A method for estimating casualties due to the tsunami inundation flow

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Abstract   This study develops a method for estimating the number of casualties that may occur while people evacuate from an inundation zone when a tsunami has inundated an area. The method is based on a simple model of hydrodynamic forces as they affect the human body. The method uses a Tsunami casualty index (TCI) computed at each grid point of a numerical tsunami model to determine locations and times within the tsunami inundation zone where evacuation during the tsunami inundation is not possible and therefore where casualties are likely to occur. The locations and times can be combined with information about population density to compute the potential number of casualties. This information is useful in developing tsunami evacuation routes that avoid such locations. To illustrate the method, it is applied to the Seattle waterfront in Washington State, USA, that is under the threat of possible tsunami disasters due to Seattle Fault earthquakes. Preliminary results suggest that the tsunami casualties may occur within the Seattle waterfront for 15 min, during the time interval from 3 to 18 min after a large Seattle Fault tsunami is generated when the background tide level is mean high water.

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Introduction

As it is often said, the only and most effective way to survive a tsunami disaster is the immediate evacuation. During the process of development of a tsunami evacuation plan for a coastal community, we first use a numerical model to understand the expected tsunami hazard. Having the resulting tsunami hazard scenario, the evacuation procedures are then planned in order to reduce tsunami casualties. One goal of the evacuation plan is to complete the evacuation before the estimated tsunami arrival time. However, there are some communities that cannot expect to have adequate time for evacuation before tsunami arrival. In those cases, the evacuation plan needs to include the possibility that people will be evacuating during the time when tsunami inundation is occurring. When we consider how to plan an evacuation during the critical time of tsunami inundation, one requirement is to select evacuation routes that avoid as much as possible areas where tsunami inundation will disrupt people's evacuation.

Recent improvements in tsunami inundation modeling techniques have increased the accuracy and resolution of tsunami hazard mapping that estimates tsunami height, current velocity and extent of inundation zone. However, numerical models have not previously been applied to the hydrodynamic conditions that may cause casualties during evacuation. The present study aims to suggest the conditions of tsunami inundation flow that disrupts tsunami evacuation and/or cause injury or casualties during evacuation.

Developing a tsunami casualty estimation model

Estimation of tsunami casualties

Until now, no criteria have been available to estimate the number of tsunami casualties when planning tsunami disaster mitigation for a community. Kawata (2001) compiled the number of tsunami casualties due to historical tsunami disasters that have occurred in Japan, including the 1896 Great Sanriku Tsunami, the 1933 Showa Sanriku Tsunami, the 1944 To–Nankai Tsunami, the 1946 Nankai Tsunami and the 1993 Hokkaido Nansei–Oki Tsunami. From these data, he determined an empirical relationship between the tsunami casualty rate and the observed or estimated tsunami height. This empirical relationship suggests that tsunami casualties begin to occur when the local tsunami height exceeds 2 m. However, the exact casualty rate cannot be determined as a unique number for a particular value of tsunami height.

The tsunami casualty rate for a certain tsunami height has significant variation within each event and depends on the location within each community. Hence, various factors must combine to cause tsunami casualties. The most significant factor is likely to be whether the residents in a community take part in the evacuation or not. In this context, tsunami casualty estimation should include not only the static population within the expected tsunami inundation zone, but must also consider various situations. We focus the present study on tsunami casualties that may occur during the actual evacuation of the residents.

A hydrodynamic model for estimation of tsunami casualties

We assume that the occurrence of tsunami casualties is determined by the local hydro-dynamic characteristics of the tsunami inundation flow and the physical characteristics of

evacuees, such as weight and height. Thus, in the present study, the definition of tsunami casualty occurrence is equal to the minimum hydrodynamic conditions that prohibit people's evacuation movement. This occurs when the hydrodynamic force due to the tsunami inundation flow affecting the human body exceeds the resistance force of an evacuee against the inundation flow.
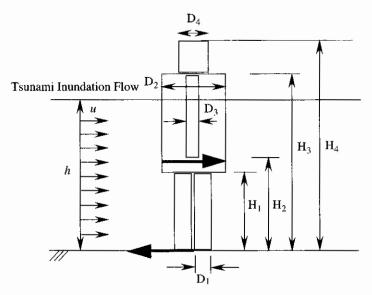
Introducing a human body model shown in Fig. 1, we formulate the conditions of tsunami casualty occurrence by Eq. (1). In the present model, the human body is approximated by a combination of cylinders. As described in the left side of Eq. (1), the resistance force against the tsunami inundation flow is defined by the friction between the land surface and the sole of the evacuee's feet, where mg is the weight of human body, w is buoyancy of the partially submerged human body and f is the friction coefficient, which is assumed to be $f = 0.5$ in the present study. The right side of Eq. (1) denotes the hydrodynamic force described by Morrison's formula, where ρ is the density of salt water, u is the water velocity of horizontal direction, $C_D = 1.0$ and $C_M = 0.5$ are drag and inertia coefficients and dS and dV are the projected area perpendicular to the flow direction and the volume element of the human body model, respectively.

Here, α is a correction factor considering the psychological effect that is obtained from Suga et al. (1995). They performed a hydrodynamic experiment to determine how people feel within the inundation flow, and obtained α as the ratio of $f(\text{mg} - w)/\int \frac{1}{2}\rho C_D u^2 \text{d}S$. Through interviews with the human subjects who had walked in water flow within a wave tank, Suga et al. (1995) categorized the feelings of the subjects in seven degrees, and plotted those vs. α as shown in Fig. 2. They concluded that people walking within the inundation flow start feeling their own danger when α is less than two.

Once the dimension of a human body is defined, we calculate Eq. (1) during each time step of the numerical modeling and within each grid of computational area. We then determine the condition of tsunami casualty occurrence by using the computed u and the inundation depth h.

$$f(\text{mg} - w) \leq \alpha \int \frac{1}{2}\rho C_D u^2 \text{d}S + \int \rho C_M \frac{\partial u}{\partial t} \text{d}V \tag{1}$$

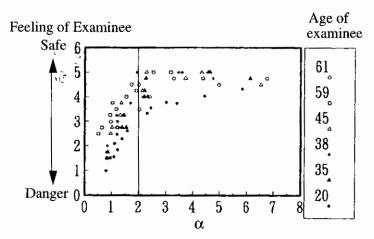Fig. 1 Schematic explanation of human body model

Fig. 2 The psychological factor of the people against the inundation flow adopted from Suga et al. (1995)

Case study

Application to the possible tsunami disaster

The model is applied preliminarily to the possible tsunami hazard within the Seattle waterfront, Washington State, USA. The Seattle waterfront adjacent to Puget Sound is under the threat of possible tsunami disaster that could be triggered by Seattle Fault earthquakes.

Koshimura et al. (2002) pointed out that a large (>$M7$) Seattle Fault earthquake will generate a >3 m tsunami that will begin striking the waterfront within 3 min after the earthquake. Such a tsunami has the potential to cause significant damage. Because of the limitations of time for evacuation, the evacuating residents and visitors within the waterfront area should try to avoid locations where the inundation flow might cause significant injury or death.

Combined with the tsunami inundation model, the present study determines the tsunami casualty potential in the spatial and time domain during a possible tsunami disaster within the Seattle waterfront area.

Tsunami hazard scenario due to the possible Seattle Fault earthquake

Paleoseismic studies in the Puget Lowlands of western Washington State demonstrate that a strong shallow crustal earthquake occurred in this region about 1100 bp (before present). This earthquake occurred on the Seattle Fault, a zone of thrust or reverse faults that cross Puget Sound between Seattle and Bremerton (Johnson et al. 1999), with a magnitude estimated at seven or larger (Bucknam et al. 1992). Bucknam et al. (1992) reported that a 5–7 m uplift occurred on the Seattle Fault zone during this earthquake.

A tsunami in Puget Sound is believed to have accompanied this event. Atwater and Moore (1992) have interpreted sand layers found at West Point and Cultus Bay as tsunami deposits. This evidence was especially well-preserved at Cultus Bay, which opens southward at the southern end of Whidbey Island, 40 km north of Seattle. By using the numerical model of tsunami propagation and inundation, Koshimura et al. (2002) validated this 1,100 bp tsunami. They concluded that an earthquake of M_w 7.6 with mean high water

as the background water level could generate a tsunami that penetrated through the coastal marsh at Cultus Bay where tsunami deposits were found.

Taking this earthquake as the tsunami-generating event, we perform the tsunami inundation modeling within the Seattle waterfront, and apply the tsunami casualty estimation model. Other studies of similar Seattle Fault-generating tsunamis striking the Seattle waterfront have been done by Walsh et al. (2002) and Titov et al. (2003). Figure 3 shows the computational domain. It also shows the computed seismic deformation of the 1,100 bp Seattle Fault earthquake using the theory of Okada (1985). Table 1 presents the fault parameters suggested by Koshimura et al. (2002).

Tsunami inundation model

We use the TUNAMI–N2 model (Imamura 1995) for modeling propagation and coastal inundation of tsunamis in Puget Sound. In this model, a set of non-linear shallow water equations with bottom friction terms are discretized by the leap-frog finite difference scheme. This model is widely used to simulate tsunami propagation and inundation on dry land.

For the present study, we use the digital elevation data provided by the Puget Sound Regional Synthesis Model (Finlayson et al. 2001). The original grid size is 30 m and the reference datum for the land elevation and water depth is NAVD29. For the computation of the tsunamis within the broad region of Puget Sound, we reprojected the original data to create a 90 m grid. For the inundation modeling within the Seattle waterfront (solid square in Fig. 3), we use the original 30 m grid, constructing a nested grid system inside the 90 m grid. Time step for the inundation modeling is selected to be 0.25 s in order to avoid the numerical instabilities.
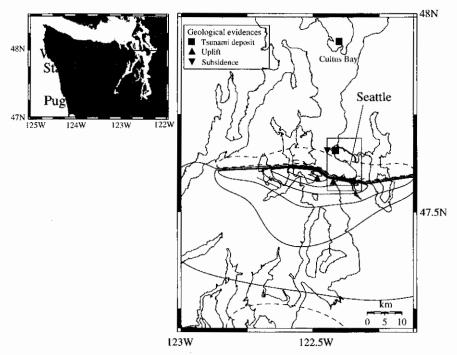

Fig. 3 The computational domain and the computed seismic deformation of the 1,100 bp Seattle Fault earthquake tsunami. The contour intervals are 1 m for uplift (solid line) and 0.25 m for subsidence (dashed line)

Table 1 Dimension of the fault and source parameters of a Seattle Fault earthquake used in this study, as suggested by Koshimura et al. (2002)

n	L (km)	W (km)	D (km)
Shallower fault segments (≤5.5 km)			
1	15.2	6.0	4.0
2	6.3	6.0	6.0
3	8.9	6.0	8.0
4	3.2	6.0	8.0
5	11.5	6.0	6.0
6	14.9	6.0	4.0
Deeper fault segments (≥5.5 km)			
1	15.2	38.0	2.0
2	6.3	38.0	4.0
3	8.9	38.0	6.0
4	3.2	38.0	6.0
5	11.5	38.0	4.0
6	14.9	38.0	2.0

n indicates the number of fault segment, which increases from west to east along the strike direction. *L* is the strike length of each fault segment, *W* is the downdip width and *D* is the fault displacement

Figure 4 illustrates the computed maximum tsunami inundation depth and waveforms within the Seattle waterfront area adjacent to Puget Sound. The tsunami strikes the waterfront with more than 4 m of its water level at the northern shore of Elliott Bay and 3 m at the head of the bay shortly after the earthquake. The extent of the computed inundation zone is up to 1 km inland at the northern shore of the bay, though this area is not very populated. However, along the eastern shore of the bay, there is significant potential for tsunami casualties, since this area is heavily populated by residents, workers and visitors.

Based on the computed inundation depth and current velocity obtained at each time step within the waterfront, we apply Eq. (1) to determine the hydrodynamic conditions that would prevent people from evacuating and would lead to casualties. Figure 5 plots the
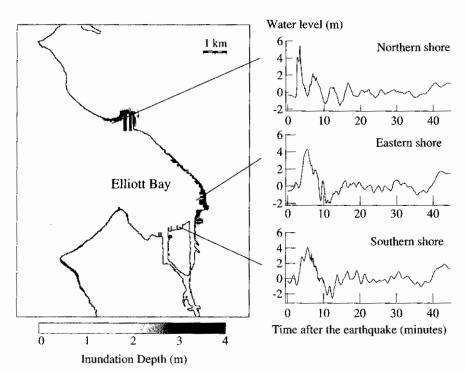

Fig. 4 Computed tsunami inundation depth and waveforms within the Seattle waterfront

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relationship of Fr $(= u/\sqrt{gh})$, where u is the computed current velocity of the tsunami inundation flow and h is the computed inundation depth and the non-dimensional inundation depth. The non-dimensional inundation depth is calculated as the ratio of computed inundation depth that is measured from the local ground to the surface of surging water, divided by the height of a hypothetical evacuee. Here, the height and weight of the evacuee is hypothetically supposed as 170 cm and 70 kg. The dotted area of Fig. 5 indicates the flow condition that greatly disrupts the evacuation process. If we obtain the distribution of tsunami variables (u and h) and the dimension of the human body, we can determine if the tsunami casualty should be expected. For instance, if we suppose 170 cm as the evacuee's height and $h = 70$ cm as the inundation depth, we can determine from Fig. 5 that $u = 1.3$ m/s is the minimum current velocity that would cause tsunami casualties at this location.

Figure 6 shows snapshots of the spatial distribution of potential tsunami casualty occurrence. These are the results of application of Eq. (1) at 3, 8, 13 and 18 min after the tsunami generation. Using black dots, each snapshot illustrates the hydrodynamic condition that satisfies Eq. (1), i.e., the potential zone that may cause tsunami casualties at that time. The figure shows that the tsunami inundation flow between 3 and 18 min after the tsunami generation time has potential to cause tsunami casualties.

Tsunami casualty index (TCI)

We introduce an index to illustrate the spatial distribution of tsunami casualty potential from the comprehensive point of view. TCI is defined as

$$\text{TCI} = \frac{T_C}{T_I} \quad (2)$$

where T_C is the duration of the tsunami inundation flow that satisfies Eq. (1) and T_I is the total duration of the tsunami inundation flow that occurs within the area inundated by the

Fig. 5 Tsunami casualty diagram as the relationship between Fr and the non-dimensional inundation depth
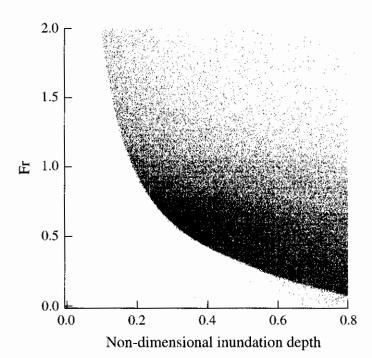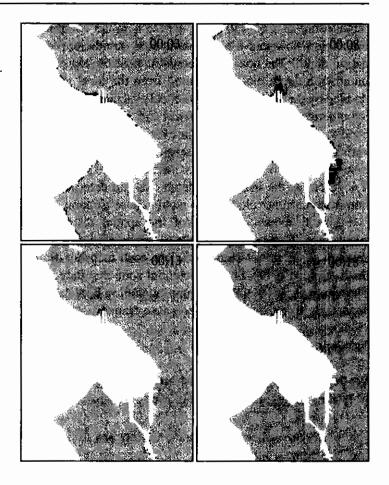
Fig. 6 Tsunami casualty
occurrence in time and spatial
domain

tsunami. TCI can be used as an index to show the tsunami casualty potential at a location. Figure 7 indicates the spatial distribution of TCI. Since TCI is calculated in each computational grid within the inundation zone, it identifies high-risk areas. Combined with the geographic information system data and more detailed tsunami inundation modeling, TCI can be used as the quantity to plan and find the best evacuation route to minimize casualties due to tsunamis.
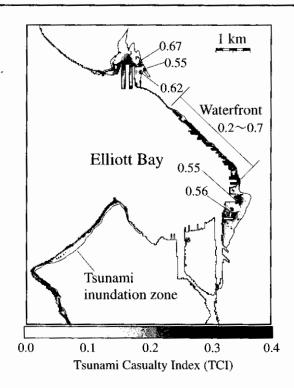
Conclusions

The present study illustrates a method for determining the hydrodynamic conditions of tsunami inundation flow that disrupt the evacuation process. Calculations are made using a hydrodynamic model and a vulnerability formula for evacuees. The detailed tsunami inundation model can be used not only for the estimation of the inundation zone and current velocity, but also for indication of area at high-risk for tsunamis. From a practical point of view, the results of the method provide important information on tsunami evacuation planning for tsunami-prone areas where adequate time is not available for evacuation.

The present study applies the method to the possible tsunami hazard at the Seattle waterfront and suggests that tsunami casualties may occur for 15 min during the time of 3–18 min after the tsunami generation time. Also, we have introduced a TCI based on a

Fig. 7 Spatial distribution of the TCI to illustrate relatively high-risk zone for evacuation route finding problem

tsunami casualty estimation model. It can be used to identify the spatial distribution of potential tsunami casualties in tsunami inundation areas.

We believe that the recent improvements in tsunami inundation modeling, combined with the use of geographic information systems, enable more practical tsunami evacuation planning.

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