Effects of the Tsunami Countermeasures Focusing on the Tsunami Arrival Time in Kamakura

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While tsunami hazard maps show the expected maximum inundation depth, most of them do not show the minimum arrival time that is useful for considering evacuation plans and countermeasures. The objectives of the present study are thus to introduce a concept of an integrated tsunami minimum arrival time that can be used for considering evacuation strategy and countermeasures in order to maximize the least evacuation time among all the expected tsunamis. We applied this concept to the coastal area of Kamakura, Japan, as a case study and created maps for this integrated minimum time using an unstructured grid circulation model, FVCOM. We then considered three types of countermeasures (construction of elevated road, water gate, and elevated river wall) and evaluated them in terms of maximizing the expected least evacuation time and reducing the inundation area. This concept is considered to be useful for planning countermeasures because their effectiveness can be evaluated quantitatively.

Key Words : *Tsunami minimum arrival time, hazard map, countermeasures, inundation, FVCOM.*

1. INTRODUCTION

Tsunami hazard maps have essential roles in effective evacuation as part of a tsunami warning system, showing expected inundation areas and depth. They are useful for residents to consider how to evacuate and for administrative bodies to consider countermeasures, including construction of disaster prevention facilities¹⁾. Most of the tsunami hazard maps, however, do not show the minimum tsunami arrival time. One of the reasons for excluding the information about the minimum arrival time may be its potential misleading effect on the residents' decisions¹⁾.

Although it is necessary to beware of a potential risk of misleading residents' decisions, provision of reliable information about the minimum tsunami arrival time may lead to prompting residents to remind the limited time and to consider their evacuation strategies, including the importance of their prompt action. Using this information, local governments can also decide which area should be pri-

oritized during evacuation. In addition, development of a map for an integrated least tsunami arrival time considering all the expected major tsunamis may contribute to evaluating countermeasures in terms of maximizing the least evacuation time among all the expected tsunamis²⁾. An application of tsunami arrival time map was, for example, presented as part of an integral framework for the formulation of tsunami evacuation plans in the Western Coastal Plain on the Salvadoran coast, El Salvador³⁾.

Yuigahama Coast, a concave bay located in Kamakura City, Kanagawa, Japan, has experienced damages due to past tsunamis. One of the major residential areas and the main road connecting the coastal road and the downtown area are located close to Namerigawa River. A hazard map for tsunami arrival time seems crucial to approximate evacuation time in this area. Kamakura City government and Kanagawa Prefectural government, however, do not show a map for arrival time in the expected inundation area except along the coastline^{4, 5)}. The objectives of the present study are thus to introduce

Fig. 1 Mesh system of: a) Whole domain, b) Kamakura area, c) Countermeasures in Kamakura.

a concept for an integrated tsunami minimum arrival time considering all the expected tsunamis and to consider effective measures for increasing the least evacuation time.

2. METHODOLOGY

Since the spatial scale of Kamakura area is much smaller than that of major tsunami propagation areas, application of an unstructured mesh model is an effective way to analyze the phenomena. Thus, an unstructured grid Finite Volume Coastal Ocean Model (FVCOM)⁶⁾ is utilized to simulate tsunamis. The mesh size varies from 50 km in the ocean, 1 km in tsunami source areas, and 5 m in inundation areas in Kamakura (Fig. 1a, b). The mesh systems for the propagation area and inundation area consist of 667,834 nodes and 1,290,815 triangular elements and 886,122 nodes and 1,720,490 elements, respectively. The mesh for tsunami propagation area was constructed using Surface-water Modeling System 10.1 (Aquaveo), covering from 120° to 177.2° E in longitude and from 1.4° to 59.7° N in latitude.

Bathymetric data provided by ETOPO with 10 minute resolution was adopted for the whole domain

except the area around Japan using GEBCO_08 bathymetric data with 30 s resolution. Ground heights in 5-m resolution, provided by Geospatial Information Authority of Japan (GSI), Ministry of Land, Infrastructure, Transport and Tourism, were interpolated over the expected inundation area in Kamakura.

Spatial variations in the initial surface elevation were constructed using a fault model of Okada⁷⁾. To develop a map for the minimum arrival time, a critical value of inundation depth should be determined and its value of 0.5 m was chosen in this study, considering that people and cars are likely to be swept away when the inundation depth exceeds this value⁸⁾.

A contour map for the minimum arrival time were prepared, integrating simulation results for all the expected major tsunamis cases hitting Kamakura, including Meiou, Keichou, Genroku Kanto, Kannawa-Kouzu Matsuda, Minami Kanto, Kanagawa-ken Seibu, and Bousou Peninsula earthquakes and tsunamis. Their fault parameters are summarized in Table 1. For each earthquake and tsunami, four types of countermeasures considered to be effective in Kamakura were investigated in terms of the magnitude of tsunami arrival time, inundation area and

Table 1 Fault model parameters

Fault Model	Distance from Kamakura [km]	Lon. [°]	Lat. [°]	Depth [km]	Strike [°]	Dip [°]	Rake [°]	Length [km]	Width [km]	Slip [cm]
Meiou	208	138.55	33.63	35.61	62	60	270	220	80	800
Keichou	176.4	138.95	33.79	35.61	250	60	270	285	80	800
Genroku Kanto	71.5	139.63	35.26	12.60	315	30	153	85	50	670
		140.40	35.01	4.03	255	20	90	57	23	1200
Kannawa- Kouzu Matsuda	23.2	141.30	34.92	12.60	300	30	135	100	50	710
		139.27	35.27	4.88	145	50	90	29.56	12.56	300
Minami Kanto	7.5	139.29	35.29	4.79	280	75	90	15.26	10	300
		139.21	35.36	11.30	285	26	147	22	45	740
Kanagawa-ken Seibu	37	139.79	34.25	12.20	296	23	138	63	55	470
		139.16	35.23	11.80	170	80	90	14	14	500
Bousou P.	317.1	139.19	35.11	8.89	170	80	90	14	14	500
		142.65	34.03	17.70	0	45	90	185	50	1500

inundation depth.

Case 1 is a control without countermeasures, used to evaluate the effectiveness of the cases with countermeasures. Case 2 is elevating the coastal road by 1 m by constructing a dike-like structure to reduce tsunami inundation. Case 3 is installing a 5.5-m high water gate at the mouth of Namerigawa River to reduce inundation depth along the river. Case 4 is elevating a 5.5-m high river wall by 1 m to reduce tsunami overflow along the river wall (Fig.1c).

The time step for the external gravity mode is 0.05 s. A wet and dry treatment method was utilized to compute inundation. The drag coefficient was determined from the logarithmic law of the wall posing the minimum value of 0.0025. Horizontal two-dimensional computations were performed on a MPI-parallel supercomputer HA8000 (Hitachi Ltd.) at the University of Tokyo and Kyushu University⁹⁾.

3. RESULTS AND DISCUSSION

(1) Map for the integrated minimum time

A series of simulations were performed for case 1 (no countermeasure) adopting seven types of tsunami. The minimum time when inundation depth reaches the critical value of 0.5 m at each mesh was determined and compared among the results of the seven types of tsunamis. The minimum time was then extracted at each mesh among the minimum times for all the types of tsunamis. Finally a contour map for the extracted minimum time was made as shown in Fig.2. In this case, the present coastal road and 5.5-m high river wall were considered. The minimum times less than 30 minutes across the domain are due to Genroku Kanto, Minami Kanto, and Kanna-wa-Kouzu Matsuda tsunamis while those between 50-60 minutes are due to Meiou and Keichou tsunamis. Tsunami flows basically reach the tip of the bay and the area along the river earlier than the area in the bay sides.

(2) Map for the difference in the minimum time

Fig.3 shows maps for the difference in the minimum time t_{diff} between a case with one of the countermeasures and the control given by:

$$t_{\text{diff}} = t_i - t_1 \quad (1)$$

where t_i is the minimum time for a case with one of the countermeasures and t_1 is the minimum time for case 1 without countermeasures. Blue or pink color shows the areas where the minimum time becomes longer or shorter after an application of a countermeasure, respectively. Yellow color shows the areas where the time difference is less than 0.5 min.

Fig. 2 Map for the integrated minimum time for case 1 (control).

Fig. 3 Maps for the difference in the minimum time: a) case 2, b) case 3, and c) case 4.

Fig.3a shows a map for the difference in the minimum time for the case 2 of the elevated road. Blue colored areas are observed around the elevated road. In case 3 (Fig.3b) and case 4 (Fig.3c), blue

colored areas showing longer minimum time are localized around the implemented places. Almost no pink colored areas with the minimum time becoming shorter are seen except the places at the edges of the inundation area where wave reflection causes inundations in the neighboring areas.

After applications of countermeasures, the area with the minimum time being extended increases by 13.1%, 4.8%, and 4.3% for cases 2, 3 and 4, respectively. The highest reduction in the inundation area is achieved by case 2 (elevated road), followed by case 3 (water gate) and then case 4 (elevated river wall). The elevated road can reduce the inundation area more than the other two countermeasures probably because the elevated road can block more volume of water than the other two cases.

(3) Map for integrated maximum velocity

Fig.4 shows a map for an integrated maximum velocity for case 1 (no countermeasure) extracting the maximum velocity at each mesh from the seven types of tsunamis. Larger velocities are observed in the area along the coastline and the downstream area of Namerigawa River while smaller velocities are seen in the northern inundation area. The smaller velocity area corresponds to the area with smaller inundation depth or the area with higher ground elevation.

(4) Map for the difference in maximum velocity

Fig.5 shows maps for the difference in the maximum velocity v_{diff} between a case with one of the countermeasures and the control given by:

$$v_{\text{diff}} = v_i - v_1 \quad (2)$$

where v_i is the maximum velocity for a case with one of the countermeasures and v_1 is the maximum velocity for case 1 without countermeasures. Blue or pink color shows areas where the maximum velocity becomes larger or smaller after an application of a countermeasure, respectively. Yellow color shows the areas where the difference in the maximum velocity is smaller than 0.5 m/s.

Fig.5a shows a map for the difference in the maximum velocity for case 2 with the elevated road. Maximum velocities are reduced along the elevated road. Fig.5b shows a map for the difference in the maximum velocity for case 3 with the water gate. Maximum velocities are reduced around the river mouth and up to approximately 650 m from the mouth. Fig.5c shows a map for the difference in the maximum velocity for case 4 with the elevated river wall. Maximum velocities are found to decrease along the river. Applications of countermeasures lead to an increase in the area with reduction in the maximum velocities by 23.2%, 19%, and 18.6% of

Fig. 4 Map for integrated maximum velocity for case 1 (control).

Fig. 5 Maps for the difference in the maximum velocity: a) case 2, b) case 3, and c) case 4.

the inundation area for cases 2, 3 and 4, respectively.

Blue color shows the areas where the maximum velocities become larger after applications of measures, which areas are seen around the location of countermeasures. In some areas the maximum velocities increase because of an increase in the ground level due to implementation of the countermeasures.

These results show that the difference in the maximum velocities can be clearly seen around each

of the measures. In particular, case 2 (elevated road) is considered to be most effective in increasing the area with reduction in the maximum velocities.

(5) Inundation depth and flow velocity at point A

The results shown in Fig.3 and Fig.5 indicate that case 2 is the most effective countermeasure leading to the highest percentage of the area where the minimum time increases and the maximum velocity decreases. Time series of inundation depth and velocity at point A (see Fig.2) for case 1 (no countermeasures) and case 2 (elevated road) are shown in Fig.6. After elevating the road, the inundation depth and velocity decrease by 0.37 m in Meiou tsunami (Fig.6a) and by 0.65 m/s in Keichou tsunami (Fig.6b), respectively. The velocity, however, increases by 0.21 m/s in Meiou tsunami, probably because of the wave reflection around the south side of point A.

4. CONCLUSIONS

A concept of an integrated minimum time was introduced, which time means, at each location, the least time when the inundation depth firstly reaches some threshold value amongst all the expected tsunami simulation cases. This concept was applied to the coastal area of Kamakura, Kanagawa, Japan, using FVCOM, and maps for the integrated minimum time were created supposing the threshold value of the inundation depth to be 0.5 m and considering seven expected earthquake and tsunamis (Meiou, Keichou, Genroku Kanto, Kannawa-Kouzu Matsuda, Minami Kanto, Kanagawa-ken Seibu, and Bousou Peninsula).

Using this concept, we considered the effectiveness of countermeasures to maximize expected minimum evacuation time, including the implementation of elevated road, water gate in a river mouth, and elevated river wall. Among these countermeasures, the elevated road case was the most effective for maximizing the expected minimum evacuation time and reducing the inundation area as well as lowering the maximum velocities. The effects of water gate and elevated river wall are localized to the area around the location of the implementations while the elevated road is more influential due to its large magnitude of the scale.

Fig. 6 Time series of inundation depth and velocity at point A

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