- Technical Paper -

DAMAGE TO STRUCTURES DUE TO TSUNAMI AND EVALUATION OF TSUNAMI VELOCITY IN SHIZUGAWA

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ABSTRACT

The Great East Japan Earthquake and the resulting tsunami hit the coastal areas of Japan. It is found that 18% RC and 100% timber buildings were destroyed while 41% bridges were swept off in survey area of Shizugawa. The tsunami velocity is estimated as 5.8m/s by video recording tsunami disaster. The outflow of bridge superstructure in Shizugawa is able to be judged by the level of ratio β between superstructure resistance and wave horizontal force primarily.

Keywords: tsunami, damage, tsunami velocity, ratio β

1. INTRODUCTION

The 2011 Tohoku Earthquake, known as the Great East Japan Earthquake, occurred at 2:46 p.m (JST) on March 11th with the magnitude 9.0. It was one of the most powerful earthquakes to have hit Japan. The earthquake caused an extremely destructive tsunami which induced an extensive loss in Shizugawa, located at Minamisanriku town of Miyagi prefecture, as illustrated in Fig. 1-(a). Based on the field survey, many structures including buildings and bridges suffered tremendous damage.

In this paper, we focus on the structure damage extent, the estimation of tsunami velocity and the analysis of bridge outflow condition in Shizugawa. Firstly the authors present the damage survey result of buildings and bridges in Shizugawa. Next, after the tsunami velocity in Shizugawa estimated, the velocity characteristic of Shizugawa is discussed with the comparison with the velocities in other 4 areas (Fig. 1-(b) to (e)). Finally, by using the estimated velocity, the ratio β between superstructure resistance and tsunami force is computed to judge the outflow of bridge superstructure in Shizugawa.

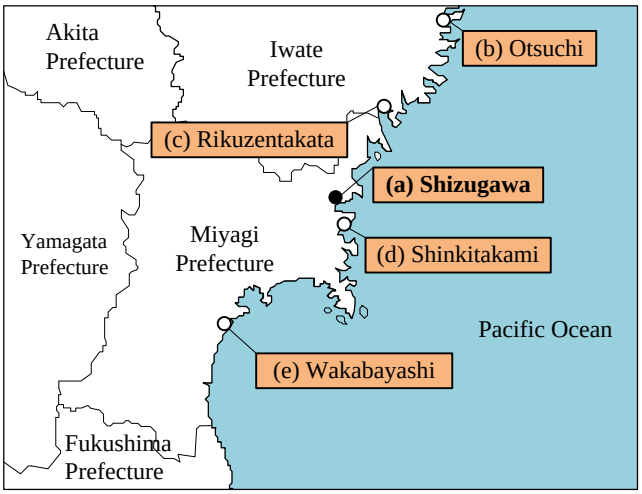

Fig. 1 Location of Shizugawa area

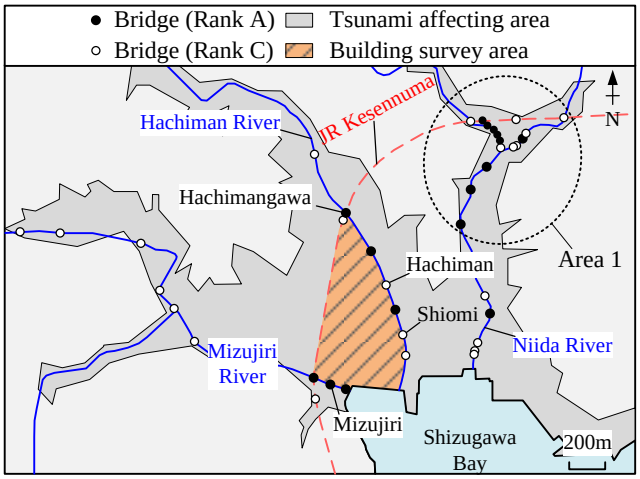

Fig. 2 Survey area in Shizugawa

2. DAMAGE TO STRUCTURES

2.1 Damage to Residential Buildings

According to the work of Geospatial Information Authority Japan[1], the tsunami affecting area of Shizugawa has been outlined in Fig. 2. Due to the most severe damage, we did a survey on the damage to buildings zoomed in the area outlined by Hachiman River, JR Kesennuma Line, Mizujiri River and the shoreline of Shizugawa Bay (Fig. 2).

For simplicity, the buildings are classified into 2 types: timber building and reinforced concrete building

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(RC building) including steel-frame structures.

For the buildings subjected to tsunami, we define the damage state as plotted in Table 1. In order to gain a better understanding, the damage performance to building of each rank is given in Fig. 3, and the corresponding locations of buildings are shown in Fig. 4-(a) to (c).

The Rank A building (Fig. 3-(a)) is a 2-story, steel-frame reinforced concrete structure. After the tsunami surge, a devastating structural damage occurred to it. The second floor collapsed completely.

Fig. 3-(b) illustrates the damage to Rank B building. The exterior walls and non-structural steel-frames of 2 buildings were washed away or bend while the structural steel-frames still stand, which is a serious non-structural damage.

Fig. 3-(c) shows the performance of Rank C building which has a large scale. It withstood the tsunami effect and only experienced the damage to doors and windows. Compared to the Rank B buildings, its concrete wall contains adequate strength against tsunami load.

After classification of damage, the statistical damage result is obtained. In the building survey area, originally 492 buildings had been built. Among them, there are 39 RC buildings totally, the scales and locations of which could be checked in Fig. 4. The proportion of each rank is plotted in Fig. 5-(a). Obviously about 18% RC buildings experienced structural damage of Rank A. Besides that, it is noted that compared to the buildings of Rank B and C, the buildings of Rank A have relatively smaller size. For the damage to timber building, it was more devastating than RC buildings and all of timber buildings were washed away or crashed into pieces (Fig. 5-(b)).

From the investigation result, it is known that most main structures of RC buildings could withstand the tsunami effect, while all the timber buildings are destroyed completely.

2.2 Damage to Bridges

Based on the satellite photograph and the field investigation, the outflow condition of 39 bridges (locations plotted in Fig. 2) in tsunami affecting area are decided.

Table 1 Damage state of buildings

Damage rank	Definition
A	Significant structural damage
B	Non-structural damage only
C	Slight damage

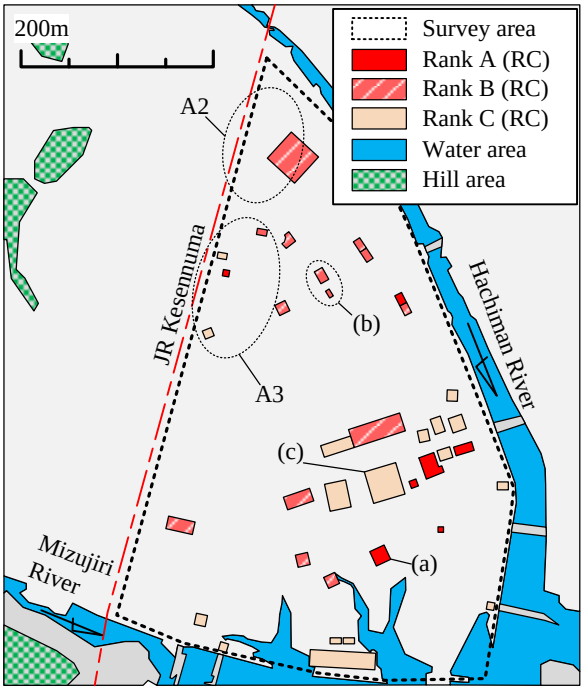


Fig. 4 Investigation area of buildings

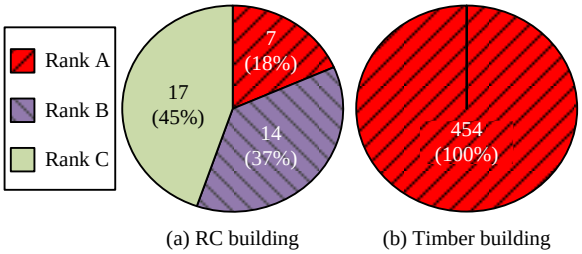
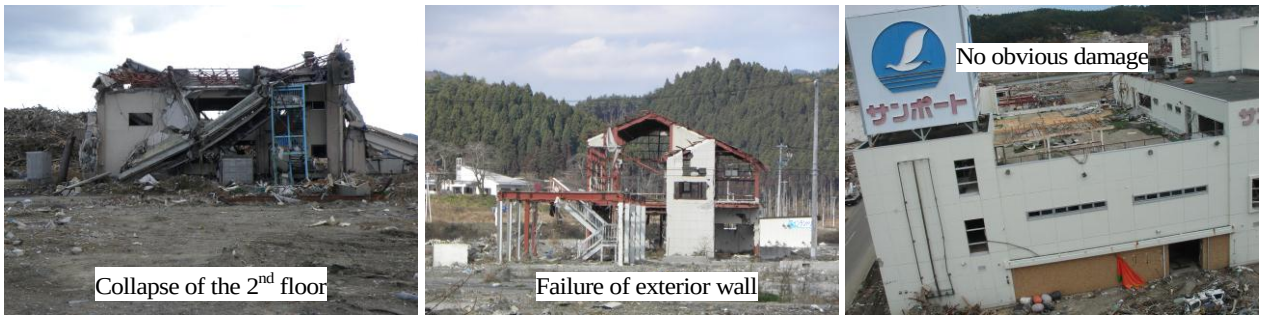


Fig. 5 Investigation result of buildings



(a) Rank A (b) Rank B (c) Rank C

Fig. 3 Damage performance of buildings

Similar to the analysis of buildings, the damage state of bridges is classified in Table 2. Herein, the outflow condition of superstructure is considered as the key factor to define the damage state. Rank A refers the superstructures separated from their substructures completely and could not be used; Rank B means the superstructures moved relative to their substructures but not divorced from supports; Rank C means that only slight damage occurred like guardrail loss and spalling of concrete of bridge components.

As a result, for the superstructures of the 39 bridges, 41% flowed out and belong to Rank A, as illustrated in Fig. 6. Further, all the superstructures of Rank A bridges are confirmed to flow out to the upstream direction.

In addition, compared to other tsunami affecting areas in Shizugawa, the inland Area 1 (Fig. 2), is farther to coastal line (around 1.3km), so the tsunami energy in Area 1 was weaker, due to ground friction. However, on the contrary, among the 16 bridges in Area 1, 9 bridges belong to Rank A, namely the damage in Area 1 is more serious. Therefore, it is concluded that even if for the bridges in farther inland, they are possible to be seriously affected by tsunami as well.

3. EVALUATION OF TSUNAMI VELOCITY

From the Chap. 2, it is known that Shizugawa area suffered extensive damage caused by tsunami. Considering that tsunami velocity is one of the most significant factors deciding the damage level on structures, we estimated it in Shizugawa. Besides that, the comparison of velocities between Shizugawa and other 4 typical damaged areas is carried out to understand the level and characteristics of the velocity in Shizugawa.

3.1 Method of Velocity Estimation

During tsunami landing, some videos recording the flow process of tsunami, were made. It is possible to apply the videos estimating the tsunami velocity.

After tsunami attacking, some houses or barges were swept off and became the floating debris. In video record, it is able to search for 2 distinguished field points where a pile of floating debris, such as moving house, barge or front part of tsunami, passed through. By using the Google Earth's distance measurer and the seconds counter, it is available to obtain the distance between the 2 points and the time span for the floating debris flowed from one point to the other. Then by using Eq. 1, the velocity of debris was computed and this velocity is assumed as the tsunami velocity.

$$v = l / t \tag{1}$$

Where, v is the tsunami velocity (m/s); l is the distance between 2 field points (m); t is the time span for debris flowed between 2 points (s).

3.2 Velocity Result

In Shizugawa, 2 videos made at junior and senior schools are able to be used for the estimation of tsunami velocity. By using the method in Section 3.1,

Table 2 Damage state of bridges

Damage rank	Superstructure
A	Flowed out completely
B	Moved but not divorced from support
C	Slight damage

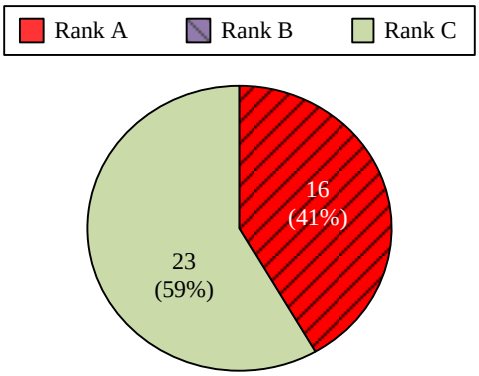


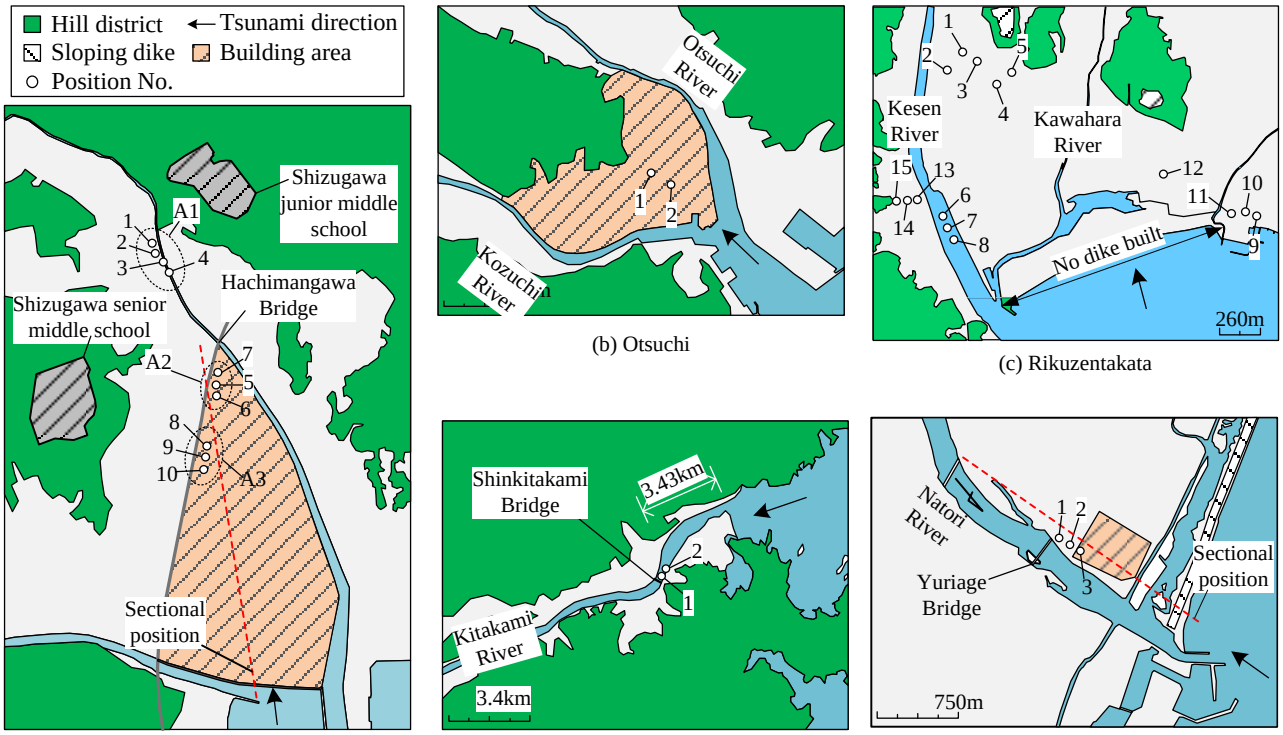
Fig. 6 Investigation result of bridges

Table 3 Tsunami velocity in Shizugawa

Area	Position No.	Debris	l [m]	t [s]	v [m/s]
A1	1	House	45	8	5.6
	2	House	37	8	4.6
	3	Vehicle	111	21	5.3
	4	House	40	6	6.6
A2	5	House	39	5	7.8
	6	House	58	9	6.4
	7	House	161	25	6.4
A3	8	House	63	10	6.3
	9	Ship	57	13	4.3
	10	House	57	14	4.1
Average velocity					5.8

the velocity is measured by 10 times at different positions and the 10 positions are plotted in Fig. 7-(a). Among the 10 positions, No.1~4, No.5~7 and No.8~10 locate at A1, A2 and A3 areas respectively. Table 3 plots the debris types and velocity result in Shizugawa. The average velocity in Shizugawa is 5.8m/s. Moreover, it is noted that the average velocity at A3 is smaller than A2 (A2: 6.9m/s, A3: 4.9m/s). Therefore, the wave action on buildings of A3 should be smaller than A2. From Fig. 4, it is confirmed that the 2 small scale buildings in A3 suffered damage Rank C while the large building in A2 suffered Rank B and this situation is a good agreement with the above different velocities between A2 and A3.

By the same process, the tsunami velocities in Otsuchi, Rikuzentakata, Shikitakami and Wakabayashi have been estimated and the measure positions are illustrated in Fig. 7-(b) to (e). The velocities of each measure position and the average velocity in each area are given in Fig. 8. The overall average is 5.6m/s. It is obvious that the average velocities in Shizugawa,



(a) Shizugawa (b) Otsuchi (c) Rikuzentakata (d) Shinkitakami (e) Wakabayashi

Fig. 7 Velocity result

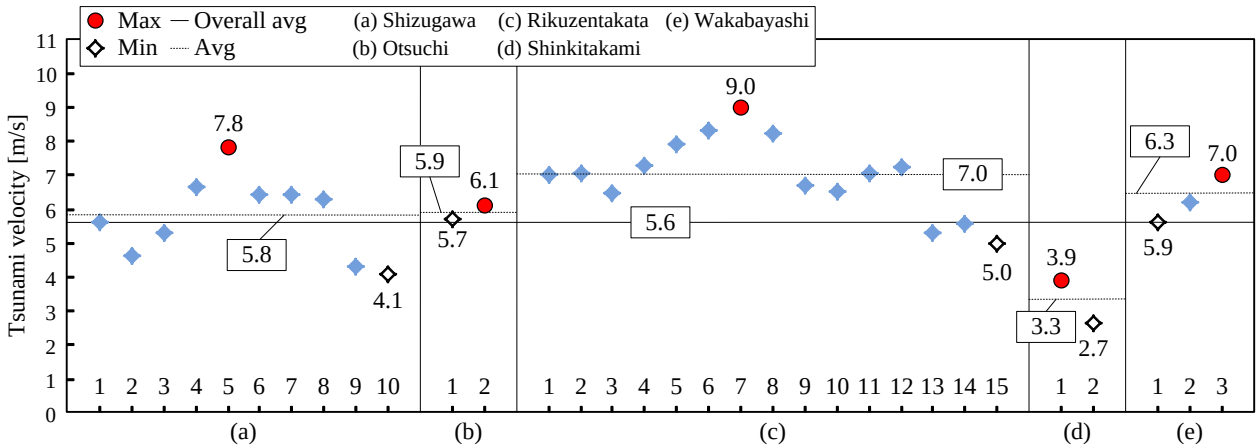


Fig. 8 Maximum, minimum and average velocities

Otsuchi and Wakabayashi have the same level (about 6.0m/s) and are close to the overall average. In addition, the average velocities in Rikuzentakata is greater while in Shinkitakami is smaller than Shizugawa. The velocity in Rikuzentakata change greatly in different positions as well as Shizugawa and it is common that in different measure positions, the velocities have 0~50% difference from the overall average velocity.

3.3 Comparative Analysis on Tsunami Velocities in Shizugawa and Other 4 Areas

In this section, firstly the possible reason why the velocities in Rikuzentakata and Shikitakami are different from Shizugawa is discussed. After that, the authors interpret the probable reason why the velocities in Shizugawa and Wakabayashi show the similar level.

According to the research[2], dikes could bring great resistance on wave strength. In the case of Rikuzentakata, after investigation, it is confirmed that no dike had been built, before tsunami coming, at coastal line (Fig. 7-(c)) while the seawall (4.6m high) stood at the coastal line in Shizugawa. This is the possible reason why the tsunami velocity in Rikuzentakata is larger than Shizugawa.

In Shinkitakami, the velocity measure area is about 3.4km (Fig. 7-(d)) far away from coastal line while the farthest velocity measure area in Shizugawa (A1 in Fig. 7-(a)) is 1.5km far away from coastal line. Therefore, a larger energy loss, caused by ground friction, might occur to the tsunami in the velocity measure area of Shinkitakami. Therefore the velocity in Shinkitakami is smaller than Shizugawa.

In terms of the velocity resemblance among Shizugawa and Wakabayashi, it is possible to explain from the aspect of wave shape characteristics. In order to compare the wave shape, we draw the wave sectional figures of 2 areas, at the time point when the wave went on land about 1km.

Fig. 9 plots the video screen recording the front part of wave in Wakabayshi. From video, the shape and height of forward wave is outlined. Further, by checking the inundation depth[3] (T.P), the maximum wave height at coastal line is confirmed smaller than 10m (as shown at the coastal line in Fig. 10-(a)). In this way, the tsunami sectional Fig. 10-(a) in Wakabayshi was plotted (sectional position listed in Fig. 7-(a)). By the same method, the tsunami sectional figure of Shizugawa is obtained (Fig. 10-(b), sectional position in Fig. 7-(e)). As a result, the waves are able to be simplified as triangle wave, as shown in Fig. 11. The angles of forward wave (γ_1, γ_2) are much smaller than 1° and this demonstrated the 2 waves possibly have the same shape. Thus on the premise of similar wave barrier condition (buildings mainly), the tsunami velocities in 2 areas show the similar level.

4. JUDGEMENT OF BRIDGE OUTFLOW

In this section, the method to judge the outflow condition of bridge superstructures in Shizugawa is described. The Shiomi, Hachiman, Hachimangawa and Mizijiri Bridges are analyzed as typical ones (locations shown in Fig. 2), the details of which are shown in Table 4. All the bridges are highway bridges except for Hachimangawa Bridge (JR Line).

According to former research[4], the authors apply the ratio β between superstructure horizontal resistance and wave horizontal load to judge the damage ranks of bridges. The wave horizontal force, superstructure horizontal resistance and ratio β are able to be evaluated by the following equations.

$$F = 1/2\rho C_d v^2 A \quad (2)$$

$$S = \mu W \quad (3)$$

$$\beta = S / F \quad (4)$$

Where, F is the wave horizontal force (kN); ρ is the sea water density (1.03g/cm^3); C_d is the drag coefficient which is determined according to the Japan specification[5]); v is the tsunami velocity (average

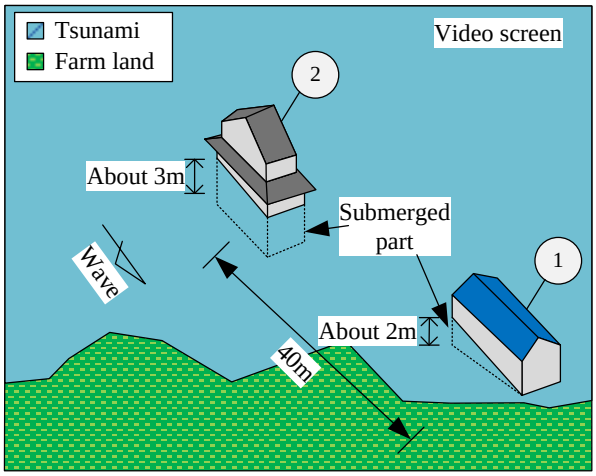


Fig. 9 Estimate of tsunami height

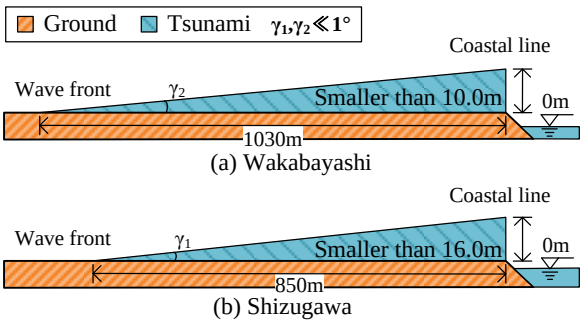
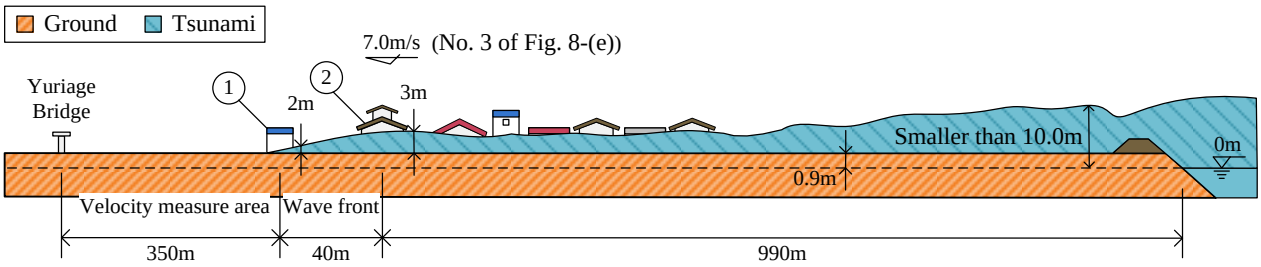
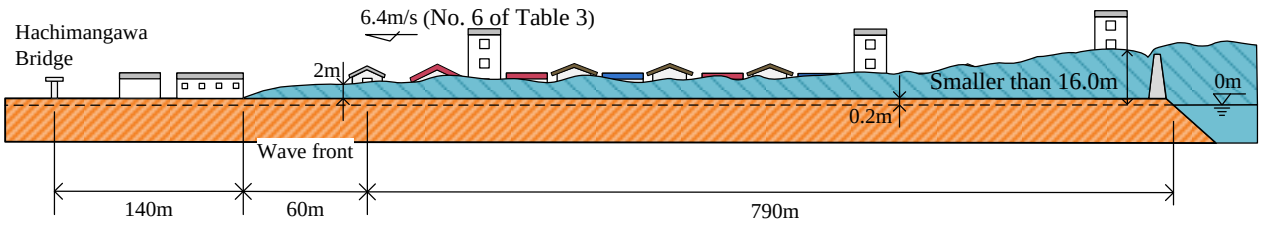


Fig. 11 Comparison of simplified wave shapes



(a) Wave shape in Wakabayashi



(b) Wave shape in Shizugawa

Fig. 10 Wave shapes in Shizugawa and Wakabayashi

Table 4 Bridge details

Bridge	Span Amount	Girder Type	Damage Rank	Span Length L[m]	Width B[m]	Height D[m]	Drag Coefficient Cd	β
Shiomi	3	PC-I girder	C	13.5	11.3	1.365	1.30	3.79
Hachiman	3	PC-I girder	C	11.98	8.2	1.069	1.33	4.88
	1	S 1: PC-I girder	A	22.9	5.5	2.05	1.83	0.52
Hachimangawa	2	S 2, 3: RC-I girder	A	19.8	5.9	2.2	1.83	0.67
	1	S 4: H steel girder	A	13.3	5.6	1.12	1.60	1.36
Mizujiri	3	H steel girder	A	10.5	5.85	1.37	1.67	0.61

velocity of Shizugawa: about 6.0m/s); A is the wave pressure area of projection of superstructure (m^2); S is the superstructure resistance (kN); μ is the friction coefficient (0.6 based on the research[6]); W is the superstructure self-weight (kN).

The β result of 4 bridges is illustrated in Fig. 12. It is notable that the β of 2 damage ranks have different levels. Most of the superstructures of Rank A give the β smaller than 1.0, except for S4 of Hachimangawa Bridge. The average β of Rank C gives a great value which is about 5.5 times as great as Rank A. Besides, compared with that, the 18 bridges damaged by tsunami induced by Sumatra Earthquake have been analyzed by using β, and the average β of Rank C is about 2.8 times as great as Rank A (Rank A: 0.8, Rank C: 2.2)[4]. Therefore, it indicates β is effective to evaluate the outflow condition of bridge superstructure.

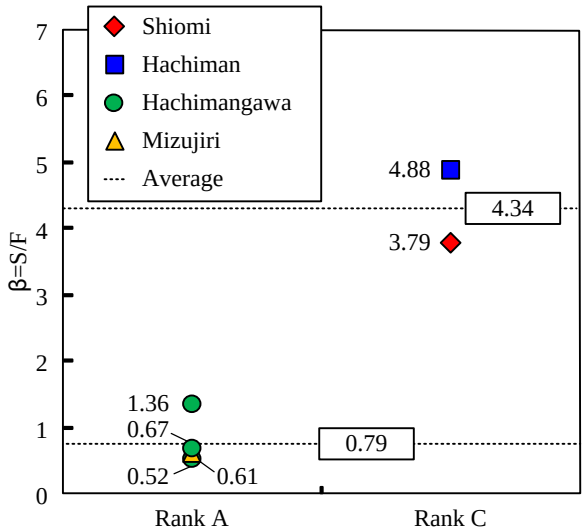


Fig. 12 β result of the bridges in Shizugawa

5. CONCLUSIONS

Based on the field investigation, estimated tsunami velocity and damage analysis of bridges in Shizugawa, the following conclusions are summarized:

(1) Based on the field investigation, in the survey area of Shizugawa, after tsunami attacking, about 55% RC buildings destroyed while all timber buildings were swept off. And the small scale RC buildings suffered more serious damage. Among 39 bridges, about 41% flowed out.

(2) By using video, the average tsunami velocities in Shizugawa, Otsuchi, Rikuzentakata, Shinkitakami and Wakabayashi are computed as 5.8m/s, 5.9m/s, 7.0m/s, 3.3m/s and 6.3m/s respectively. And the average tsunami velocity in Shizugawa (5.8m/s) is close to the overall average (5.6m/s). The wave shapes, when tsunami went 1km inland, of Shizugawa and Wakabayashi have the similar type, which possibly caused the similar level of velocities.

(3) In the case of the 4 bridges in Shizugawa, the average ratio β of Rank C is about 5.5 times as great as Rank A which gives the similar trend to the β of bridges in other research[4]. Therefore, it is possible to apply β evaluating the outflow condition of bridge superstructures.

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