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# Estimation of fatality ratios and investigation of influential factors in the 2011 Great East Japan Tsunami

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ABSTRACT

The 2011 Great East Japan earthquake caused a wide-ranging and devastating tsunami that reached a maximum height of 40 m and caused 19,000 fatalities, particularly along the Tohoku coast of Japan. The purpose of this study is to present a new estimation of the fatality ratios based on tsunami arrival times and evacuation perspectives and to present lessons learned for future tsunami loss assessments in other areas. In addition, this study investigates influencing factors, such as age, gender, and two coastal topography types (Sanriku ria-coast and Sendai plain). The fatality ratio is calculated by the number of fatalities divided by the population at the town scale along the shoreline, and the tsunami arrival time is calculated using the TUNAMI model with nesting grids of 1350 m, 450 m, 150 m, and 50 m. Then, linear and nonlinear regression analyses are performed to develop a relationship between the fatality ratios and tsunami arrival times. For different topography types, different distributions of fatality ratios with tsunami arrival times were observed; the fatality ratios of the Sendai plain were generally higher than those of the Sanriku ria-coast for the same arrival time. Based on the results, a strong inverse correlation between the fatality ratios and the tsunami arrival times was found in the Sendai plain, while the Sanriku ria-coast must be divided into two groups to obtain this correlation. Furthermore, other influencing factors, such as age and gender, contributed to differences in estimating the fatality ratios.

## 1. Introduction

### 1.1. Background and previous studies

The 2011 Great East Japan tsunami was generated by a magnitude 9.0 earthquake and caused widespread damage, including a large number of fatalities, whereas fatalities caused by the earthquake alone were less severe. The Tohoku coast includes two main coastal topography types characterized by ria and straight coastlines (Sanriku ria-coast and Sendai plain), as shown in Fig. 1. Leelawat et al. [1] found a high correlation between the coastal topography type and inundation depth for the 2011 tsunami and also explained the potential variables that relate to the damage level of buildings. Suppasri et al. [2,10] gathered data on more than 250,000 surveyed buildings to determine the causes of the building damage, which includes a data set of nearly complete damage. The number of fatalities increased as the destruction of a building increased. Based on past studies of fatalities in the 2011 tsunami, factors that increased or reduced the fatality ratio, which is defined as the number of fatalities divided by the population, can be classified into tsunami characteristics for a specific area and personal characteristics from an evacuation perspective [3]. Yun and Hamada [3] show that differences in the coastal topography types lead to differences in the tsunami characteristics (e.g., tsunami heights and tsunami arrival times), and personal characteristics (e.g., age, gender, preparedness, and occupation) influence evacuation behaviour and survival based on 1153 interviews of witnesses. Although the tsunami height is a key factor affecting fatalities, the tsunami arrival time is also a critical factor for the evacuation of people to safe areas. In addition to 150 survivor interviews, Ando et al. [4] studied the causes of death and indicated that the effect of tsunami defenses may have been harmful due to misunderstanding of the mitigation effects; the decision to evacuate was rarely influenced by locally official warnings but strongly associated with self-warning based on experiences of previous tsunamis. Goto [5] studied on evacuation features of the residents in two city areas and found that the effect of no tsunami evacuation drills was responsible for the failure to evacuate at least 20% of the residents. This

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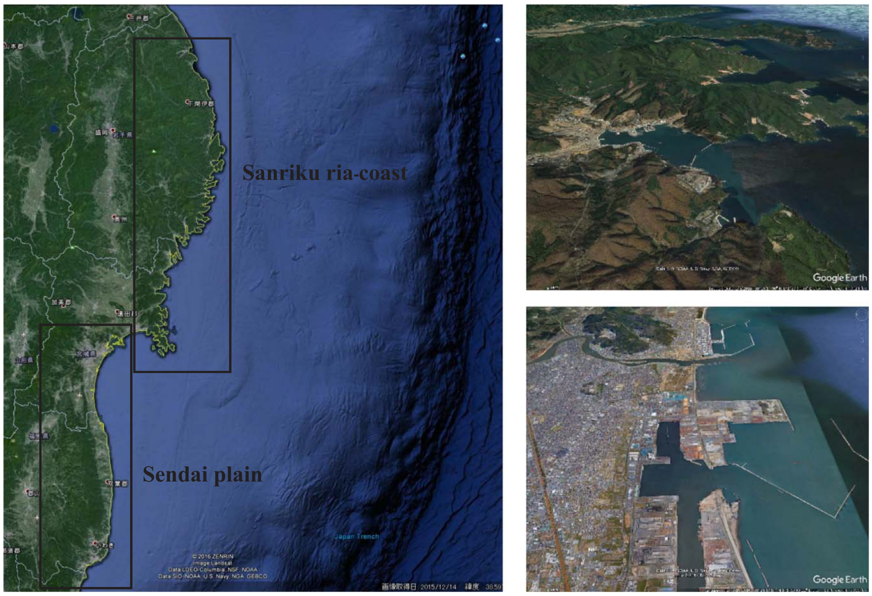


**Fig. 1.** Coastal topography type along the Tohoku coast of Japan (Google Earth).

study aimed to propose a model that can estimate the fatalities from influencing factors to assist local governments and insurance companies with future tsunami loss assessments.

Based on previous events, Sugimoto et al. [6] presented a tsunami human damage prediction method to estimate the loss of life that utilized numerical calculations and geographic information system. Koshimura et al. [7] developed a method, which is based on a numerical model that considers the effects of hydrodynamic forces on the human body, to estimate a number of fatalities that may occur during evacuation in an inundated area. Marchand et al. [8] developed a capable model focusing on the coastal defense measures to quantify the potential damages and fatalities associated with the 2004 Indian Ocean tsunami in Banda Aceh, Indonesia. Yeh [9] introduced a simplified model of a human body using anthropometric data and demonstrated the tsunami fatality predictions vary with ages and genders. Suppasri et al. [2,10] proposed a method to quantify a tsunami risk to the coastal population in the Indian Ocean and the South China Sea based on the 2004 Indian Ocean event.

### *1.2. Objectives of this study*

Since fatality ratio is the number of fatalities divided by the population of an inundated area, the size of the sample area directly influences to the calculation of the fatality ratios. Previous studies have discussed fatality ratios of large areas, which is not totally inundated. Such ratios can include populations falling outside of the tsunami inundation zones and can present inconsistencies because of the use of a large area. These assumptions can lead to errors when developing relationship models between fatalities and influential factors. In addition, several past studies have focused on tsunami height or inundation depth as the main factors affecting fatalities [11,12,3]. This study presents a relationship model between fatality ratios and tsunami arrival times based on survey data collected at the town scale for each affected coastal area and investigates the influence of two coastal topography types that not only controlled tsunami characteristics [13] but also related to experience from historical events. Survey data on fatalities at the town scale were collected from the reconstruction support survey archive [14], which covers the affected area in the 2011 tsunami event. In the present study, both linear and nonlinear regression analyses were performed, and several equations for estimating the fatality ratios from different definitions of tsunami arrival times were developed. The results of this study are expected to facilitate the estimation of fatalities based on other considerations, such as age and gender, and to predict fatality ratios for future tsunamis in other areas, that may have shorter arrival times than those of the 2011 Great East Japan tsunami.

## 2. Method of calculation

### *2.1. Numerical tsunami simulation*

To obtain the tsunami arrival times for different coastal towns, a numerical tsunami simulation was performed using the TUNAMI model [15] with nesting grids of 1350 m, 450 m, 150 m, and 50 m, as shown in Fig. 2. Tsunami arrival times were calculated within a 50-m grid along the shoreline of each town.

The TUNAMI model was originally developed at Tohoku University to simulate tsunami propagation and inundation based on a staggered leap-frog scheme using nonlinear theory. To simulate tsunami propagation and inundation, the initial seafloor deformation was calculated using a rectangular fault model [16] and the fault parameters of the 2011 Great East Japan earthquake based on the 55-subfault model [17], as shown in Fig. 3. The towns examined in this study were selected based on the fatality data collected from an insurance company. The tsunami arrival times were calculated using the TUNAMI numerical simulation for 46 towns along the Sanriku ria-coast from Misawa city in the Aomori prefecture to Iwate prefecture until Ishinomaki city in the Miyagi prefecture and for 17 towns along the Sendai plain from Ishinomaki city to Kitaibaraki city in the Ibaraki prefecture.

Definitions in the following explanation are based on three components of the tsunami arrival time [18]. The definition of “Initial” refers to the level of a tsunami threat that can harm people [19].

- Initial: tsunami arrival time when the inundation depth is equal to or greater than 0.5 m
- First: tsunami arrival time when the first peak in the tsunami flows occurs
- Max: tsunami arrival time when the maximum inundation depth is reached

### *2.2. Validation of the tsunami arrival time*

Table 1 shows the tsunami arrival times collected from survey data determined from stopped clocks and eyewitness accounts after the 2011 Great East Japan tsunami collected by Muhari et al. [20] and TTJS group [21]. Since relatively insufficient survey data were collected,