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Simulated tsunami evacuation behavior of local residents and visitors in Kamakura, Japan

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ABSTRACT

Currently, it is believed that evacuation is the most effective method of protecting lives from tsunamis, in particular after the events of the 2011 Tohoku Earthquake Tsunami. In many coastal areas tsunamis pose a threat not only to local residents, who know the area well, but also to visiting tourists, and thus it is important to consider both these groups when preparing evacuation plans. However, while numerous studies and simulations on tsunami evacuation have been made, research focusing on the influence of visitors on evacuation processes is limited. To clarify this the authors developed an agent-based tsunami evacuation model which considers the different behavior of local residents and visitors, which can estimate the evacuation time, number of individuals reaching each evacuation area, the location of bottlenecks and the number of casualties. The model was applied to study the case of Yuigahama Beach, Kamakura, Japan, with results indicating that the behavior and number of visitors have a significant impact on evacuation processes, especially the location of bottlenecks and the number of casualties. Results also show that heavy congestion will occur during evacuation in places where there are many visitors and thus, in such a situation, the decrease of the moving speed owing to the congestion needs to be appropriately taken into account to simulate the evacuation process. It can be concluded that reducing congestion (i.e., widening roads, guiding visitors to less congested roads) is a crucial countermeasure for a sightseeing location to reduce the casualties that can result from a tsunami.

1. Introduction

The 2011 Tohoku Earthquake Tsunami devastated large parts of Japan's northeastern coastline and claimed over 15,800 lives [23]. During this event coastal infrastructure such as breakwaters, seawalls and coastal dykes sustained significant damage [20,21]. Although it was recognized that reinforced concrete buildings were often strong enough to withstand tsunami forces [7], many of these were severely damaged and some were washed away [21,24]. One important lesson that can be drawn from this devastating tsunami is that it is difficult to protect coastal areas and human life from extreme tsunamis using only hard measures (e.g., coastal dykes, seawalls, buildings). Following this event the Japanese Coastal Engineering Community started classifying tsunami events into two different levels based on their level of severity and intensity (as reported by Shibayama et al. [30]). Level 1 events have a return period of several decades to 100 years or more and generate relatively lower inundation heights (typically less than 7–10 m). Level 2 events are less frequent, with return periods ranging from a few hundred to a few thousand years. The tsunami inundation heights would be much higher (typically, over 10 m), possibly even reaching 20–30 m in height. The construction of hard measures to protect human life and property is impractical for the case of Level 2 events, given the expense involved [6]. Therefore, evacuation is the most effective way to protect against the loss of human life for Level 2 tsunamis [30]. This in turn has highlighted the need for further research into designing and establishing good evacuation plans.

For some coastal areas not only local residents but also visitors are at risk of suffering the consequences of a tsunami. Generally speaking, visitors have less knowledge than local residents about the location of tsunami shelters and the safer routes to reach them. Their presence and behavior should therefore affect evacuation time, the number of evacuees reaching each shelter, the locations of bottlenecks and casualties. Thus, in order to establish effective evacuation plans it is important for disaster risk managers to consider both local residents and visitors. One effective way of investigating human behavior under extreme conditions is to conduct evacuation drills. Through such drills, not only is it possible for participants to learn evacuation routes and the location of safe areas [35], but disaster risk managers can also clarify

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other important issues regarding evacuation, such as total evacuation time, the required capacity of tsunami shelters and the locations of congested roads. However, it is often difficult to obtain the collaboration of all local residents and visitors regarding participating in evacuation drills. Therefore, tsunami evacuation simulations, especially those utilizing agent-based models, are helpful to investigate evacuation behavior during extreme tsunami events and establish appropriate evacuation plans.

Agent-based modeling is a technique for simulating the behaviors and interactions of a large number of individual agents. In an agent-based model, each agent is modeled as a decision-making entity that decides its own movement (e.g., where to go, how fast to move), following user-defined rules [2]. While each agent moves individually, the researcher can trace a macroscopic response, which is generated by the interactions between these individual agents [5]. To date, agent-based modeling has been utilized to analyze the evacuation process during emergency situations, including not only tsunamis but also earthquakes, fires and floods. For example, Pan et al. [28] proposed an agent-based model for simulating an emergency evacuation from a building by considering crowd behavior, such as competitive behavior, queuing and herding. Liu et al. [14] introduced an agent-based framework that connects human behavior and building damage caused by an earthquake and thereby investigated the impact of building damage on the behavior of those evacuating. Dawson et al. [2] presented a methodology integrating a hydrodynamic simulation with an agent-based model of human evacuation from a flood and used it to evaluate the effectiveness of flood management measures. For the case of tsunami evacuation, Mas et al. [18] developed an agent-based tsunami evacuation simulation model, named *TUNAMI-EVAC1*, in which tsunami inundation simulation and human behavior are integrated. The novelty of their model is that it can consider different evacuation start times among evacuees and interaction effects between pedestrians and cars. Several case studies of their model can be found in Mas et al. [16–18]. Wang et al. [36] investigated the impact of evacuees' behavior (e.g., different evacuation start times, different choices of evacuation methods (walking, automobile), different moving speeds of evacuees) on the estimation of the number of casualties using an agent-based approach. Other recent developments and applications of an agent-based modeling for tsunami evacuations can be found in Makinoshima et al. [15] and Mauro et al. [19].

Another well-known approach for simulating tsunami evacuations is to use geographic information system (GIS). For example, Sugimoto et al. [32] analyzed the effects of early evacuations on the estimation of casualties by employing a GIS approach. Wood and Schmidtlein [38] and Wood and Peters [37] used the least-cost-distance (LCD) model implemented in GIS to assess variations in population exposure to tsunamis. An integrated GIS model with multi-decision making was proposed by Tsai and Yeh [34] to determine the optimal locations for evacuation shelters. However, although GIS approaches can aggregate much information related to tsunami evacuations, they are not able to consider individual human behavior and the interactions of individuals under emergency situations. Moreover, agent-based modeling can provide valuable insights into evacuation processes and human behaviors that will induce jamming or casualties [17].

As mentioned above, an agent-based modeling is a helpful tool for simulating disaster emergency evacuations (Mundai et al., 2012), and thus the number of studies related to agent-based modeling and tsunami evacuations have increased in recent times [17]. However, to the authors' knowledge there are no studies that have focused on the effects of the behavior of visitors on evacuation. Some coastal areas are famous sightseeing locations, and if a tsunami takes place during daytime there are likely to be many visitors in the area. In order to minimize the loss of human life and develop effective evacuation plans it is necessary to investigate the impact that the behavior of visitors may have on evacuation processes. To address this gap in scientific knowledge in the present work the authors propose an agent-based tsunami evacuation model in which the differentiated behavior of local residents and visitors is taken into account. In order to investigate evacuation processes in a realistic manner the model proposed can consider many important aspects of evacuation, such as the change in moving speed depending on crowd density, change in destination depending on the capacity of a shelter, and different starting times for evacuation. The evacuation model was coupled with a tsunami inundation simulation model to estimate the number of casualties for a range of different scenarios. The model was then applied to Yuigahama Beach in Kamakura City, Japan, as it is considered one of the areas that is most vulnerable to tsunamis in Japan, and is also an important sightseeing destination.

The paper is structured as follows. In the following section details of the proposed agent-based evacuation model are given. In Sections 3 and 4, the model is applied to Yuigahama Beach. Finally, in Section 5 significant findings and venues for future research are discussed, and some conclusions are outlined.

2. Agent-based tsunami evacuation model

In the present study an agent-based tsunami evacuation model that considers the differentiated behavior of local residents and visitors was constructed using the agent-based modeling platform *Artisoc* [39]. This modeling platform, *Artisoc*, developed by KOZO KEIKAKU ENGINEERING Inc. [12], provides users with many functions, which are useful to depict human behavior, and helps to visualize the simulation results. The programing language used in *Artisoc* is similar to Visual Basic (VB). It can also use GIS data as input to construct the road network. Using *Artisoc*, users can easily define the rules of agent's movement and investigate complex human behavior. In the model a road network can be defined by using node points and connected links, as shown in Fig. 1. Agents move along the links, and every time they reach node points they decide which link they will go to next.

2.1. Choices of evacuation routes

In order to investigate the impact of the behavior of visitors on the evacuation process, two types of agents, namely local residents and visitors, are included in the proposed model. Local resident agents are assumed to know the location and shortest route to the closest evacuation areas from the point in which they are situated at the beginning of the simulation. The closest evacuation places and the shortest routes for each agent are calculated using the Dijkstra method [3]. Although this assumption is adopted by many authors (e.g., [36,19]), it is known that after an earthquake occurs even local residents, who know an area well, are sometimes irrational and likely to gather information and/or try to find their family instead of directly evacuating to a safe place [4]. In this study, for the sake of simplicity, the authors assume that all local resident agents go straight towards the nearest evacuation places, in order to clarify the differences between

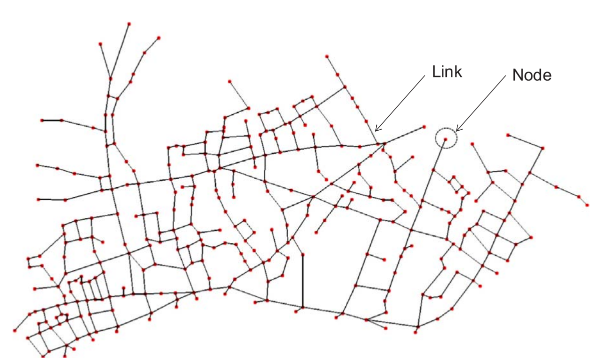

Fig. 1. Road network for the proposed simulation model, consisting node points and connected links. Red circles show node points and black lines show links.