第15回性能に基づく橋梁等の耐震設計に関する
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Tsunami Propagation Analysis in Shizugawa District based on Recorded Videos

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1. INTRODUCTION

The 2011 Tohoku earthquake, also known as the 2011 Great East Japan Earthquake, was a magnitude 9.0 undersea megathrust earthquake that occurred at 14:46 (JST) on 11 March 2011, with its epicenter about 130km southeast to Oshika Peninsula. It was one of the most powerful earthquakes to have hit Japan. Due to the great tsunami triggered by the earthquake, areas along the pacific coast of Japan's northern islands suffered tremendous destructions. According to the report of Japan Meteorological Agency[1)], inundation heights were observed between about 7m and about 12m from the northern part of Fukushima Prefecture to the southern part of Iwate Prefecture as shown in **Fig. 1**. The tsunami induced an extensive loss in Shizugawa city, located at Minamisanriku town of Miyagi prefecture.

According to the work of Geospatial Information Authority Japan[2)], the tsunami affecting area of Shizugawa has been outlined in **Fig. 2**. There were 39 bridges in the affecting area originally. After the tsunami impact, 41% bridge girders of the bridges have been flowed out (defined as Rank A damage) and 59% of them were survived (defined as Rank C damage).

Fig. 3 shows the study flow of this paper. The authors will focus on the characteristics of tsunami in the propagation process. Study is based on the videos shot when tsunami came. For the study objective, we will investigate the tsunami propagation process firstly. The different characteristics for tsunami propagation speed and direction between in river and on land area will be investigated. Secondly, the time depended variation of tsunami height and the relation between tsunami height and tsunami velocity will be estimated. At last, two different wave inundation conditions will be evaluated based on the characteristic of tsunami height variation. The estimations for outflow of Hachiman Bridge will be conducted based on different wave shapes. For the further study subjects, we want to summarize the most

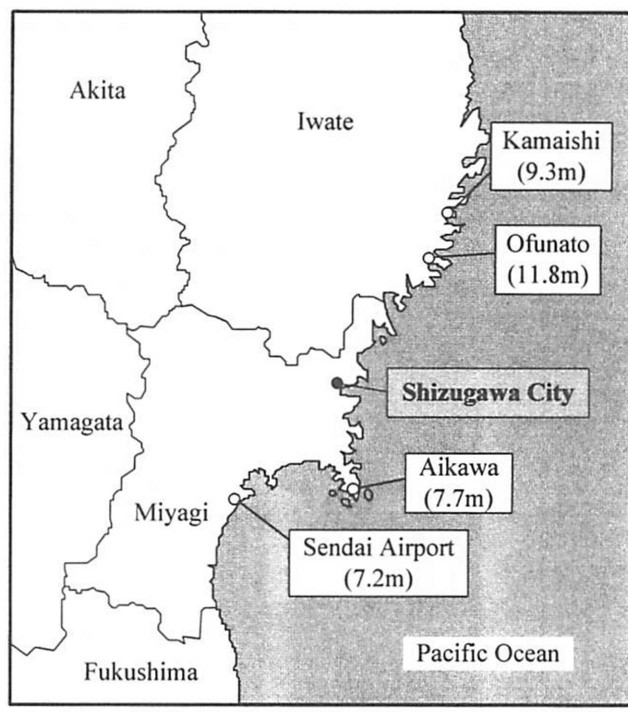


Fig.1 Location of Shizugawa City

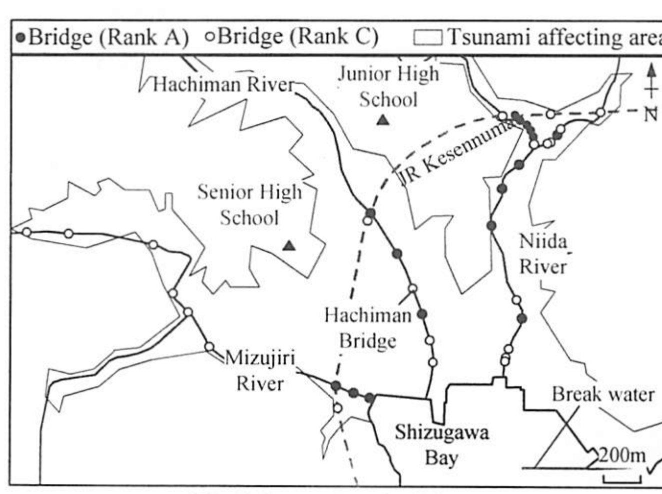


Fig. 2 Survey Area in Shizugawa

severe condition during the tsunami propagation for the damage of structures. The influence from hydrostatic force on the tsunami impact is also expected to be figured out based on the current study.

2. EVALUATION OF PROCESS FOR TSUNAMI PROPOGATION:

In order to check the features of the tsunami propagation, this chapter will introduce the study basis and area firstly. After that, the characteristics for the different propagation speed and direction of tsunami in river and on land area will be discussed.

(1). Study Basis and Study Area

The authors possessed two videos that were shot when tsunami came. The shoot position was located in Shizugawa Junior high school and Senior high school, respectively. The video shot areas can be referred from **Fig. 4**. Thus, based on these video shot areas and the damage condition, the A area, framed in **Fig. 4** and being the central part of Shizugawa, is taken as the study area. The process for the tsunami propagation in this area will be evaluated.

In the following contents, the key phenomena at some time points from the reordered videos will be introduced. The authors defined the time point when tsunami began inundating the breakwater (position illustrated in **Fig. 2**) as 0:0. As shown in **Fig. 5**, tsunami overflowed the breakwater (position ①) at 3:59. After overflow to the water gate (position ②), tsunami began inundating the Hachiman River at 5:30. 19s later, tsunami began inundating Niida River (position ③) because the smaller width compared with Hachiman River. 33s later from the beginning of inundation for Hachiman River, the tsunami came to the Shiomi Bridge (position ④) which is about 230m far from the water gate (position ②). From this, we know the tsunami velocity is near to be 7.0m/s in the initial inundation stage. At 08:35, tsunami overflowed from the Mizujiri

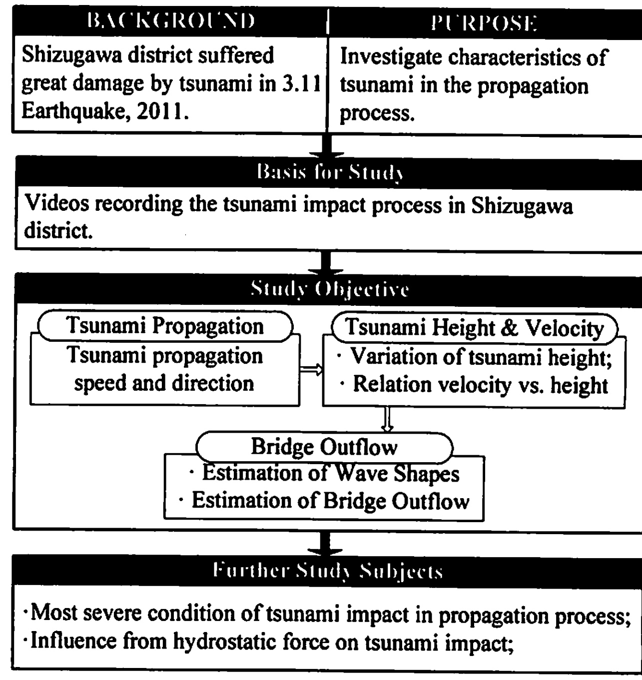


Fig.3 Flow of Study

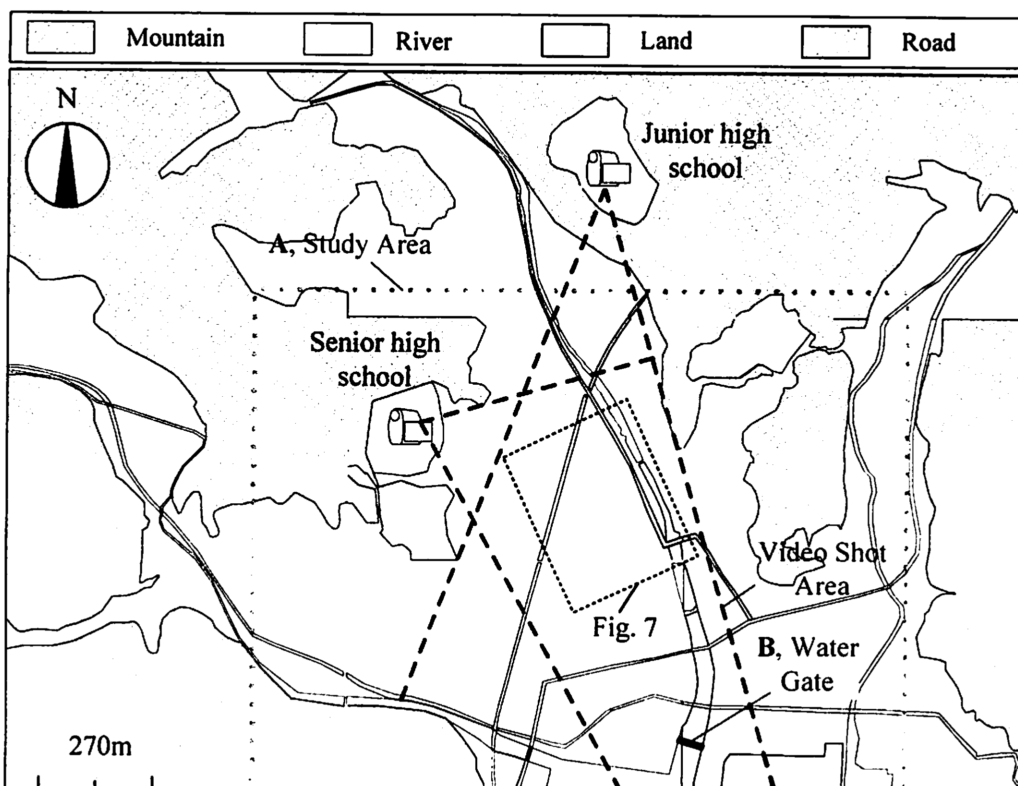


Fig. 4 Study Area

River inundated into the land area along JR line as shown in position ⑤. After the overflow of JR line near Hachiman River, girders and piers of Hachimangawa Bridge (position ⑥) were flowed out at 9:50.

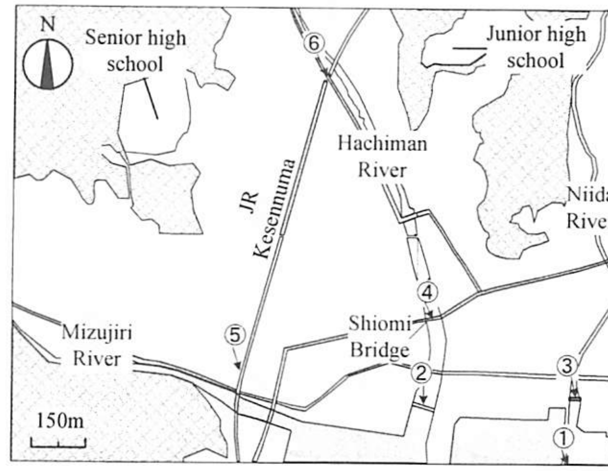
(2). Process of Tsunami Propagation

For obtaining the tsunami propagation process, the position of the tsunami wave front and the inundation direction in some time points should be estimated. The authors will explain the evaluation methods in the following contents. Tsunami in the reordered videos can be divided into two conditions. One condition is that tsunami can be observed directly combined with the use of Google earth. Thus, the wave front position and direction can be judged immediately. While in the second condition, the tsunami cannot be observed directly due to the shelter of view from buildings. With respect to the second condition, the evaluation method is presented in **Fig. 6** and **Fig. 7**. When the tsunami was trapped into the building area, dust was raised due to the tsunami impact. As shown in **Fig. 6**, the raising dust is near the building (1), the position of which can be found through Google earth. This position is considered as the position for the tsunami wave front. Soon after the raising of dust, building (1) was washed away by the impact. Flowed direction can be judged as roughly toward to building (2) which was not flowed out currently. By searching positions of building (1) and (2) in the Google earth (**Fig. 7**), the propagation direction can be estimated.

Based on the evaluation methods introduced above, the conditions of tsunami propagation in different time points were estimated as illustrated in **Fig. 8**.

Fig. 8-(a) shows the time point in which the tsunami began to inundating. Though all equipped with water gates in the mouths of three rivers (Mizujiri, Hachiman and Niida River), tsunami inundated more quickly in the river than on land. Tsunami in the river area (such as point A) inundated along the river. However, inundating direction on the land area (point B) is tilted from the river to the land. And it seems that tsunami inundating the land area is overflowed from river area. With the development of propagation, the tsunami in river areas inundated further as presented in **Fig. 8-(b)**. It has the trend that among the three rivers, tsunami inundated more quickly in the Hachiman River which has greater width than the others. For the further propagation condition as illustrated in **Fig. 8-(c)**, tsunami (Point C and D) overflowed from Mizujiri River inundated laterally towards the land area along the JR Kesenuma Line, with relatively high foundation. Afterwards, as presented in **Fig. 8-(d)**, tsunami overflowed to the JR line. Tsunami that was laterally overflowed from river area (E region) seems joining together with the tsunami flowing on the land area (F region).

As a result, based on the analysis above, the following contents can be known. Tsunami inundate



Position	Passed Time	Key Phenomena from Video
①	3:59	The breakwater is overflowed by tsunami
②	5:30	Tsunami began inundating the Hachiman River
③	5:49	Tsunami began inundating the Araita River
④	6:03	Tsunami began impacting the Shiomi Bridge in Hachiman River
⑤	8:35	Tsunami overflowed from Mizujiri River inundated to land area along JR line
⑥	9:50	Piers and girders of Hachimangawa Bridge were flowed out

Fig. 5 Key Phenomena from Videos

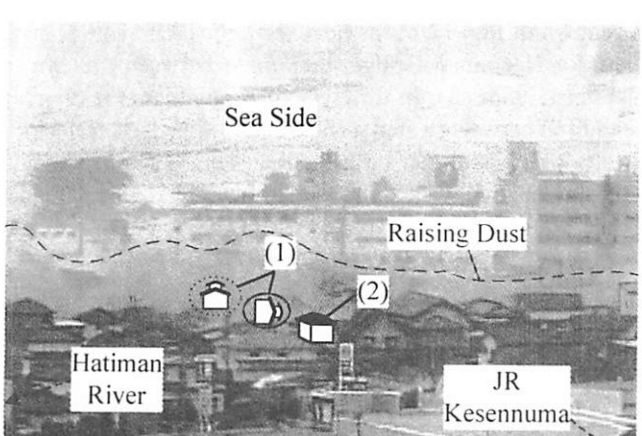


Fig. 6 Video Screen

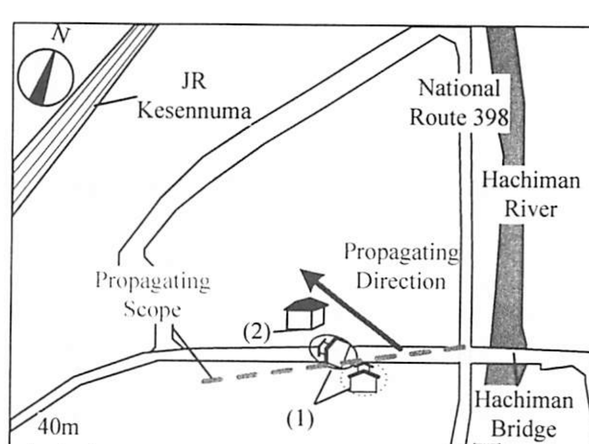
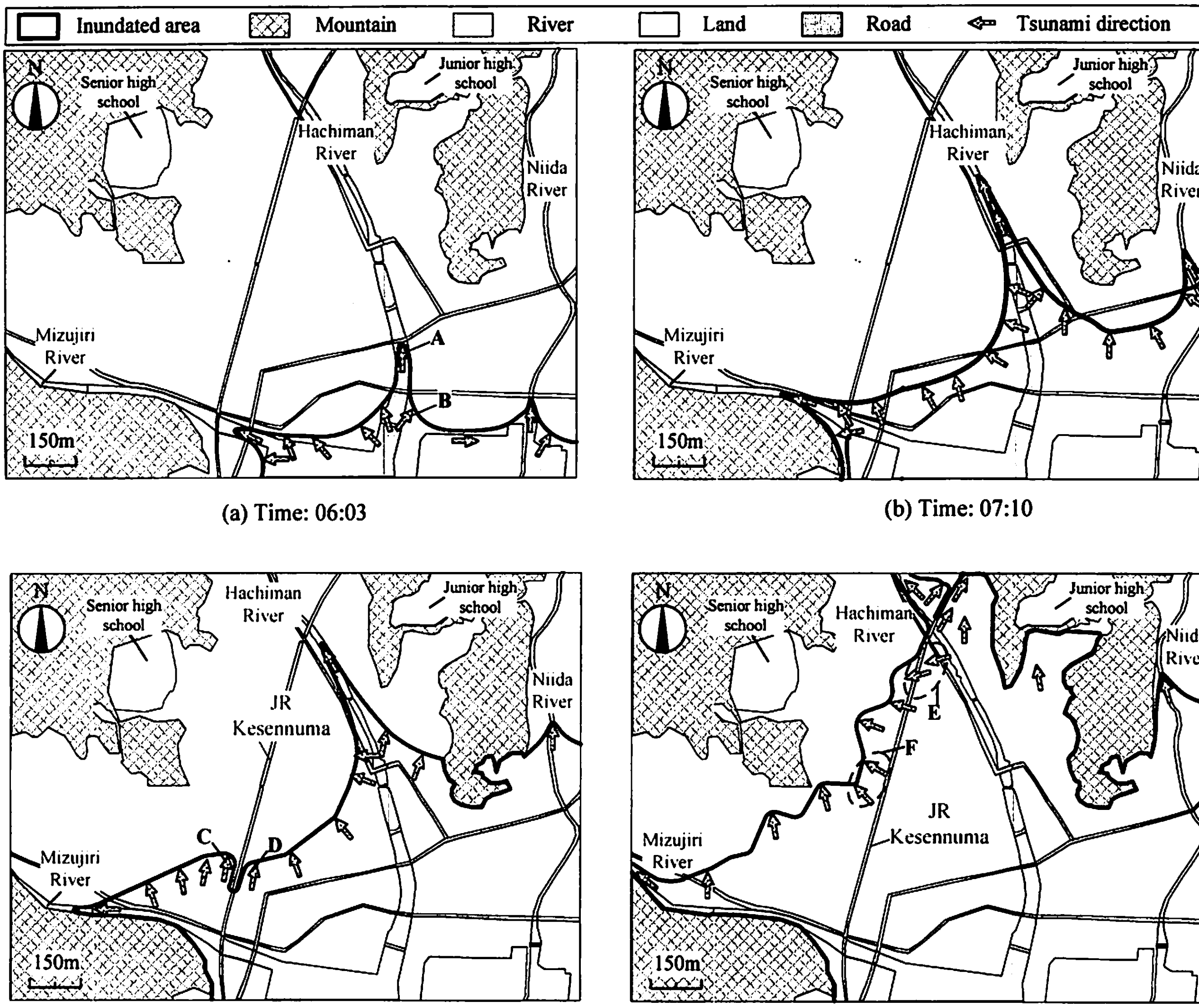


Fig. 7 Confirmation of Propagation Direction



(a) Time: 06:03

(b) Time: 07:10

(c) Time: 08:35

(d) Time: 10:10

Fig. 8 Process of Tsunami Propagation

faster in the river area than on the land. For the overall tsunami propagation process, it is considered that tsunami will inundate the river area firstly. Then, it will be overflowed laterally from river area and inundate on the land area. Afterwards, the overflowed tsunami from river area will join together with the tsunami inundating the land area. The different inundating directions are considered would produce different damage capacity to structures in river and on land. This should be investigated as a future topic.

3. VARIATION OF TSUNAMI HEIGHT AND VELOCITY:

For studying the characteristic of tsunami height, the time depended variations of tsunami height will be evaluated firstly. Afterwards, based on the estimation of tsunami velocities, the relation between tsunami height and velocity will be studied secondly. The results obtained in this chapter will be the basis for estimation of wave shapes and bridge outflows in the next chapter.

(1). Time Depended Variations of Tsunami Height:

The methods for estimation of tsunami height (tsunami height 0 is defined as water level just before the tsunami coming to the estimation position) will be introduced by taking the Hachiman Bridge as an example. As shown in **Fig. 12** of the next section which is the plan view for Hachiman Bridge, the length between the two piers is 11.98m (l_a). In different time points, the relative height (l_b) between water surface and bridge deck surface (in the front side) can be estimated from its proportion with the length l_a. Thus, the tsunami height is calculated by the **Eq. (1)**:

$$h = l_{b0} - l_b \tag{1}$$

Where,

l_{b0} is the relative height between water and bridge deck surface right before the tsunami coming to the estimation position.

The variation of tsunami height near Hachiman Bridge is presented in **Fig. 10**. Further, use the same method, the variation of tsunami height for the breakwater is also estimated and presented in **Fig. 9**.

Firstly, the variation of tsunami height near breakwater (**Fig. 9**) will be studied. Before 3.5 min, tsunami height raised with smaller pace as 0.7 m/min (2.45 m in 3.5 min). During the time interval from 3.5min to 6.2 min, the raising pace become faster as 2.46 m/min. After 6.2 min, tsunami height cannot be estimated due to the lack of reference object. In the total 6.2min, the tsunami height near breakwater raised from 0m to 9.1m with the average raising speed as 1.47 m/min.

Secondly, the variation of tsunami height near Hachiman Bridge is shown in **Fig. 10**. At 5.4min, the tsunami came from the breakwater to the Hachiman Bridge. Before 9.0min, the tsunami height raised in the speed 3.19 m/min (11.5m in 4.6min). Afterwards, the tsunami height varied to be the maximum value 14.8m at the time point 12.0min with relatively small pace as 1.1 m/min. The average raising speed of tsunami height is estimated as 2.24 m/min.

Further, before the time point 9 min, the raising speed of height near Hachiman Bridge is in greater level (3.19 m/min) which is different with the trend in Breakwater. This is considered to be the influence from the water gate (B in **Fig. 4**) where the gather of tsunami made the tsunami with greater power and height variation for inundation.

As a result, the average raising speed for tsunami near breakwater and Hachiman Bridge is 1.47 m/min and 2.24 m/min. Tsunami height was rising in relatively small pace inferring the wave shape not to be bore type.

(2). Relation between Tsunami Velocity and Tsunami Height:

From the recorded videos, much debris is found to flow through the Hachiman Bridge. Two distinguished positions near the bridge can be found. The distance between them can be measured through the function of Google Earth. The needed time for the procedure of debris flowing through these two points is obtained by checking the timer of video. Thus, the tsunami velocity is estimated as the ratio between the distance and the time span. Based on this method, many velocities have been estimated in some tsunami heights near the Hachiman Bridge.

The relation between tsunami height and tsunami velocity is shown in **Fig. 11**. Herein, we treat the velocity as 0 when tsunami height is 0. As tsunami would flow back to the sea side after tsunami height varied to the maximum, the velocity was also treated as 0 when tsunami reached the maximum height. Before the tsunami height of about 2m, the tsunami velocity reached to be about 6m/s. After a slight decrease, the velocity increased continually when tsunami attached the bridge deck. Maximum velocity as 7.02m/s occurred during the time span when tsunami was attacking the bridge deck. After the tsunami height of about 6m, entire bridge has been inundated. The tsunami velocity began decreasing and kept to be about 4.5m/s during the heights from 7m

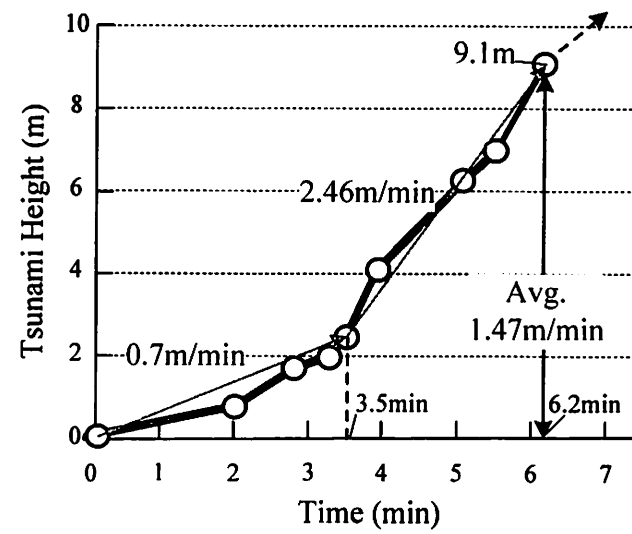


Fig. 9 Time-depended Variation of Tsunami Height (Breakwater)

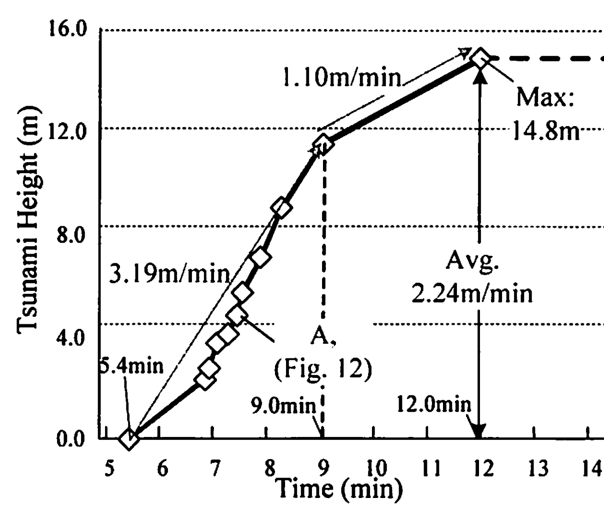


Fig. 10 Time-depended Variation of Tsunami Height (Hachiman Bridge)

to 11.5m. After that, velocity varied to be 0 with the increasing of tsunami height.

From **Fig. 11**, two characteristics can be observed. First one is that tsunami velocity increased and became to be the maximum when tsunami attacked the bridge deck. Second one is that tsunami velocity was decreased suddenly to smaller level when the bridge was entirely inundated. With respect to these two characteristics, the following is considered.

The first characteristic will be discussed. Much debris was discovered to flow together with tsunami when bridge deck was impacted (explained in **Fig. 12**). From the influence of debris, tsunami will be obstructed and accumulated in the impacting side of bridge deck temporarily. After that, with the increase of height, tsunami will flow suddenly with great energy and velocity. This is considered to be the reason for the increase of velocity when the bridge deck was impacted.

Further, the second characteristic will be discussed. The deck of Hachiman Bridge is in the same level with the embankment. Tsunami would overflow to the land area in lateral direction when the deck began to be inundated entirely. Thus, due to the overflow of tsunami to the land area, the velocity has a decrease.

Therefore, due to the influence of debris, tsunami velocity becomes to be the maximum when bridge deck is impacted. For the bridge with its bridge deck in the same height level to the surface of embankment, tsunami velocity will get to be decreased when the bridge deck is entirely inundated due to the overflow of tsunami from the river to the land area.

4. ESTIMATION FOR BRIDGE OUTFLOW:

In this chapter, the authors will introduce the damage condition of Hachiman Bridge which is mentioned in former contents firstly. Secondly, based on the results obtained in the former chapter, the outflow condition of Hachiman Bridge will be evaluated.

(1). Damage Condition of Hachiman Bridge:

Hachiman Bridge with its position shown in **Fig. 2** is located in the National Route 398. It has survived in the tsunami impact. From the plan view of the bridge as presented in **Fig. 12**, it is composed by three spans with the length as 11.98m for each. Due to the tsunami impact, only the handrails of the bridge were curved. Bridge girders have survived, which infers the sufficient resistance of it.

For checking the actual condition of tsunami impact to the bridge in different tsunami height, the point A (7.3 min, 4.8 m) in **Fig. 10** is taken as an example. We know the tsunami has reached the top of handrail in the tsunami impacting side and reached in the bottom of bridge deck in the opposite side. Tsunami is in relatively flat shape but not in the bore type. Further, the authors noticed that much debris was mixed into the tsunami in the Hachiman River. As shown in point B of **Fig. 4**, due to the obstruction of water gate, part of the tsunami inundating the river area changed the inundating direction to the land area at the initial time stage. Thus, many buildings have been washed away from the tsunami impact. Therefore, much debris flowed into the river area together with the tsunami.

The sectional view of the bridge can be referred from **Fig. 14**. The bridge girders belong to the PC-I type with the width as 8.2m, height D as 1.069m (0.4m is added to the pure height of bridge deck[3]).

(2). Estimation for Bridge Outflow:

Before the estimation of the outflow for Hachiman Bridge, the wave shape conditions of tsunami will be evaluated firstly. As concluded in Chap. 3, the tsunami

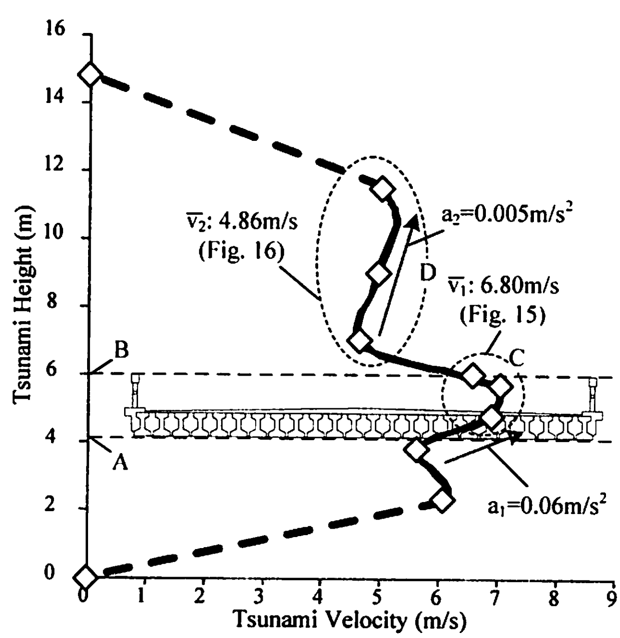


Fig. 11 Relation between v-h (Hachiman Bridge)

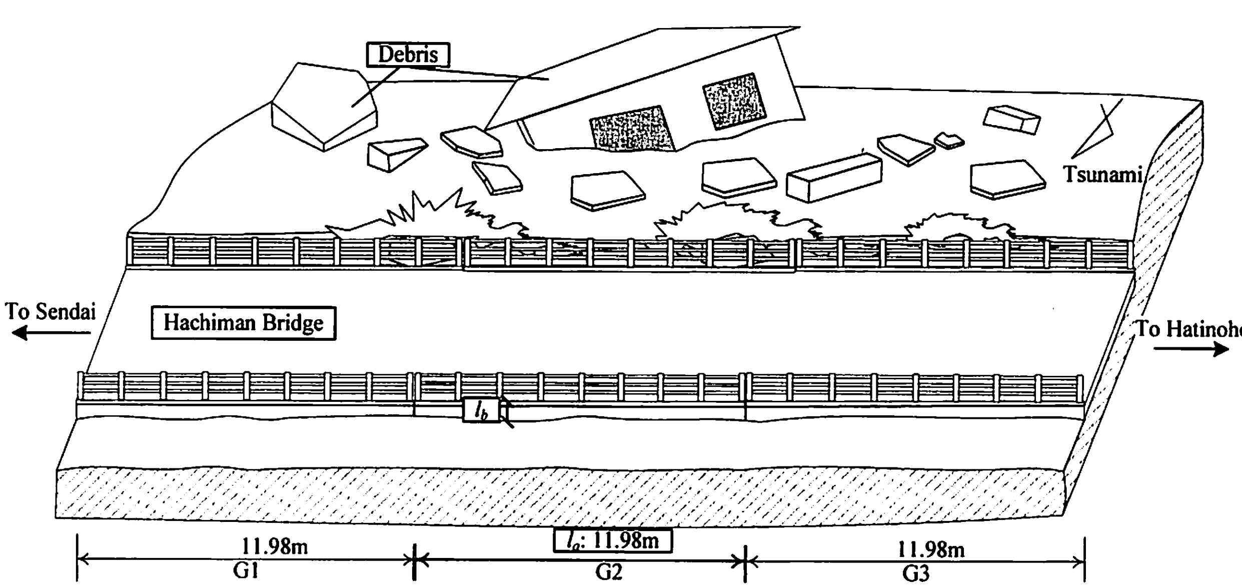


Fig. 12 Plan View of Hachiman Bridge

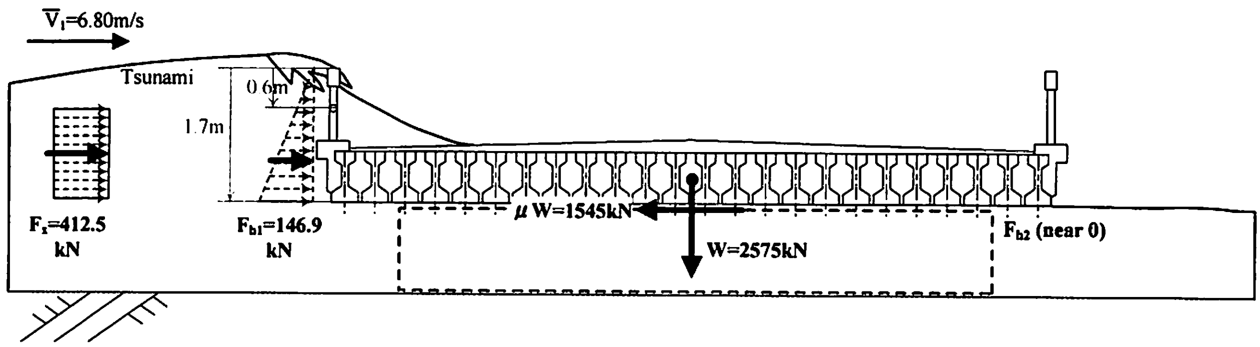


Fig. 13 Wave Shape 1 (Tsunami just Impact on Bridge Deck)

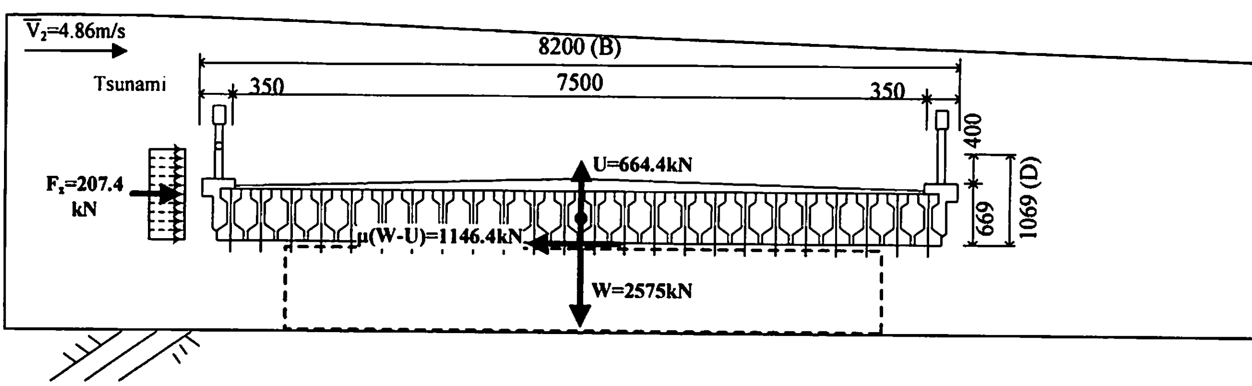


Fig. 14 Wave Shape 1 (Bridge Deck is Entirely Inundated)

height varied in relatively smaller pace which infers the tsunami not to be the bore type. Thus, based on this image and the recorded video screen, two different kinds of the wave shapes have been evaluated as illustrated in **Fig. 13** and **Fig. 14**.

Firstly, as shown in **Fig. 13**, wave shape 1 reflects the condition when tsunami just impacted on the bridge deck. From the actual tsunami condition presented in **Fig. 12**, the tsunami surface in the impacting side was in the similar height with the top of bridge handrail. However, tsunami in the opposite side just reached the bottom of bridge deck. The difference of tsunami height between the impacting side and the opposite side is about 1.7m (sum of the height for bridge deck as 0.7m and the height of handrail as 1.0m). Therefore, the difference of water heads is 1.7m in this condition. Small level of the water head difference further confirms tsunami not being the bore type. The wave shape 1 is corresponding to the C area (**Fig. 11**), in which, the average velocity is estimated to be in greater level as 6.80m/s.

Secondly, the wave shape 2 is presented in **Fig. 14**. Bridge deck was inundated entirely. The tsunami surface at this time is relatively in flat shape without great difference of water head between the impacting side and the opposite side. The wave shape 2 is corresponding to area D (**Fig. 11**), in which the average velocity is estimated as 4.86m/s.

In the two different estimated wave shape conditions, the bridge outflow by evaluating the impact force and resistance will be discussed.

For wave shape 1 condition (**Fig. 13**), the tsunami impact force is considered to be composed by two parts. First one the hydrodynamic force and second is the hydrostatic force[4)], it can be calculated based on **Eq. (2)**:

$$F_x = \frac{1}{2}\rho_w C_d A v^2 + C_m \rho_w A B \frac{dv}{dt} + (\rho_w g h_1 A_1 - \rho_w g h_2 A_2) \quad (2)$$

Where,

F_x is tsunami impact force; ρ_w is density of water (1030kg/m^3); C_d is drag coefficient[5)], which is calculated as 1.33; v is tsunami velocity; A is effective projected area of the bridge girder in horizontal direction; C_m is inertia coefficient which is assumed to be 1.0 here; B is bridge width as 8.2m; dv/dt is acceleration of tsunami velocity; h_1 and A_1 is the water depth and impacting area in the impact side of tsunami; h_2 and A_2 is the water depth and impacting area in the opposite side.

Firstly, the hydrodynamic force part will be evaluated. As concluded in **Fig. 11**, average velocity 6.80m/s in area C is used for calculation. The greatest acceleration a_1 as 0.06m/s^2 near the area C is adopted. Thus, the drag force in wave shape 1 is calculated to be 412.5kN as shown.

Secondly, the hydrostatic force part will be computed. As presented in **Fig. 13**, tsunami in the impacting side is assumed to just attach the top of handrail. Between the water depths from 0.6m to 1.67m (bridge height is

1.07m), the hydrostatic pressure is integrated. For the opposite side, as the tsunami is just attaching the bottom of bridge deck, hydrostatic force is treated as 0. Thus, the hydrostatic force in wave shape 1 condition is calculated as 146.9kN. The hydrodynamic force (412.5kN) is about 2.81 times of hydrostatic force, which is caused by the smaller difference of water head.

Further, the resistance of the bridge is computed by the **Eq. (3)**:

$$S = \mu(W - U) \tag{3}$$

Where,

S is bridge resistance; μ is friction coefficient (0.6, based on research of Rabbat[6]); W is dead load of the superstructure calculated as 2575kN; U is buoyancy which is computed by **Eq. (4)**:

$$U = \rho_w g V \tag{4}$$

Where, V is volume of the bridge deck inner the tsunami.

In the wave shape 1, as bridge deck is just attacked by tsunami, the volume V is near 0, thus the buoyancy is treated as 0. From calculation, the resistance is 1545kN.

Thus, an indicator β is defined as **Eq. (5)**:

$$\beta = \frac{S}{F} \tag{5}$$

In wave shape 1, the resistance is 1545kN which is 2.76 (β) times of tsunami impact force as 559.4kN.

With respect to the wave shape 2, as the tsunami is in flat shape (**Fig. 14**), the difference of water head is ignored and only the hydrodynamic force is considered. Further, as the bridge deck is entirely inundated in this condition, the buoyancy is considered. From **Fig. 11**, the average velocity 4.86m/s and greatest acceleration $0.005 m/s^2$ in area D are used. After computation, the resistance is 1146.4kN (buoyancy as 398.6kN) which is 5.52 times of the impact force as 207.7kN. Therefore, β in both two conditions can explain why the bridge girders of Hachiman Bridge are survived. β is considered effective for evaluating the bridge outflow, which is also confirmed in former study[7].

As a result, β of Hachiman Bridge is 2.76 and 5.52 in the wave shape 1 and wave shape 2 conditions (**Fig. 15**), respectively. From the comparison of β, wave shape 1 condition is considered to be more dangerous though without consideration of buoyancy. This is caused by the greater tsunami velocity in this condition.

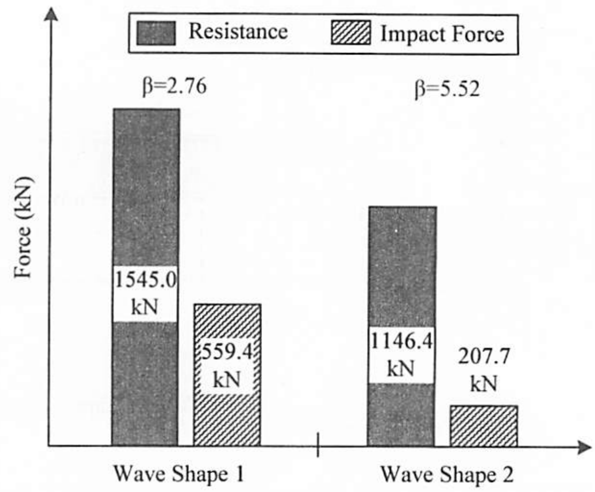


Fig. 15 Calculation of β in Two Wave Shapes

5. CONCLUSIONS

From the investigations for the tsunami propagation, study of variations for tsunami height and velocity, and the estimation of outflow for Hachiman Bridge, the following conclusions are obtained:

(1) From the analysis of tsunami propagation, it is known that tsunami will inundate the river area firstly. Then, it will be overflowed laterally from river area and inundate on the land area. Afterwards, the overflowed tsunami from river area will join together with the tsunami inundating the land area. The different damage capacity to structures in river and on land due to different inundating directions will be the further study object.

(2) Based on the study of variation for tsunami height, the average raising speed for tsunami height near breakwater and Hachiman Bridge is 1.47 m/min and 2.24 m/min. Tsunami height was rising in relatively small pace inferring the wave shape not to be the bore type.

(3) From the relation between tsunami height and velocity, we know that for the bridge with its bridge deck in the same height level to the surface of embankment, tsunami velocity will get to be the maximum when bridge deck is impacted. Velocity will decrease when bridge deck is entirely inundated due to the overflow of tsunami from the river to the land area.

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