A Method for Estimating Casualties due to the Tsunami Inundation Flow

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Abstract. The present study aims to suggest a method to estimate tsunami casualties that may occur while people evacuate from tsunami inundation zone. The method is based on a simple model of hydrodynamic force as it affects the human body. The model is applied to the Seattle Waterfront that is under the threat of possible tsunami disaster due to the Seattle Fault earthquake. The preliminary result indicates that the tsunami casualty may occur within the Seattle Waterfront for 15 minutes, during the time from 3 to 18 minutes after the tsunami is generated.

Keywords: Tsunami, Casualty, Inundation Flow, Evacuation

1. Introduction

As it has been said, the only and most effective way to survive from tsunami disaster is the immediate evacuation. During the process of development of tsunami evacuation plan in a coastal community, we use numerical model to understand the expected tsunami hazard. According to the obtained tsunami hazard scenario, the evacuation activity is planed to reduce tsunami casualties. If, in a community, any amount of time can be expected before tsunami arrival, the goal for an evacuation plan is to terminate the evacuation activity before the estimated tsunami arrival time. However, there should be some communities that cannot expect adequate time for evacuation before tsunami arrival. In that case, the evacuation plan should be supposed that people need to evacuate during the time of tsunami inundation. When we consider to plan an evacuation activity during the critical time of tsunami inundation, the assumed evacuation route needs to avoid where the tsunami inundation disrupt people's evacuation activity.

Recent improvements in tsunami inundation modeling techniques have increased the accuracy and resolution of the tsunami hazard mapping that estimates tsunami height, current velocity and extent of inundation zone. However, we still have a question of what the hydrodynamic condition is, to cause tsunami casualty during the evacuation activity. We have never used the numerical model results from such point of view. The present study aims to suggest the condition of tsunami inundation flow that disrupts the evacuation activity or causes injury or casualty.

2. Developing a Tsunami Casualty Estimation Model

2.1. Estimation of Tsunami Casualty

As whether tsunami casualty occurs or not reflects local aspect of tsunami disaster, there has never been any criterions to estimate the number of tsunami casualties when we plan a tsunami disaster mitigation in a community. Kawata (2001) compiled the data in terms of the number of tsunami casualties due to the 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 1993 Hokkaido Nansei–Oki Tsunami, and obtained an empirical relationship between the tsunami casualty rate and the observed or described tsunami height. This empirical relationship suggests that tsunami casualty begins to occur when a local tsunami height exceeds 2 m. However, even from the relationship of Kawata (2001), the exact number of casualty rate cannot be determined as the unique number for a certain value of tsunami height. Since the number of tsunami casualty rate for a certain tsunami height has significant variation according to each event itself and the location of each community, it is determined as the result of various factors that causes tsunami casualty. The most significant factor is likely to whether the residents in a community take evacuation activity or not. In this context, tsunami casualty estimation should be performed by not only counting the static population included in the expected tsunami inundation zone, but also considering various situations. We focus the present study on the tsunami casualty that may occur during the residents' evacuation activity.

2.2. A Hydrodynamic model for Estimation of Tsunami Casualty

We assume that tsunami casualty occurrence reflects the local hydrodynamic characteristics of tsunami inundation flow and the physical condition of evacuee, such as weight and height. Thus, in the present study, the definition of tsunami casualty occurrence is equal to the hydrodynamic condition that disrupts residents' evacuation activity, i.e., the hydrodynamic force due to the tsunami inundation flow that affects human body exceeds the resistance force of evacuee against the inundation flow.

Introducing a human body model shown in Fig. 1, we formulate the condition of tsunami casualty occurrence by Eq. (1). In the present model, human body is approximated by the 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 evacuee's foot sole, where m is the weight of human body, w is buoyancy that affects human body, and f is the friction coefficient supposed $f = 0.5$ 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 and C_M are drug and inertia coefficient, where $C_D = 1.0$ and $C_M = 0.5$. dS and dV are projective area against the flow direction and volume element of human body model. 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 $f(mg-w)/\int \frac{1}{2}\rho C_D u^2 dS$. Through the interview from the examinees experienced walking in the inundation flow generated in a wave tank, Suga et al. (1995) categorized the feeling of examinees in 7 degrees, and plotted those for α as shown in Fig. 2. They concluded that people walking within the inundation flow starts feeling their own danger when α is less than 2.

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

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

3. Case Study

3.1. 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 is under the threat of possible tsunami disaster that is

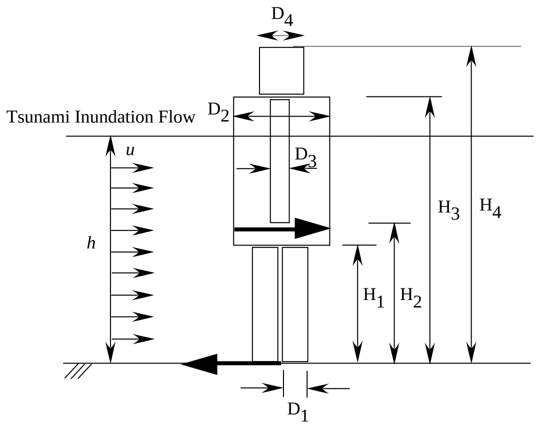

Figure 1. Schematic explanation of human body model

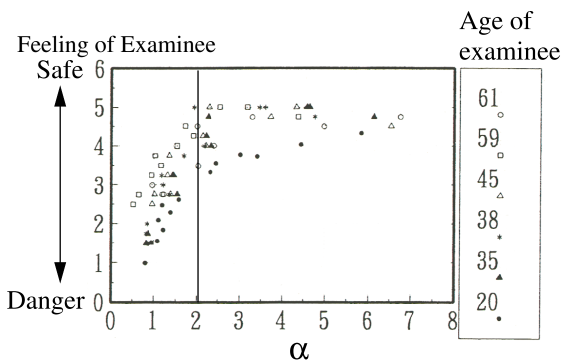

Figure 2. The psychological factor of the people against the inundation flow adopted from Suga et al. (1995)

triggered by the Seattle Fault Earthquake. Koshimura et al. (2002) pointed out that the Seattle Fault earthquake will generate a more than 3 m tsunami and it will strike the waterfront within 3 minutes after the earthquake triggered, and the tsunami has a potential to cause significant damage within the waterfront. Because of the limitation of time for evacuation, the residents and visitors within the waterfront are expected to evacuate within the inundated zone avoiding where the inundation flow causes significant injury or casualty.

Combined with the tsunami inundation model, the present study determines the tsunami casualty potential in the spatial and time domain during the expected tsunami disaster within the Seattle Waterfront .

3.2. 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 years ago. 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) and the magnitude is estimated at 7 or larger (Bucknam et al., 1992). Bucknam et al. (1992) reported that 5 to 7 m uplift occurred on the Seattle Fault zone during the earthquake of 1100 years ago.

A tsunami in Puget Sound is believed to have accompanied this earthquake. 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 1100 bp tsunami, and concluded that the earthquake of M_w 7.6 and MHW as background water level could generate the tsunami that penetrated through the coastal marsh at Cultus Bay where tsunami deposit was found.

Assuming this earthquake as the possible event, we perform the tsunami inundation modeling within the Seattle Waterfront, and apply the tsunami casualty estimation model. Fig. 3 represents the computational domain and computed seismic deformation of the 1100 bp Seattle Fault earthquake by the theory of Okada (1985). Table I represents the fault parameters suggested by Koshimura et al. (2002).

3.3. 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 nonlinear shallow water equations with bottom friction term are discretized by the leap-frog finite difference scheme. This model is widely used to simulate tsunami propagation and inundation on a dry land.

For the modeling of tsunamis, we use the digital elevation data provided by Puget Sound Regional Synthesis Model (Finlayson et al., 2001). The original grid size is 30 m and the datum for the elevation is based on NAVD29. For the computation of tsunamis within the broad area of Puget Sound, we reprojected the original data to create 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

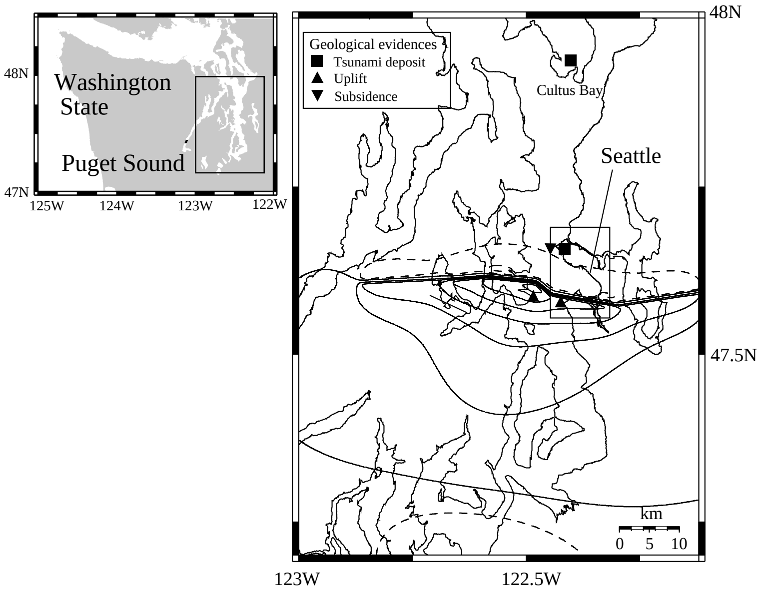

Figure 3. The computational domain and the computed seismic deformation of the 1100 bp Seattle Fault earthquake tsunami. The contour intervals are 1 m for uplift (solid line) and 0.25 m for subsidence (dashed line).

grid system inside the 90 m grid. Time step for the inundation modeling is selected as 0.25 sec. to avoid the numerical instability.

Fig. 4 illustrates the computed maximum tsunami inundation depth and waveforms within the Seattle Waterfront. The tsunami strikes the waterfront with more than 4 m of its water level at the northern shore and 3 m at the head of the bay shortly after the earthquake. The extent of computed inundation zone is up to 1 km inland at the northern shore of the bay, though this area is not much populated. At the eastern shore of the bay, since this area is populated, the significant tsunami casualties are expected.

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 condition that disrupts the residents' evacuation activity. Fig. 5 plots the 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 over the height of the hypothetical evacuee. Here, the height and weight of evacuee is hypothetically supposed as 170 cm and 70 kg. The dotted area of Fig. 5 indicates the flow

Table I. Dimension of the fault and source parameters for the present scenario. 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.

Shallower Fault Segments ($\leq$ 5.5 km)	n	L (km)	W (km)	D (m)
	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 ($\geq$ 5.5 km)	n	L (km)	W (km)	D (m)
	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

condition that disrupts evacuation activity, thus may cause the tsunami casualties. If we obtain a current field (u and h) and the dimension of human body, we can determine if the tsunami casualty should be expected. For instance, if we suppose 170 cm as evacuee's height and $h = 70$ cm as inundation depth, we can determine, from Fig. 5, $u = 1.3$ m/s as the minimum current velocity that may cause tsunami casualty.

Fig. 6 are the snapshots of spatial distribution of tsunami casualty occurrence. These are the results of application of Eq. (1) at 3, 8, 13 and 18 minutes after the tsunami generation. Each figure illustrates, by the black dots, the hydrodynamic condition that satisfies Eq. (1), i.e., the potential zone that may cause tsunami casualties. These figures suggest that the tsunami inundation flow, during the time of 3 to 18 minutes after the tsunami generation time, has potential to cause tsunami casualties.

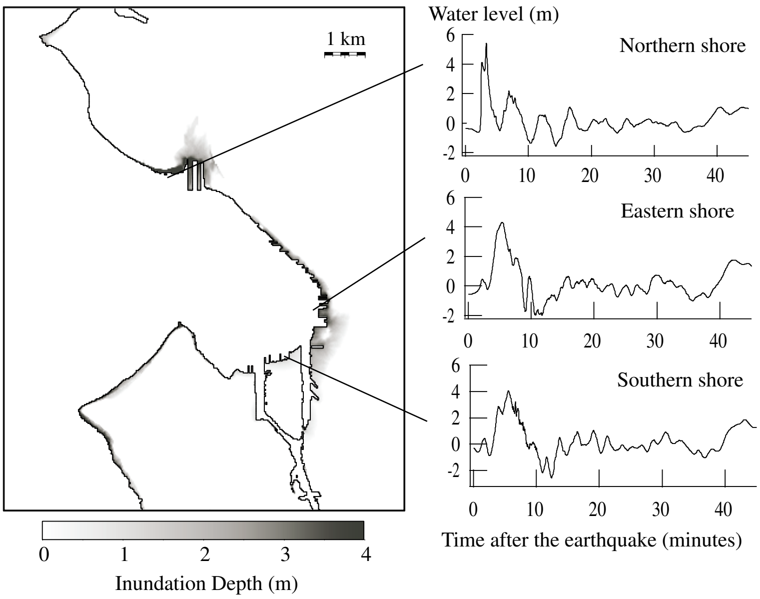

Figure 4. Computed tsunami inundation depth and waveforms within the Seattle Waterfront

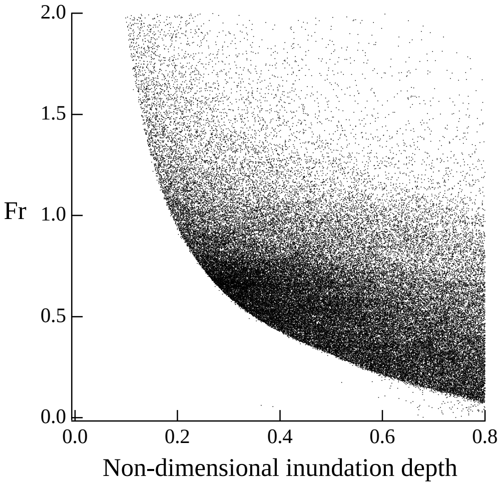

Figure 5. Tsunami casualty diagram as the relationship between Fr and the non–dimensional inundation depth.

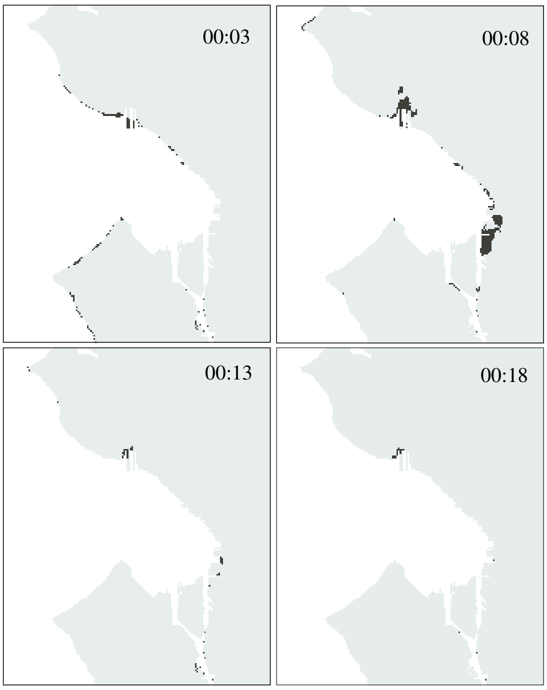

Figure 6. Tsunami casualty occurrence in time and spatial domain.

3.4. Tsunami Casualty Index (TCI)

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

$$TCI = \frac{T_C}{T_I} \tag{2}$$

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 water front. TCI can be used as an index to show the tsunami casualty potential within the inundated area. Fig. 7 indicates the spatial distribution of TCI. Since TCI is calculated in each computational grid within the inundation zone, it illustrates the relatively high risk area in terms of the possibility of tsunami casualty due to the tsunami inundation flow. Combined with the Geographic Information System and the more detailed tsunami inundation modeling, TCI can be used as the material to plan and find the best evacuation route to minimize the casualty due to the inundation flow.

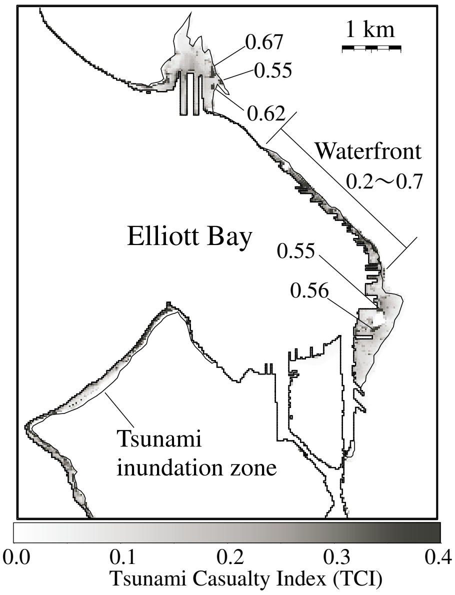

Figure 7. Spatial distribution of Tsunami Casualty Index (*TCI*) to illustrate relatively high risk zone for evacuation route finding problem.

4. Concluding Remarks

The present study determined the hydrodynamic condition of tsunami inundation flow that disrupts the evacuation activity, by using a simple hydrodynamic model. 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 highly tsunami risk area from the practical point of view, such as tsunami evacuation plan in the tsunami–prone area that does not have adequate time for evacuation.

The present study was applied to the possible tsunami hazard at the Seattle Waterfront and suggested that tsunami casualty may occur for 15 minutes during the time of 3 to 18 minutes after the tsunami generation time. Also, by introducing Tsunami Casualty Index (TCI), the tsunami casualty estimation model illustrates the spatial distribution of the possibility in terms of tsunami casualty occurrence within the Seattle Waterfront.

We believe that the recent improvements of tsunami inundation modeling enables to contribute to more practical use to tsunami evacuation planning, such as finding the best tsunami evacuation route, combined with the use of Geographic Information System.

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