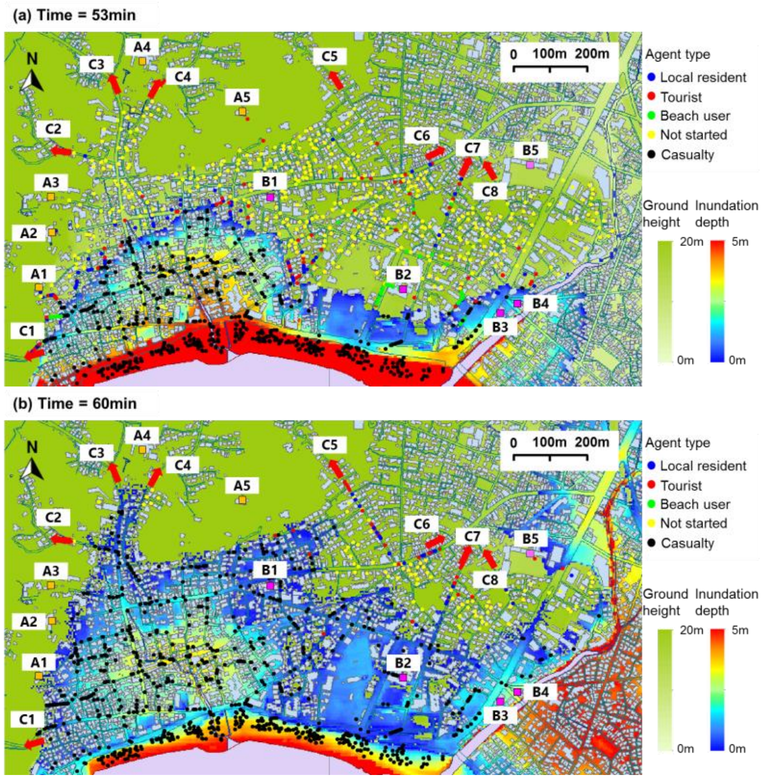
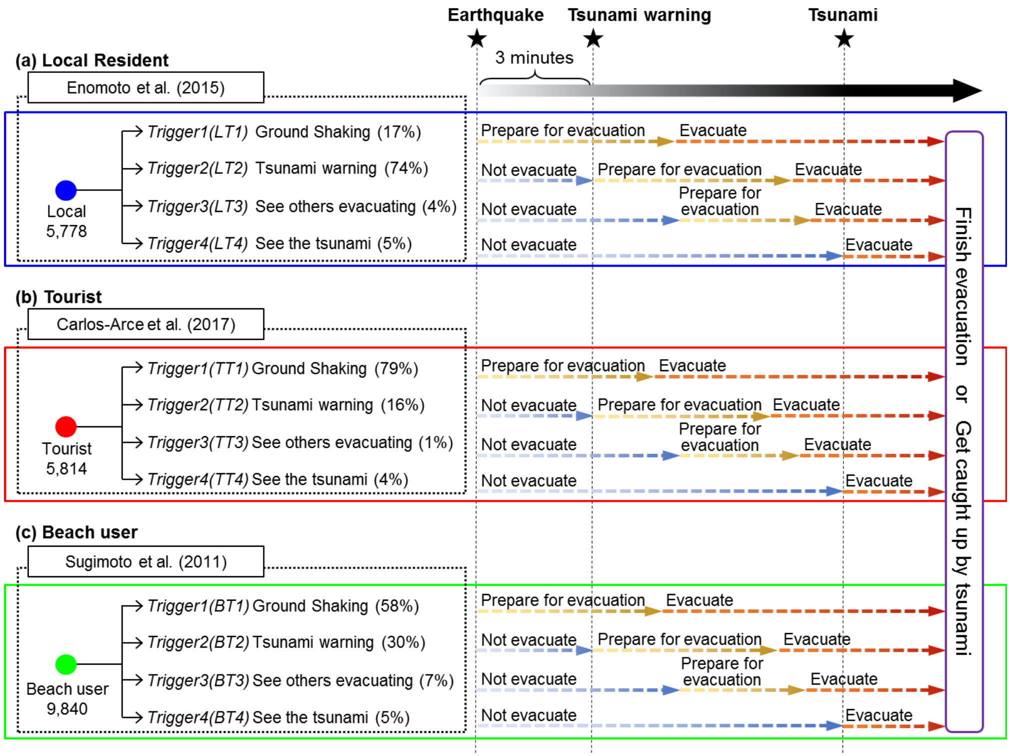
WASEDA UNIVERSITY

TSUNAMI CASUALTY ESTIMATION CONSIDERING INTENDED EVACUATION BEHAVIOR OF LOCAL RESIDENTS AND VISITORS





Tomoyuki TAKABATAKE, Tomoya Shibayama, Esteban Miguel

Waseda University, Tokyo, Japan

1. Introduction

Estimation the number of tsunami casualties

- **Tsunamis** are considered to be one of the most destructive types of natural hazards that can affect coastal regions.
- It is important to quantitatively assess the potential loss of life that can result from a tsunami to develop and prioritize effective countermeasures.
- Previously, many approaches to estimate the number of tsunami casualties have been proposed.
  - ✓ *Geographical Information System (GIS)*

    e.g.) Wood and Good (2004), Jelinek et al. (2012), and Freire et al. (2013)
  - ✓ *Agent-Based Evacuation Simulation Modeling*

    e.g.) Mauro et al. (2013), Wang et al. (2016), and Takabatake et al. (2017)
- However, most of them have not taken detailed evacuation behavior of at-risk individuals into account.

1. Introduction

- ✓ Most studies have expressed evacuation start time for evacuees in a very simple way (e.g. start at the same time / follow a simple distribution function)
  → A variety of evacuation triggers that can prompt evacuees to start their evacuation should be considered (Mikami & Shibayama 2016)

- ✓ Most studies have assumed that evacuees proceed to the closest evacuation place via the shortest route (the detailed intended evacuation behavior of visitors has been neglected)
  → Visitors' evacuation route choice should be considered (Takabatake et al. 2017)

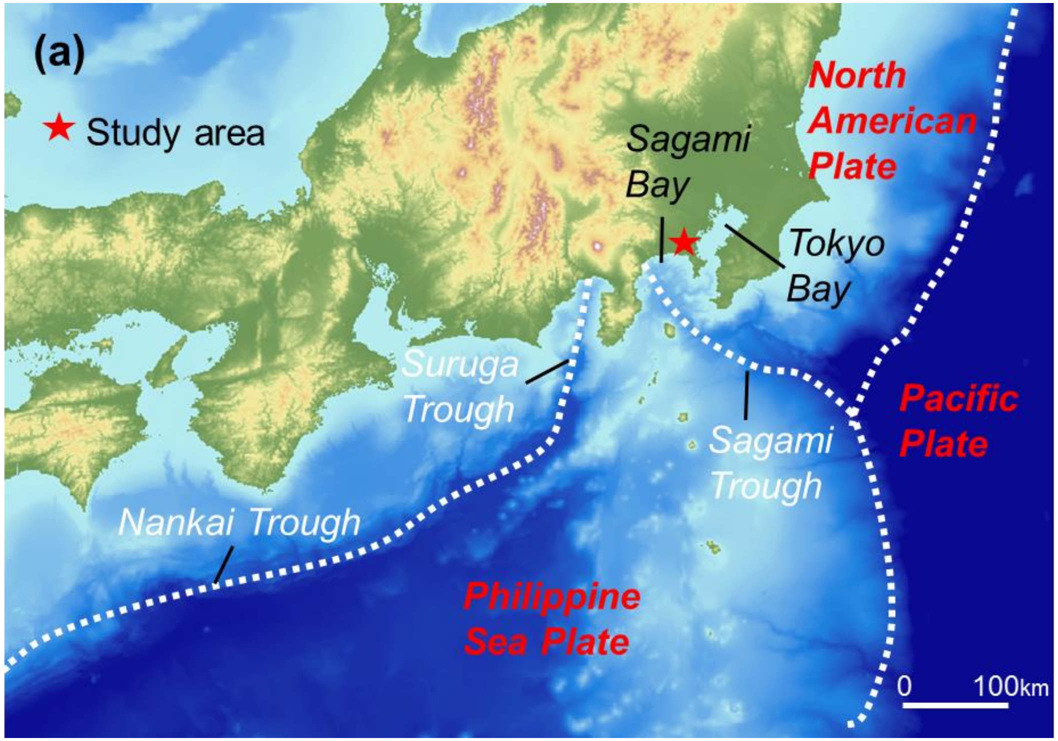
- ■ This study proposes an agent-based tsunami evacuation simulation model that considers a variety of types of intended evacuation behavior of local residents, tourists and beach users

- ■ The developed model was applied to Yuigahama Beach in Kamakura City, Japan to estimate to estimate the potential casualties that can result from a tsunami event

2. Study area & Earthquake scenarios

Kamakura City in Japan was selected as a study area

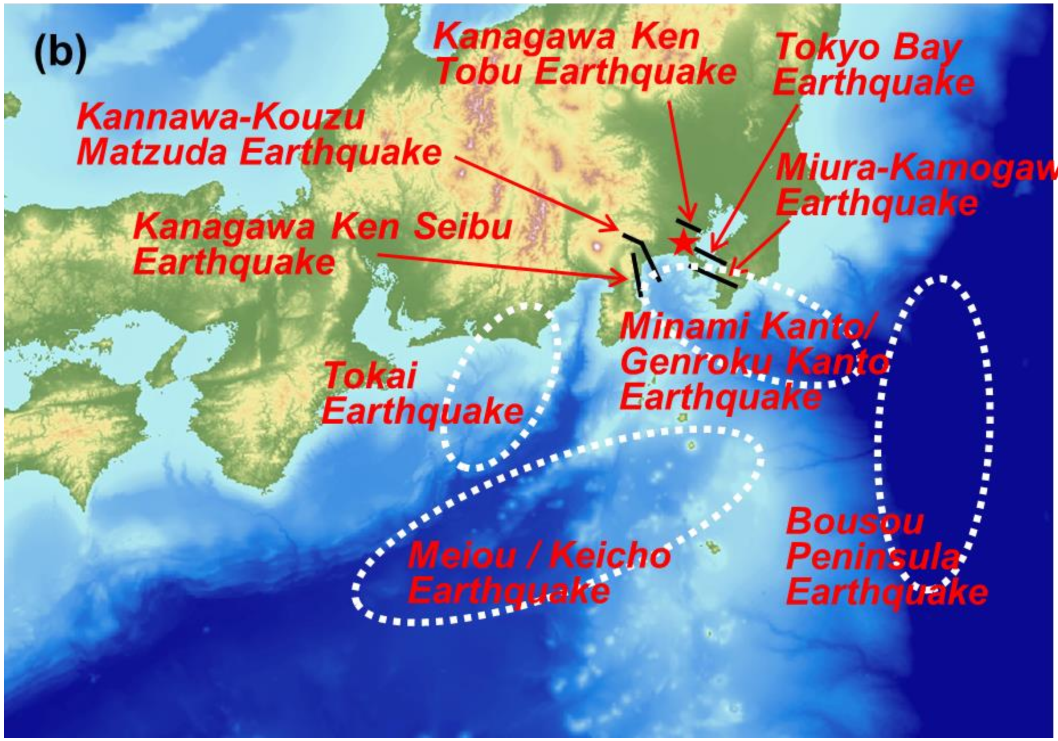
- It has a high risk of tsunami and large number of visitors and beach users throughout the whole year.
- *The North American Plate*, *the Pacific Plate* and *the Philippine Sea Plate* meet approximately 300 km away from the bay of the study area. *The Sagami Trough* and *the Nankai Trough* are also located outside of the bay.



2. Study area & Earthquake scenarios

Kamakura City in Japan was selected as a study area

- The study area has suffered a number of earthquakes and tsunamis in the past.
- The Keicho earthquake was selected as the target earthquake, which is regarded as one of the most hazardous event to the study area (Kanagawa Prefecture, 2012)



3. Methodology - Tsunami propagation & inundation simulation -

Governing equations

- The spatial distribution of the initial water level was calculated based on the Manshinha and Smylie model (1971).
- A nonlinear long wave equation and a continuity equation were applied to calculate the tsunami propagation & inland inundation processes.
- The simulation followed a nesting approach with six domains with grid sizes of 810, 270, 90, 30, 10 and 5 m.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

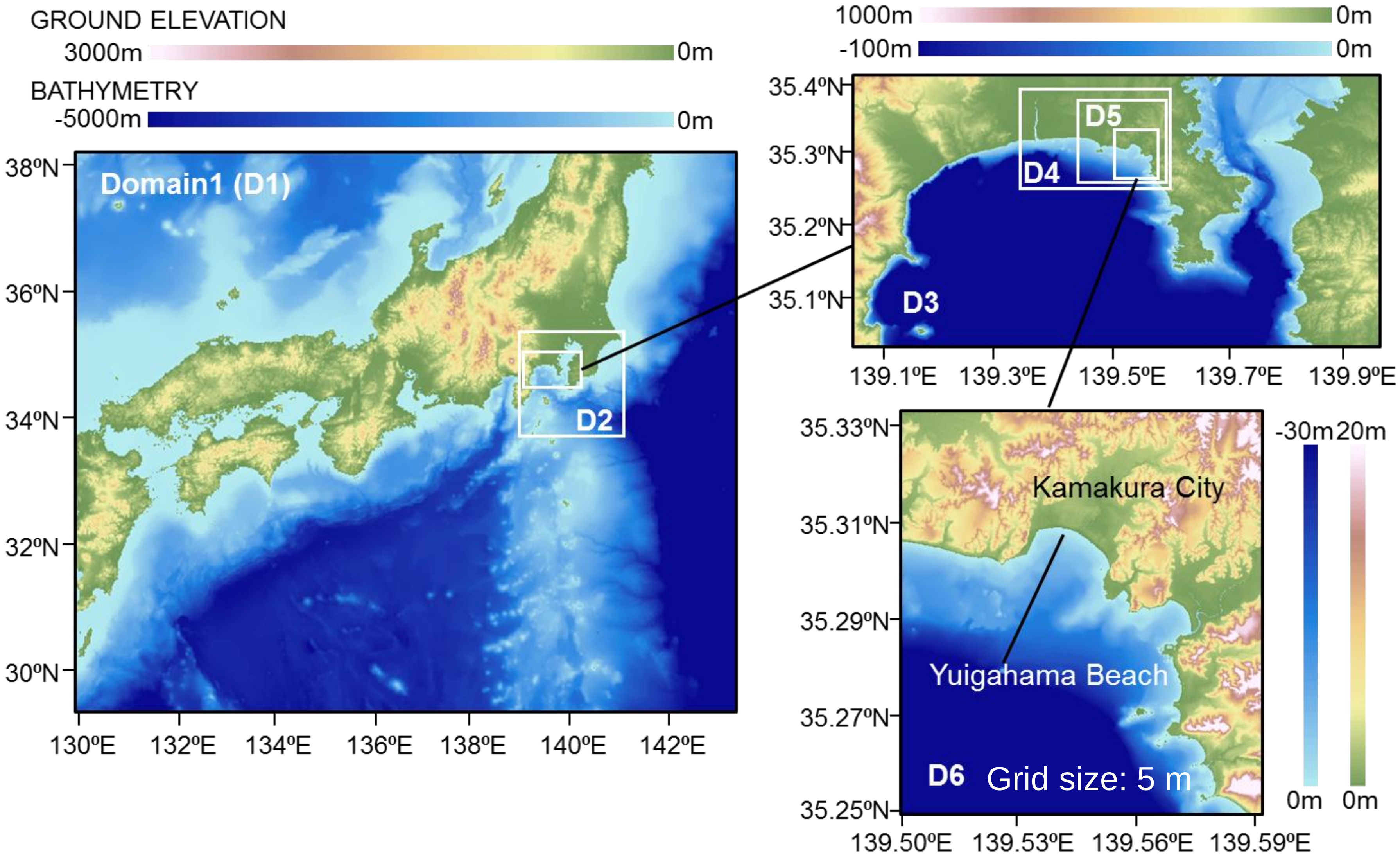
$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M\sqrt{M^2 + N^2} = 0$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}} N\sqrt{M^2 + N^2} = 0$$

η : the water level h : the initial water depth D : the total water depth

M, N : the discharge flux n : the Manning's coefficient

3. Methodology - Tsunami propagation & inundation simulation -

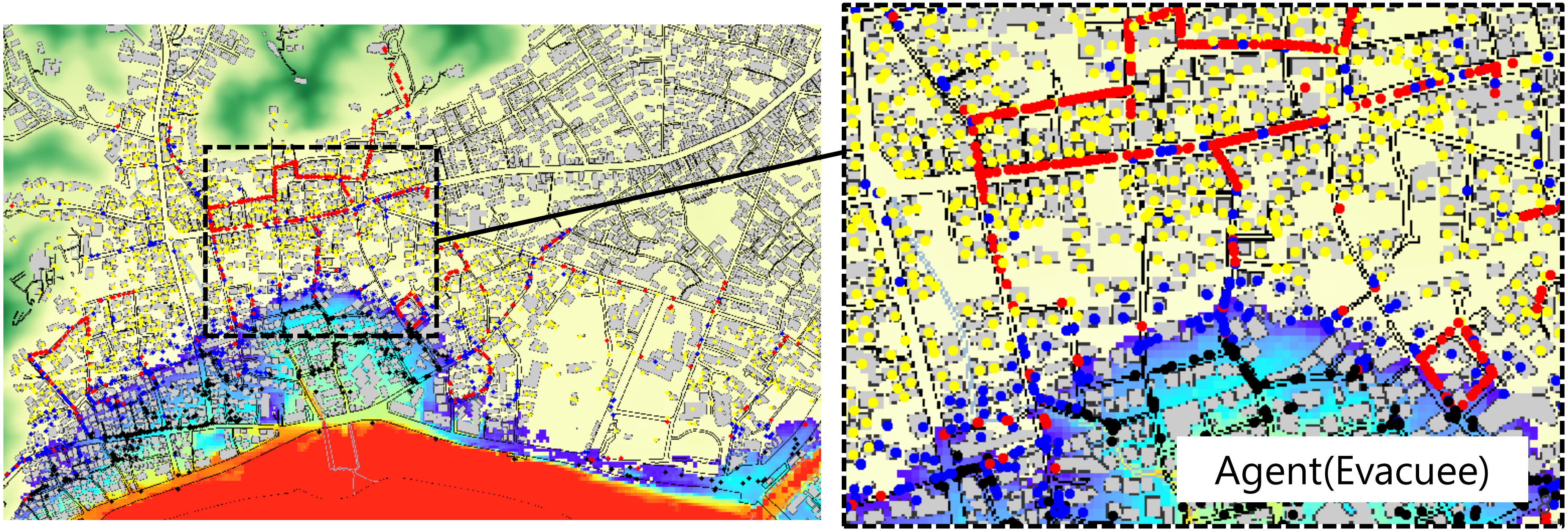


3. Methodology - Tsunami evacuation simulation -

Takabatake et al. (2018)

Tsunami evacuation simulation model

- Agent-based modeling is a technique for simulating the behaviors and interactions of a large number of individual agents.
- The model was constructed using the agent-based modeling platform *Artisoc 4.0* (KOZO KEIKAKU ENGINEERING Inc, 2016).
- The results of previous evacuation behavior survey questionnaires amongst local residents, tourists and beach users in the study area were used (Enomoto et al. 2015; Carlos-Arce et al. 2017; Yasuda et al. 2016; Sugimoto et al. 2011).

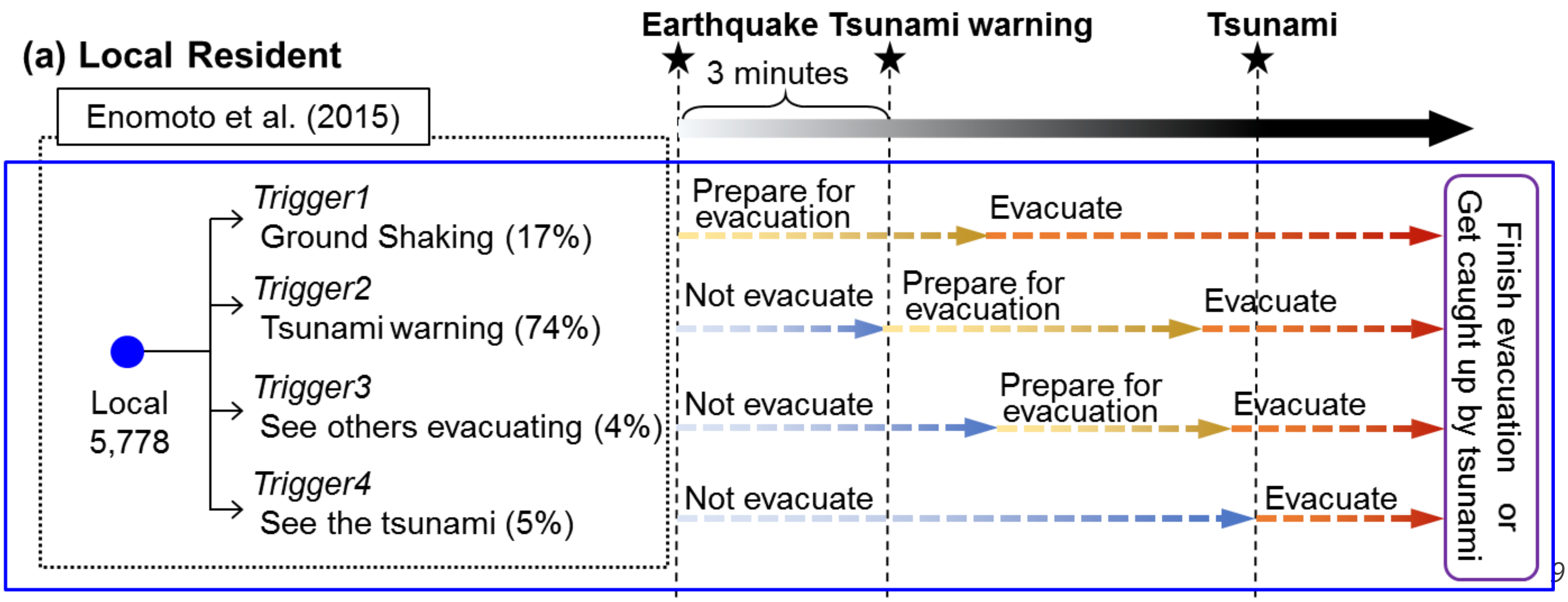


3. Methodology - Tsunami evacuation simulation -

Takabatake et al. (2018)

Starting time for evacuation

- Based on the results of the previous surveys, the evacuation triggers were categorized into four types and one trigger was assigned to each agent
- When a trigger event occurs, the agents who will respond to this trigger will decide to evacuate
- And after the preparation time (also determined based on the survey results) has passed they will start evacuating

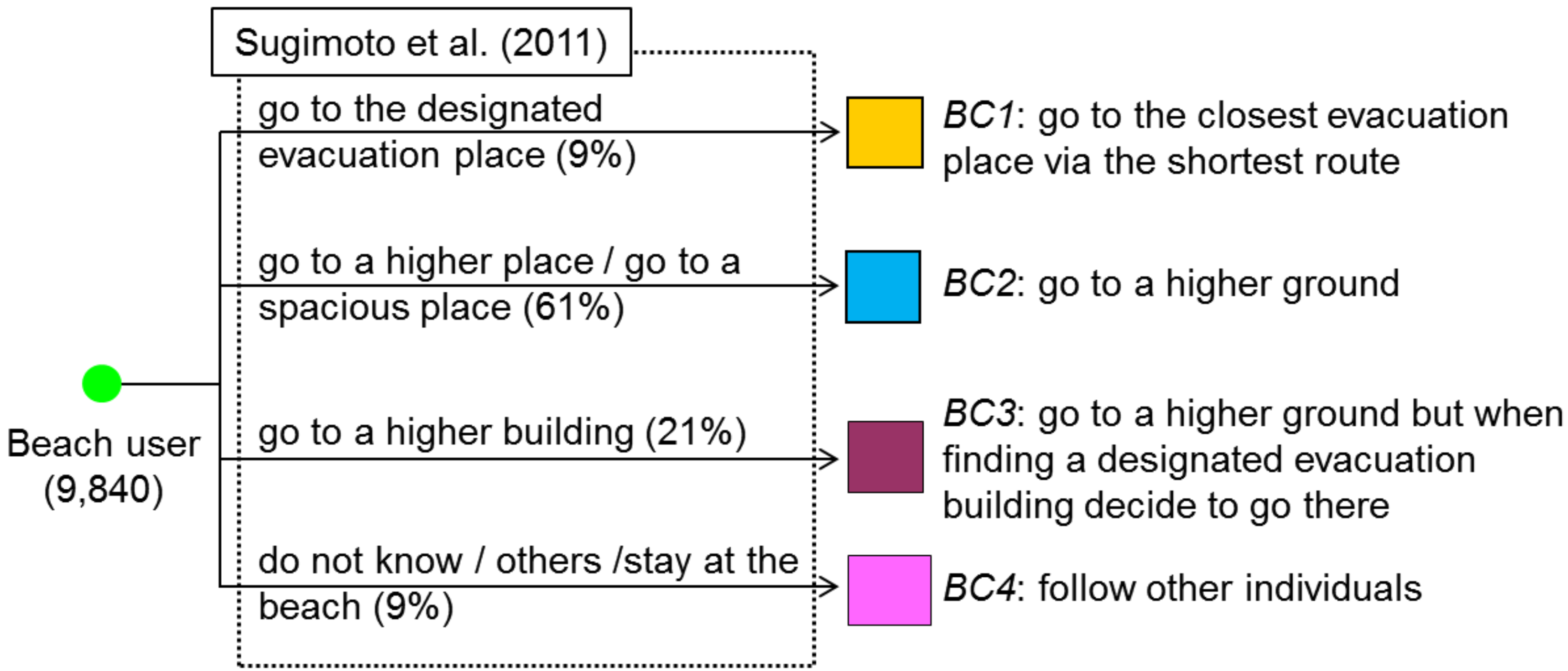


3. Methodology - Tsunami evacuation simulation -

Takabatake et al. (2018)

Evacuation route choices

- Based on the results of the previous surveys, the choice of evacuation route for local residents, tourists and beach users was defined



(c) Beach user

3. Methodology - Tsunami evacuation simulation -

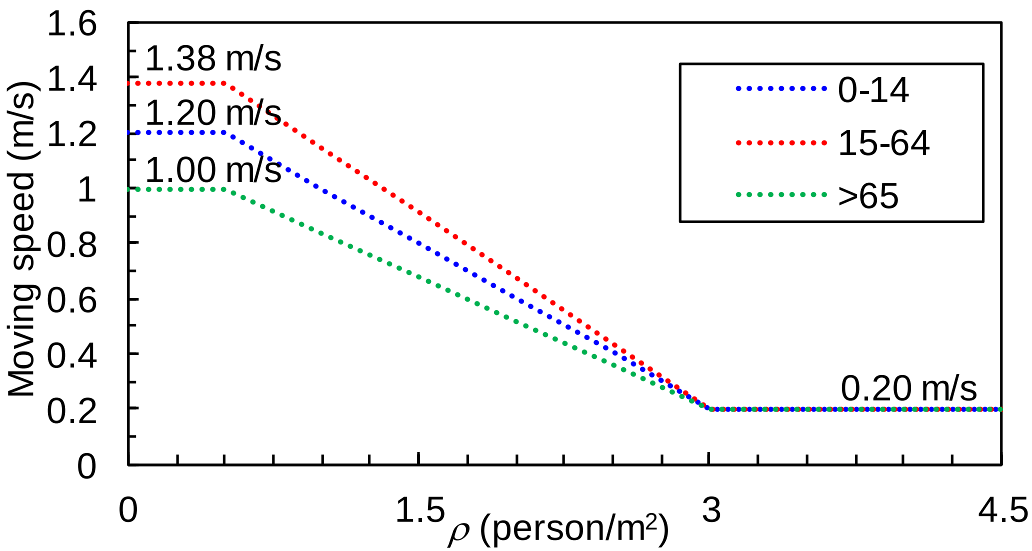
Takabatake et al. (2018)

Moving speed

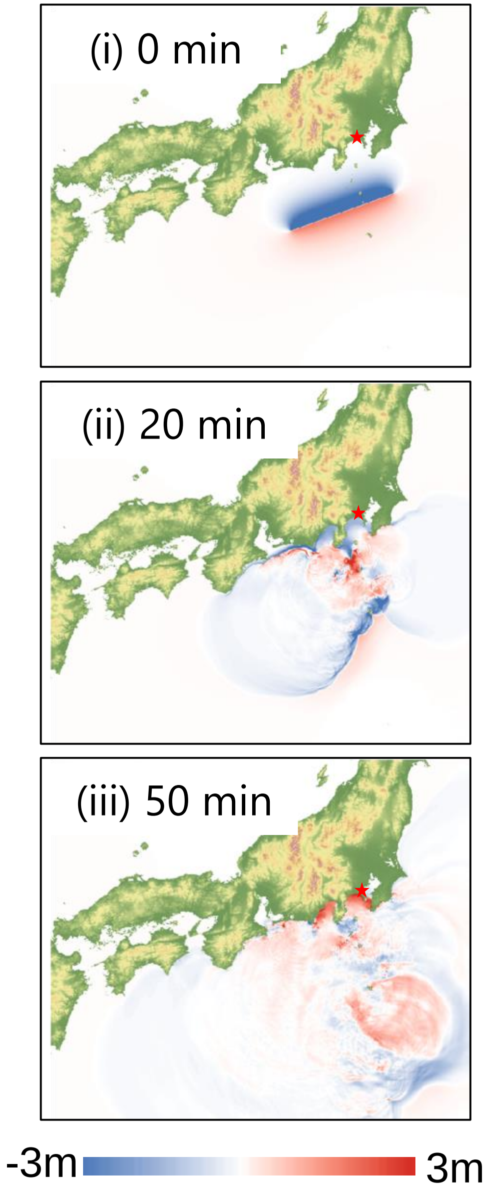
- The evacuation speed for each agent was decided by considering both age (0-14, 15-64, >65 years) and crowd density (Kumagai 2014).

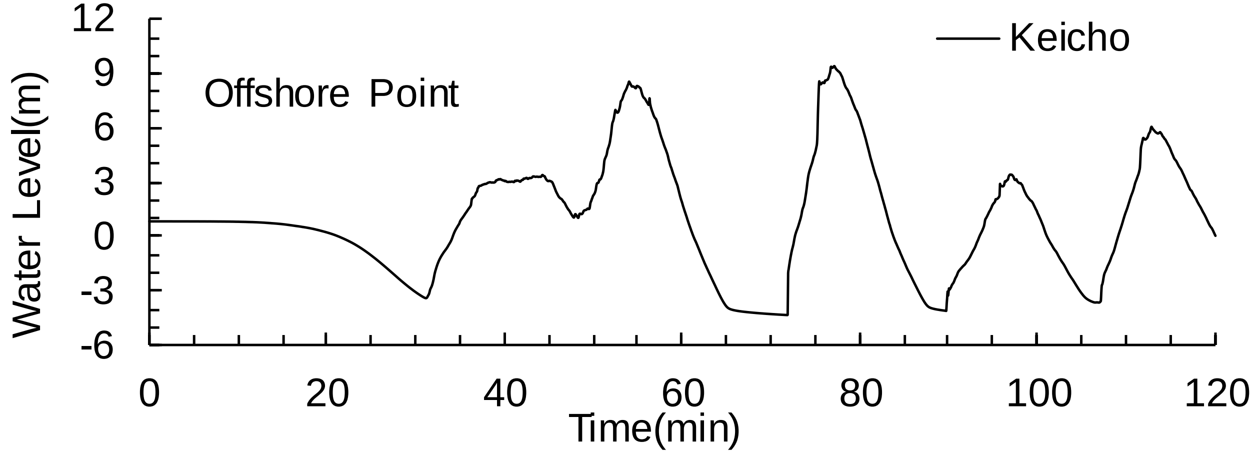
Estimation for the number of casualties

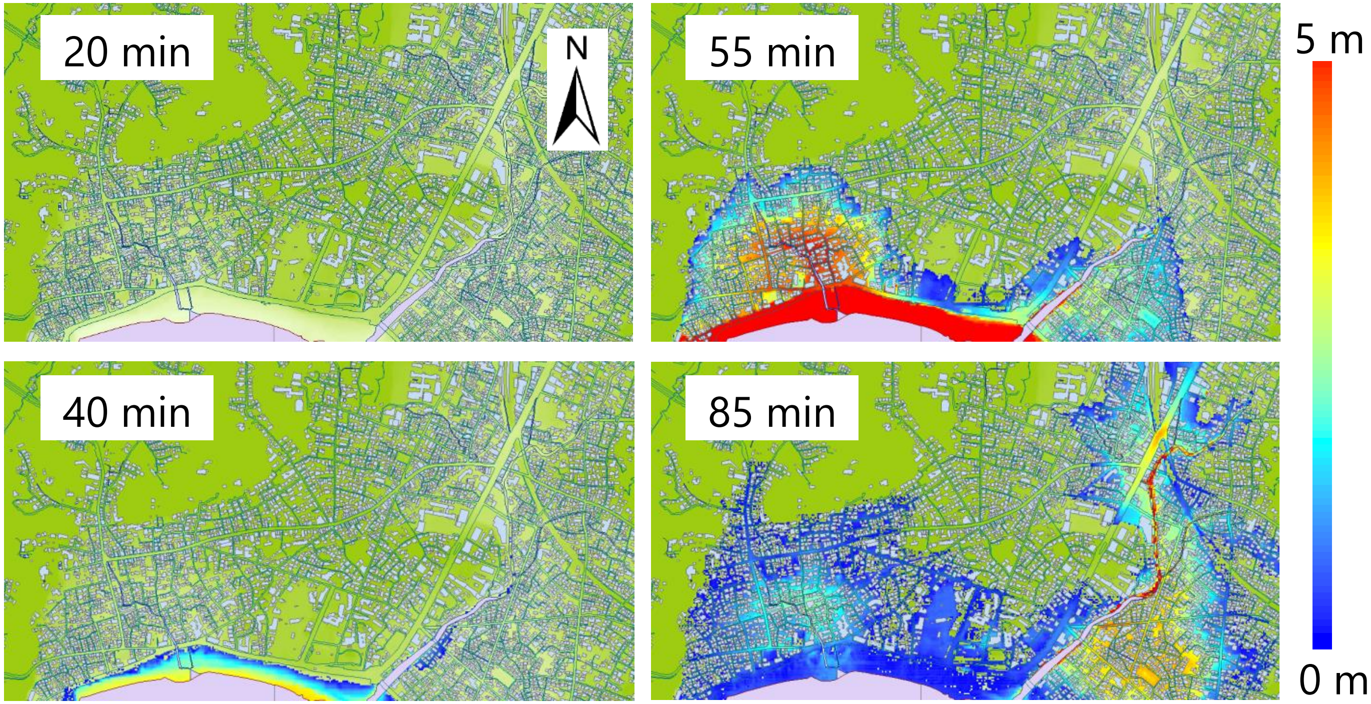
- It was assumed that an agent would become a casualty if the *DV* (depth-velocity product) at their location exceeded its stability limit.
- Following the criteria proposed in Cox et al. (2010), stability limit is defined depending on agent's age.
- Age 5-14: *DV*>0.6 m^2/s, Age15-64: *DV*>1.2 m^2/s, Age 0-4 &>65: *DV*>0.0 m^2/s



4. Results - Tsunami simulation -

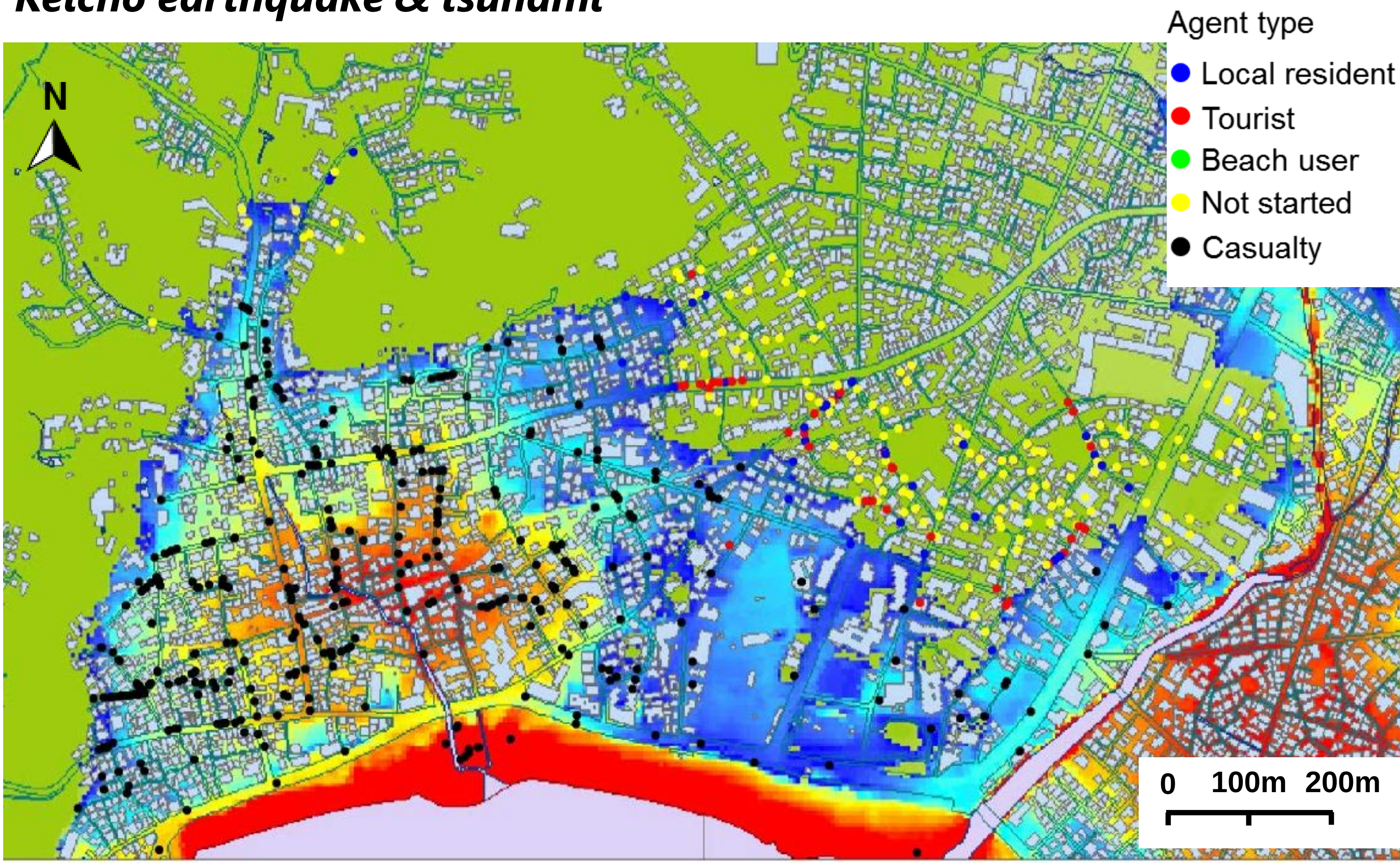






4. Results - Casualty estimation -

Keicho earthquake & tsunami



4. Results - Casualty estimation -

Casualty numbers / Mortality rate by agent types

- Keicho tsunami caused more than a thousand of casualties, when it arrives at Kamakura City during a summer season.
- Beach users are more vulnerable than the others.

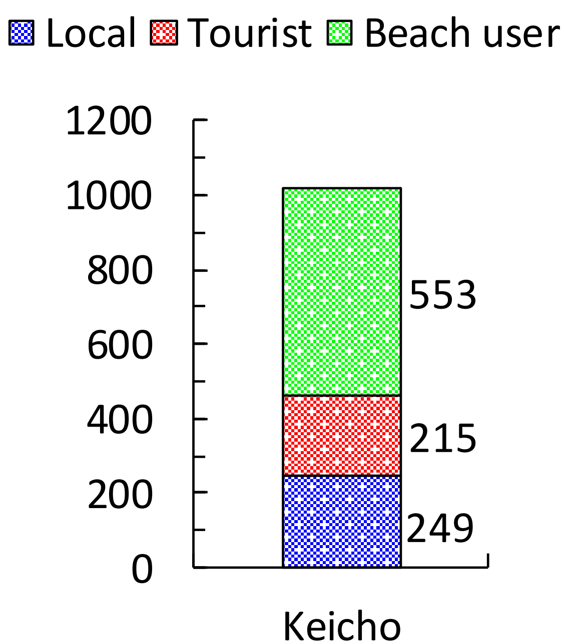


Fig. Casualty numbers

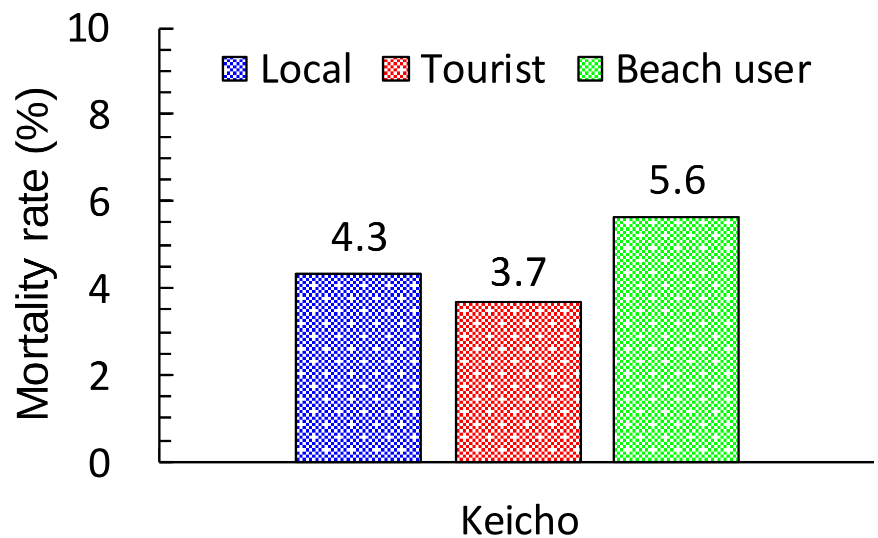


Fig. Mortality rate by agent types

4. Results - Casualty estimation -

Mortality rate by evacuation trigger

- Many of the evacuees whose trigger is T1 or T2 survived from the Keicho tsunami.
- T4 evacuees died regardless of agent types. Some local residents locate far from the evacuation roads. They have less chances seeing others evacuating.

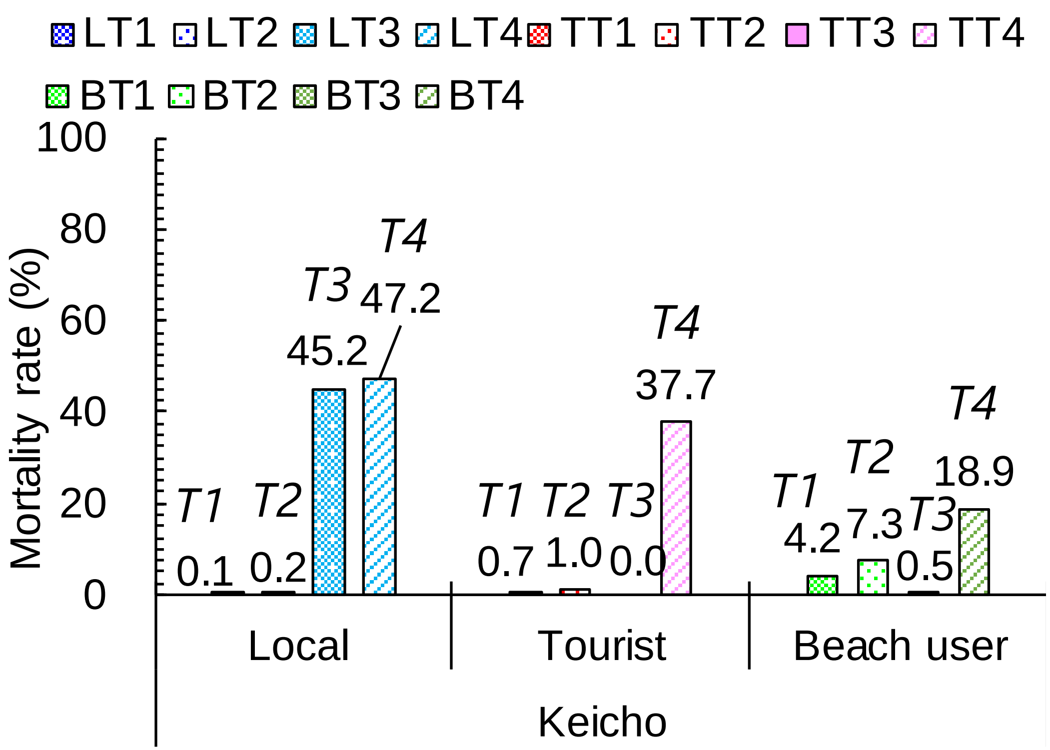


Fig. Mortality rate by evacuation trigger

Evacuation Trigger

T1: Ground shaking

T2: Tsunami warning

T3: See others evacuating

T4: See the tsunami

L : Local residents

T : Tourists

B : Beach users

4. Results - Casualty estimation -

Mortality rate by evacuation route choice

- Visitors and beach users who know the closest evacuation place were more likely to survive.
- Heading to higher ground were found to be insufficient behavior to save lives in the study area.

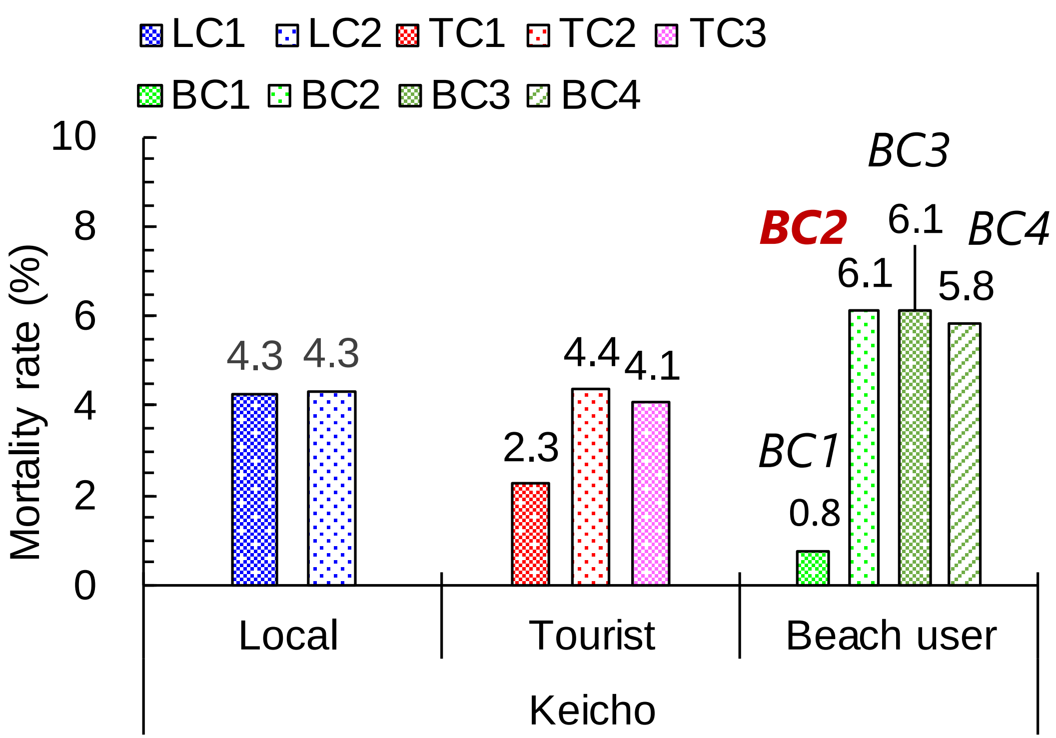


Fig. Mortality rate by evacuation route choice

Evacuation Route Choice (Beach users)

BC1: go to the closest evacuation place via the shortest route

BC2: go to a higher ground

BC3: go to a higher building

BC4: follow other individuals

5. Conclusions

- In this study, the agent-based tsunami evacuation model that considers a variety of intended evacuation behavior was proposed.
- It can provide more detailed information about the number of casualties resulting from a tsunami. (*What kind of people are more vulnerable?*)
- For the study area, it is shown to be important…
  - ✓ to consider the presence of visitors and beach users.
  - ✓ to change the intended evacuation behavior of individuals who intend to only start to evacuate after seeing tsunami.
  - ✓ to ensure that local residents start evacuating on their own will, without expecting see others evacuating.
  - ✓ to disseminate the information about safe places and the routes to reach them to tourists and beach users who don't have less knowledge about the area.
- It is possible to evaluate the effectiveness of tsunami countermeasures in terms of the number of casualties. We can compare the effectiveness of hard measures and soft measures. (*Which countermeasures should be prioritized?*)

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