high accuracy and out-of-region models with wide applicability are developed, with Machine Learning as the core. Eight regions comprising city, ward, and rural areas, Adachi, Joso, Itoshima, Katori, Kakogawa, Takahashi, Maizuru, and Toho, are selected as the research areas. As a result, all region-specific models achieved high accuracy, with an average Mean Absolute Percentage Error (MAPE) of only 6.23%. In addition, the out-of-region also demonstrated good performance with an average MAPE of 10.59%, without collecting training data from the application city. These models offer a scientific tool and foundational assurance for acquiring the required evacuation time on various routes across different regions.

Chapter 4 presents the approach to quantifying disaster vulnerability based on the predicted evacuation time and the accessibility at the pre-disaster stage. In an emergency evacuation, the capacity and layout of infrastructures such as road networks and shelters significantly influence its success. Locations requiring longer times to arrive at evacuation shelters during normal conditions would be more vulnerable to evacuation delays and even evacuation failures. Thus, understanding these factors in advance allows for better evacuation preparation and response to impending disasters. In this chapter, static vulnerability is assessed by predicting the normal travel time to the nearest evacuation shelters. Following the static assessment, the floating population estimation model is developed using the Deep Neural Network (DNN) algorithm. Subsequently, the dynamic floating population demand and the shelters' capacity are additionally considered to assess the dynamic vulnerability of individuals, shelters, and roads. Then, the proposed approaches are applied to Joso City in Japan. As a result, the dynamic population prediction model successfully forecasted the floating population across different ages and genders, with an average error of only 0.92 people per 250m grid per type. Furthermore, the proposed static and dynamic vulnerability assessment clearly illustrated the vulnerable areas, buildings, shelters, and roads that pose challenges to an efficient evacuation at various times. The results and maps provided clear answers to the question, "When and where more evacuation preparation is needed?"

Chapter 5 presents the approach to quantify spatial-temporal disaster risk based on the estimated evacuation time, considering the potential challenges during the whole process at the disaster stage. In this chapter, the flooding disaster is selected as a case scenario. First, a flooding inundation estimation model is developed based on the Rainfall Runoff Inundation (RRI) model. Then, the individual evacuation risk is quantified by the estimated evacuation time during disaster conditions. For vehicle evacuation, the evacuation time is estimated by considering the impact of flooding hazard evolution on route detours and traffic congestion on time delays. For pedestrian evacuation, the reduction of walking speed caused by flooding hazards, road slopes, age, gender, and tiredness are considered. Then, the region evacuation deadline and the corresponding evacuation schedule are determined for authorities at the disaster stage. Herein, the 2015 heavy rainfall event that occurred in Joso City is used to carry out a case study. As a result, the proposed approach explicitly reflected the time-varying risk, with up to 59.50% of buildings assessed as having the highest risk: no evacuation route. The regional evacuation deadlines were also specified. These results and maps demonstrate the practicality and applicability of the proposed approach under a flooding scenario, answering the question, "When and where should evacuation occur as soon as possible?"

Chapter 6 summarizes the results and major contributions of the study, and also makes recommendations for future research.