- Technical Paper -

DAMAGE TO STRUCTURES IN RIKUZENTAKATA REGION DUE TO TSUNAMI

Yulong ZHENG[*1], Kenji KOSA[*2], Hideki SHIMIZU[*3] and Li FU[*4]

ABSTRACT

Triggered tsunami from the Great East Japan Earthquake hit coastal areas of eastern Japan. Based on field survey to structures in Rikuzentakata, 70% RC buildings suffered non-structural damage and 100% timber buildings were destroyed while about 40% bridges flowed out. It is found that the indicator β ratio (between bridge resistance and tsunami impact force) is effective to judge outflow of bridge superstructure. Tsunami velocity in Rikuzentakata is estimated to be 7.0m/s. Tsunami velocity in river area is greater than in land area due to the effect of wave shape and friction of land.

Keywords: tsunami damage, residential building, bridge, ratio β, tsunami velocity

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. 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, inundation heights were presumed between 7m to 12m from the northern part of Miyagi Prefecture to the southern part of Iwate Prefecture as shown in Fig. 1.

Soon after the great earthquake, the authors conducted several field investigations to the disaster areas of Japan. In this paper, the authors will firstly analyze the damage conditions of structures including buildings and bridges in the Rikuzentakata region (Iwate Prefecture), which is one of the nearest areas to the epicenter and has suffered great tsunami with the inundation height as about 15m. The tsunami affecting area (from Japan Institute of Construction Engineering [1]) is illustrated in Fig. 2. Total 26 bridges over the main rivers and original 628 residential buildings in one central area (circled with long dash line, Fig. 2) will be analyzed for their damage conditions in detail. Secondly, by detailed investigation and the analysis of a number of bridges, the authors will check the reasonability of using β ratio between girder resistance with lateral load of tsunami for the evaluation of girder outflow conditions. Thirdly, for further damage analysis, the tsunami velocity in Rikuzentakata area will be estimated by two different methods, based on which the characteristics of velocity distribution are also analyzed.

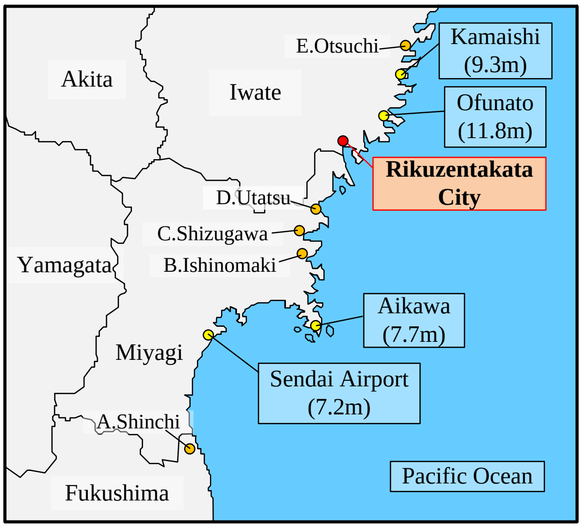


Fig. 1 General Tohoku area

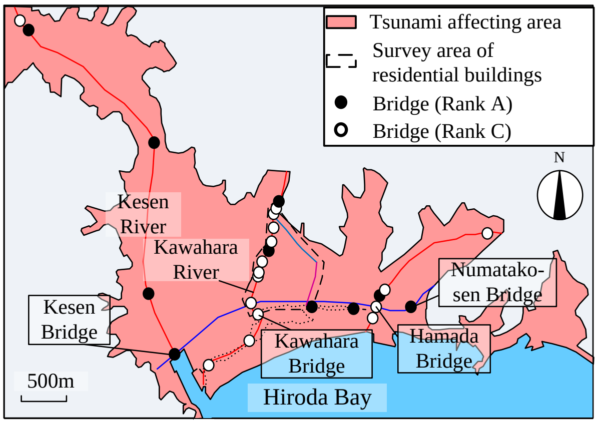


Fig. 2 Research region of Rikuzentakata

*1 Graduate Student, Dept. of Civil Engineering, Kyushu Institute of Technology, JCI Member
*2 Ph.D., Prof., Dept. of Civil Engineering, Kyushu Institute of Technology, JCI Member
*3 Senior Engineer, Structural Engineering Division, Nippon Engineering Consultants Co., Ltd., JCI Member
*4 Research Student, Dept. of Civil Engineering, Kyushu Institute of Technology, JCI Member

2. DAMAGE TO STRUCTURES

In this chapter, the damage conditions to structures including buildings (section 2.1) and bridges (section 2.2) in Rikuzentakata region will be analyzed.

2.1 Damage to Residential Buildings

Authors decided the survey area for residential buildings as illustrated in Fig. 2 and enlarged in Fig. 4. With relatively flat terrain and being close to the coastline, the survey area which is outlined by the Kawahara River, Takata Street, a small stream and the bank of Furukawa Pond suffered most severe damage. Buildings in this area are simply divided into two types: RC building (reinforced concrete building, steel-frame building included) and timber building.

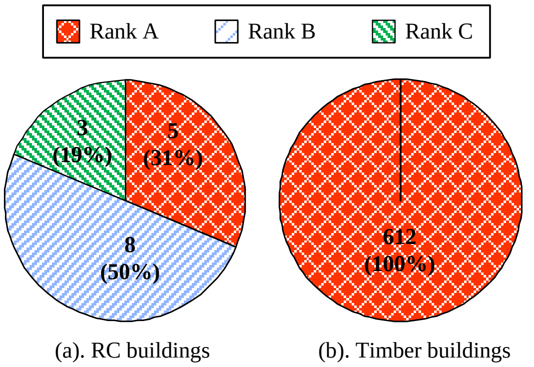
Authors defined the damage extents of residential buildings as presented in Table 1. In Fig. 3, among total 16 RC buildings, proportion is 31%, 50% and 19% for Rank A, B and C, respectively. 70% of RC buildings suffered non-structural damage (sum of Rank B and C buildings), which suggests the great resistance to tsunami impact. Further, all 612 timber buildings are washed away or crashed into pieces by tsunami effect (Rank A), from which, timber building is considered not suitable for future design of anti-tsunami building.

Fig. 4 presents the distributions of RC buildings in survey area. Compared with Rank B and Rank C buildings, there is the trend that Rank A buildings are relatively in smaller size which makes the building with smaller strength to resist tsunami impact. Further, Rank A buildings are mainly distributing in regions relatively closer to the coastline.

To introduce the detailed damage performances of RC buildings, one typical building is selected for each damage rank with their photos shown in Fig. 5. Positions can be referred from Fig. 4. Typical Rank A building is a two-floor, steel-frame structure with its structural members seriously damaged. Bearing columns of left side in second floor were washed away and beams in horizontal direction suffered seriously flexural damage and gathered to residual frame at right side; side walls of it have all been washed away; Typical Rank B building is a reinforced concrete building with its non-bearing wall in the first floor damaged; great lateral load of tsunami impact probably caused it; typical Rank C building (building (3)) is also a reinforced concrete building with relatively smaller

Table 1 Damage extent of buildings

Damage extent	Definition
A	Significant structural damage
B	Non-structural damage only
C	Slight damage (concrete spall)



(a). RC buildings (b). Timber buildings

Fig. 3 Investigation result of buildings

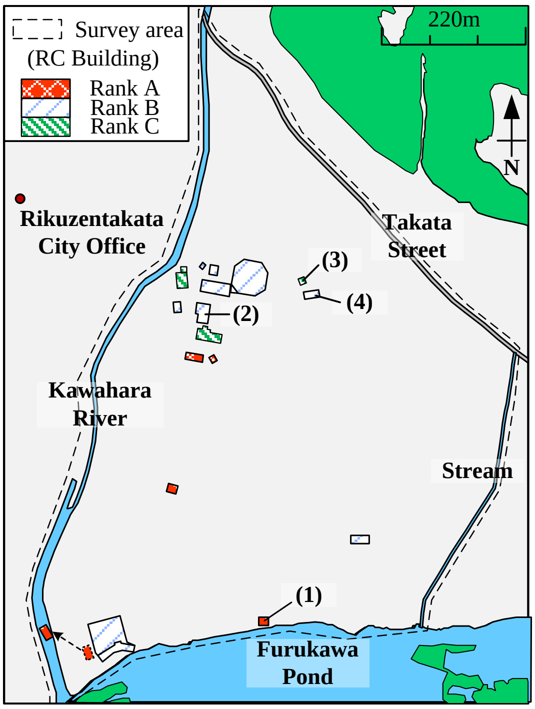


Fig. 4 Survey area to buildings

Rank A Rank B Rank C

Fig. 5 Damage performance of buildings

size. Since building (4) (Fig. 4) with greater size in front of it worked as barrier and weakened the impact, building (3) did not suffer great damage.

2.2 Damage to Bridges

Damage to bridge is also analyzed by the authors. As superstructure of a bridge is of great significance for the normal passage, the damage extent for bridges are divided by the outflow conditions of superstructure as illustrated in Table 2. Rank A means the superstructure flowed out completely by the impact of tsunami, which makes the bridge cannot be used; Rank B refers that the tsunami impact causes the superstructure to have relative movement from abutment or pier while is still passable; Rank C means the damage mainly occurred to the attached elements of bridge like the cover concrete or the hand rails.

From the investigation of authors and also combined with the satellite photographs, the damage conditions of the main 26 bridges in the tsunami affecting area are evaluated, of which the results for each bridge can be referred from Fig. 2.

From Fig. 2, the authors found 80% bridges in the Kesen River suffered Rank A damage (4 in all 5 bridges); while only 18% bridges in the Kawahara River (2 in all 11 bridges). By using distance measurement function of Google Earth, Kensen River has greater size (width in level of 120m) than Kawahara River (width in level of 15m). Direct run-up of tsunami in the greater size river is considered as the reason for more serious damages of related bridges.

As illustrated in Fig. 6, the damage conditions for the surveyed bridges are apparently divided into Rank A and Rank C, with Rank A taking the share of around 39% (10 among all the 26 bridges) while Rank C taking the share of around 62% (16 among all 26 bridges).

3. JUDGEMENT FOR BRIDGE LOSS

In this chapter, the authors will use a simplified equation to judge the outflow condition for superstructure of bridge. Based on the possessed bridge drawings, the judgment is conducted to 4 bridges (names and positions can be referred from Table 3 and Fig. 2) in Rikuzentakata region and another 25 bridges in the entire Tohoku area.

The tsunami impact force and resistance of superstructure can be computed by Eq. 1 and Eq. 2:

$$F = \frac{1}{2}\rho_w C_d v^2 A_n \quad (1)$$

$$S = \mu W \quad (2)$$

where, F is tsunami impact force; ρ_w is density of water (1030kg/m^3); C_d is drag coefficient with its value decided from reference [2]; v is tsunami velocity and A_n is effective projected area of the superstructure in horizontal direction; S is resistance of superstructure; μ is friction coefficient (0.6, based on research of Rabbat[3]); W is dead load of the superstructure.

Thus, an indicator is defined as Eq. 3:

$$\beta = \frac{S}{F} \quad (3)$$

In which, if β ratio is smaller (greater) than 1.0, resistance of superstructure is smaller (greater) than tsunami impact force, which means superstructure is easy (difficult) to outflow. For the tsunami velocity (v) in Eq. 1, based on many recorded videos in the entire Tohoku area, the average value is 6.0m/s (method will be introduced in section 4.1). Thus, v as 6.0m/s will be used as a constant to all bridges, for only concentrating on the relationship between damage conditions with the impact force. To check whether the trend of β ratio can reflect the damage ranks, Fig. 7 and Fig. 8 are made.

Fig. 7 illustrates the relationship between the computed β ratios (from bridge details in Table 3) with the damage conditions. In terms with the two Rank C

Table 2 Damage extent of bridge

Damage Extent	Superstructure
A	Flowed out completely
B	Moved but not dropped
C	Slight damage (concrete spall)

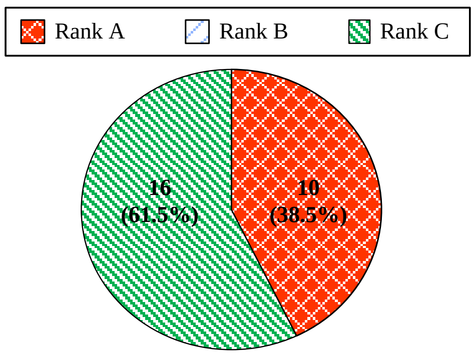


Fig. 6 Investigation result of bridges

Table 3 Bridge details in Rikuzentakata area

Bridge Name	Span Amount	Girder Type	Damage Rank	Span Length L[m]	Width B[m]	Height D[m]	Drag Coefficient C_d	Dead Load W[kN]	β
Numatakosen	3	PC-T girder	A	20.00	13.50	2.59	1.58	3400	1.34
Kawahara	1	PC hollow girder	C	28.80	14.80	1.77	1.30	8800	4.30
Kesen	5	Continuous steel girder	A	181.05	13.30	2.67	1.60	23800	0.99
Hamada	1	PC-T girder	C	22.50	14.80	1.72	1.30	4100	2.64

bridges, β ratios are all greater than 1.0 with average as 3.47, which means resistance is greater than tsunami impact force. Thus, their superstructure survived. For Rank A bridges, the β ratio is 0.99 and 1.34, respectively (average as 1.17). Average β ratio of Rank C bridges is 2.97 times of Rank A bridges.

Computed β ratios for bridges in entire Tohoku area (positions distribute from area A to area E in Fig. 1, Rikuzentakata included) are presented in Fig. 8.

Fig. 8 (a) shows the β ratios classified by areas. Average β ratio of Rank A bridges with their superstructures outflowed is 0.94. Average β ratio of Rank C bridges with their superstructures survived is 2.11 (2.24 times of Rank A).

Fig. 8 (b) shows the β ratios classified by girder type (simply divide into concrete girder and steel girder). Concrete girders have relatively great β ratios and 57% of them have survived (13 among total 23, Rank C); all the steel girders have relatively small β ratios and have flowed out (Rank A), inferring the small resistance to the tsunami impact.

From the computation results, difference of β ratios between Rank C and Rank A bridges are obvious. Trend of β ratios can fit the damage conditions well. As a result, β ratio is considered as an effective indicator to judge outflow of superstructure. However, as velocities in all areas probably not uniform to be 6.0m/s as the authors assumed. Some β ratios of Rank A bridges are greater than 1.0 (like Numatakosen Bridge, Fig. 7) while some of Rank C bridges are smaller than 1.0.

4. TSUNAMI VELOCITY IN RIKUZENTAKATA

For the damage analysis on structures like the judgment of bridge loss conducted in Chap. 3, it is of great significance to get the tsunami velocity. In this chapter, two methods will be applied to evaluate tsunami velocity in Rikuzentakata; characteristics for velocity distribution will also be analyzed.

4.1 Evaluation Methods

First method is based on the recorded videos that were shot when tsunami coming. Based on possessed materials, three videos shot in Rikuzentakata region is considered suitable to evaluate.

In each video, two distinguished positions can be found, the distance (l) between which can be measured through the function of Google Earth. Besides, numbers of debris like the floating boats or houses will pass through the two positions. The needed time (t) for this procedure can be obtained by checking the timer of video. From Eq. 4, velocity of floating debris (v) which is assumed as the velocity of tsunami can be obtained.

$$v = l / t \quad (4)$$

The evaluation positions are plotted in Fig. 10. Table 4 presents calculation parameters for total 15 groups of evaluated velocities. Average values of each sub-area are in the range from 5.29m/s to 8.50m/s; (b) area has relatively greater velocity than others, of which the reason will be analyzed in next section.

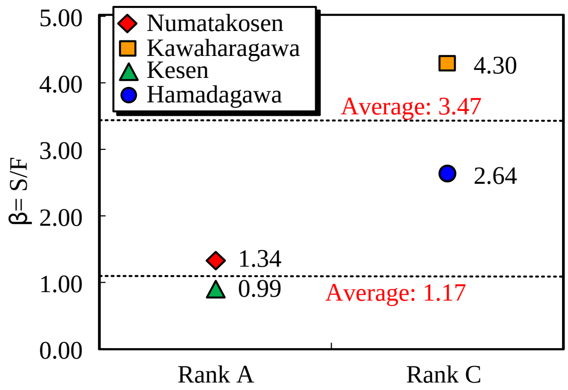
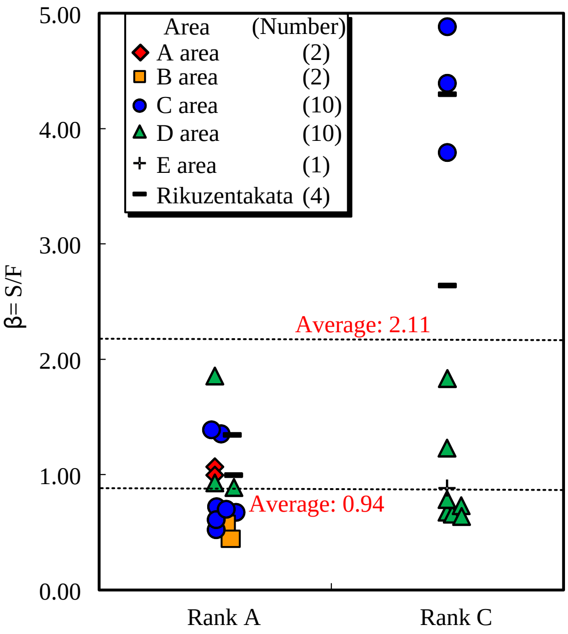
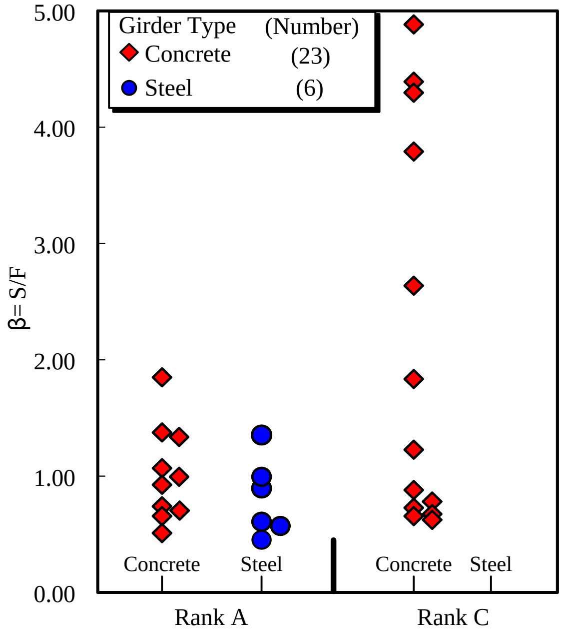


Fig. 7 β Ratios for Rikuzentakata area



(a) Classification by area



(b) Classification by girder type

Fig. 8 β Ratios for Tohoku area

With respect to the second evaluation method, the following equations which are based on the research of Mr. Matsutomi [4] will be introduced.

$$u/(gR)^{0.5} \cong \{2C_v^2 F_r^2/(F_r^2+2C_v^2)\}^{0.5}(h_f/R)^{0.5} \quad (5)$$

$$u \cong 0.58(gh_f)^{0.5} \quad (6)$$

Where u is the tsunami velocity; h_f and h_r are the inundation depth in front and behind of the building, respectively; R is the tsunami run-up height; C_v is the velocity coefficient; F_r is the Froude number; g is the gravity acceleration (9.8m/s^2). Some of the parameters are illustrated in Fig. 9.

By eliminating the same parameter R in the two side of the Eq. 5, the only two unknown parameters are the Froude number (F_r) and velocity coefficient (C_v). C_v value is chosen as 0.9 based on experimental result [4], while F_r number is given as 0.65 for the Rikuzentakata region by the investigation report from University of Tokyo [5]. Thus, based on Eq. 5, the available equation for computing tsunami velocity is derived to be Eq. 6.

As illustrated in Fig. 9, h_f' is the inundation elevation (front of building, from TP level). h is ground height (ground settlement by earthquake included, from TP level). Values of these two parameters can be obtained based on reference [6]. Thus, based on the inundation depth h_f (difference of h_f' and h), velocities

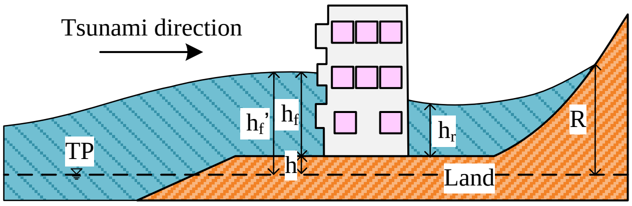


Fig. 9 Factors for equation

Table 4 Tsunami velocity by videos

Position	No.	Debris	l (m)	t (s)	v (m/s)	Avg. (m/s)
(a)No.1 Junior High School	1	House	98.30	14.00	7.02	7.15
	2	House	70.70	10.00	7.07	
	3	House	58.40	9.00	6.49	
	4	House	72.70	10.00	7.27	
	5	House	78.97	10.00	7.90	
(b)Kesen River	6	Wavefront	108.08	13.00	8.31	8.50
	7	Wavefront	35.92	4.00	8.98	
	8	Wavefront	41.04	5.00	8.21	
(c)Minshuku Yoshida	9	Boat	26.73	4.00	6.68	6.76
	10	Broken Tree	16.34	2.50	6.54	
	11	Broken Tree	27.56	3.90	7.07	
(d)Telecom Machine.Ltd	12	Wavefront	50.67	7.00	7.24	7.24
(e)Suwa Shrine	13	House	32.35	6.10	5.30	5.29
	14	House	32.35	5.80	5.58	
	15	House	32.35	6.50	4.98	

Table 5 Tsunami velocity by equation

No.	Building Name	h_f' (m)	h (m)	h_f (m)	v (m/s)
A	Roadside Station	15.20	-0.59	15.79	7.21
B	Capital Hotel	15.80	-0.59	16.39	7.35
C	Sea and Shell Museum	14.53	4.13	10.40	5.86
D	Teijyusokushin House	14.87	2.67	12.20	6.34

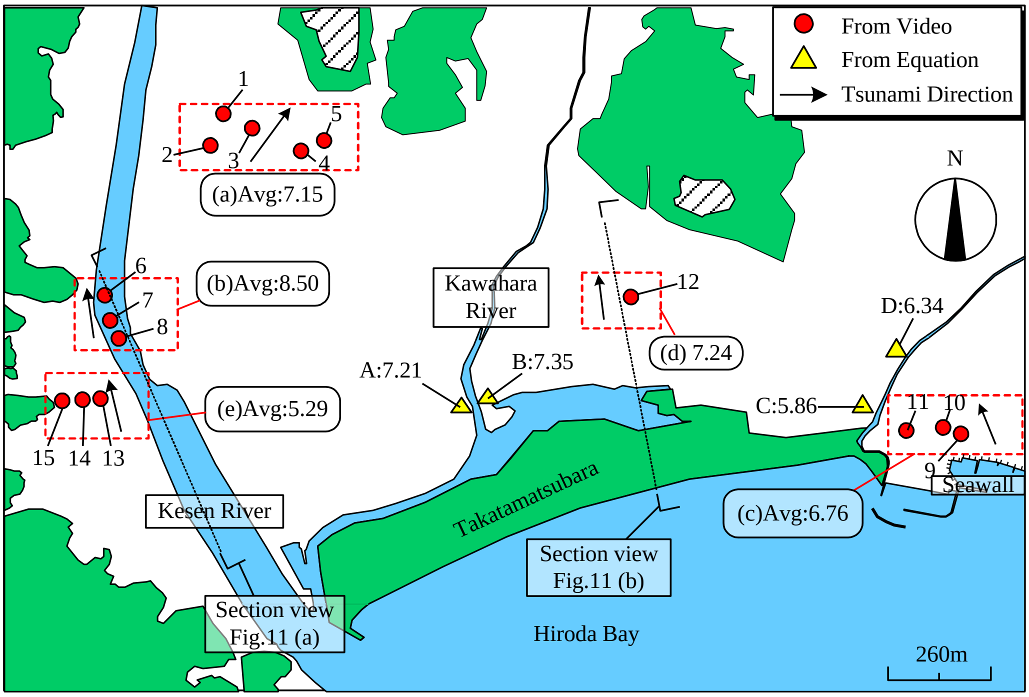
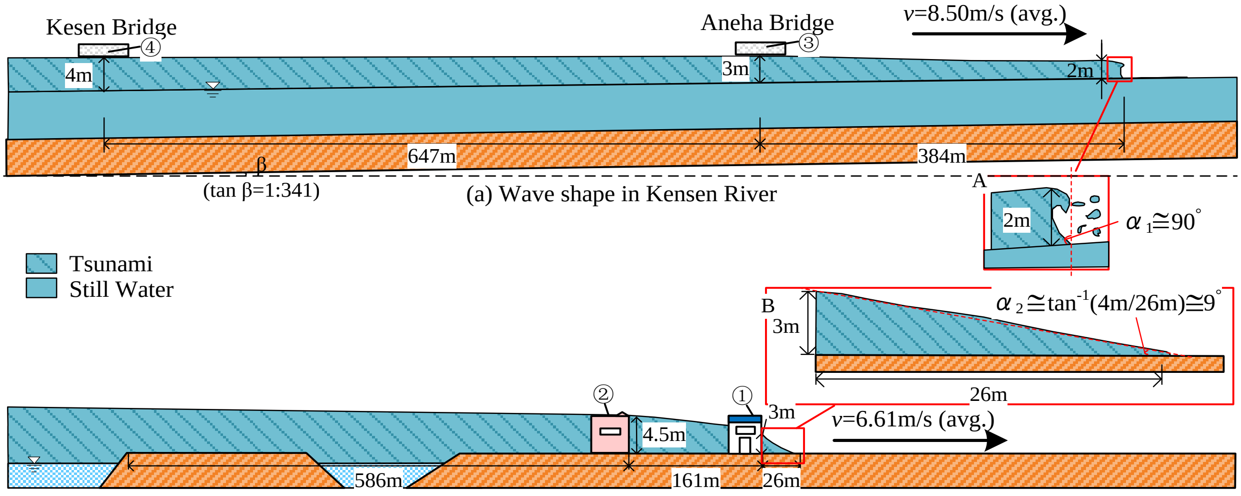


Fig. 10 Distribution of tsunami velocity



(b) Wave shape in land

Fig. 11 Different wave shapes

near four buildings (positions shown in Fig. 10) can be calculated from Eq. 6. Table 5 shows calculation parameters and results. From Fig. 10, evaluated tsunami velocities from equation can roughly coincide with those in neighboring areas from videos. (A B with (d), C D with (c), Fig. 10)

4.2 Distribution of Tsunami Velocities

Based on evaluation results presented in Table 4, Table 5 and Fig. 10, the characteristics of tsunami velocity distribution will be discussed in the following.

Tsunami velocity in river area ((b), 8.50m/s, Fig. 10) is 29% greater than land area (avg of each avg velocity in (a), (c), (d) and (e), 6.61m/s, Fig. 10). From reference [7], tsunami energy can be partly weakened by friction effect of land and plants. Further, based on video screens and relative height differences between tsunami surface with buildings (No.1, 2 building, Fig. 11) and bridges (No.3, 4 bridge, Fig. 11), sketching of wave shapes for the front part of tsunami can be drawn as shown in Fig. 11 with sectional positions referred from Fig. 10. It is confirmed that except wavefront part, entire tsunami is in shape without great variation of height for both river and land area. Since slope angle of wavefront for river area is around 90° (A, Fig. 11 (a)) and based on wave shape, wave of river area is considered as Breaker Bore, with greater energy and velocity [8]. As for land area, slope angle (around 9°, B, Fig. 11 (b)) is relatively small, inducing the smaller energy and velocity.

Thus, focus on evaluated results from videos as illustrated in Table 4 and Fig. 10, the average tsunami velocity for Rikuzentakata is about 7.0m/s, being greater than 6.0m/s of entire Tohoku area (Chap. 3).

5. CONCLUSIONS

Based on investigation results, damage analysis to structures in Rikuzentakata region has been conducted. Further, tsunami velocity is also evaluated. Thus, following conclusions can be drawn:

(1) In Rikuzentakata, 70% of RC buildings in the survey area suffered non-structural damage, which suggests the great resistance; while all timber buildings were washed away; around 40% bridges flowed out.

(2) Difference of β ratios between Rank C and Rank A bridges for both Rikuzentakata and entire Tohoku area are obvious. β ratios can coincide with damage conditions. β ratio is an effective indicator to judge outflows of superstructures.

(3) Tsunami velocity in river area is relatively greater than land area as influence from wave shape and friction effect of land and plants.

(4) The average tsunami velocity for Rikuzentakata is 7.0m/s, greater than 6.0m/s of entire Tohoku area.

REFERENCES

[1] Japan Institute of Construction Engineering, “Inundation Map for Rikuzentakata,” Sep. 2011. (http://www.jice.or.jp/sinsai/files/001393-004.pdf)

[2] Japan Road Association, “Specifications for Highway Bridges Part I Common,” Mar. 2002, pp.47-52.

[3] Rabbat, B.G. and Russel., H.G., “Friction coefficient of steel on concrete or grout,” J. Struct. Eng., ASCE, Vol.111, No.3, 1985, pp.505-515.

[4] Matsutomi, H., “Tsunami current velocity on land and its simple estimation method,” Proc. of Coastal Eng., JSCE, 1998, pp. 361-365.

[5] Institute of Industrial Science, University of Tokyo, “Preparation for building criteria in tsunami affecting area” Oct. 2012, pp.2.1-2.12. (http://www.mlit.go.jp/common/000172792.pdf)

[6] The 2011 Tohoku Earthquake Tsunami Joint Survey Group: “Field survey result,” Mar. 2011. (http://www.coastal.jp/ttjt/index.php?)

[7] Imai, K., “Hydroulic characteristics on tsunami inundation in a costal vegetated area,” J. JSCE B, Vol.62 No.3, 2006, pp. 258-269.

[8] T. Arikawa, “Tsunami Disaster due to the Great Eastern Japan Earthquake,” Concrete Journal, JCI, Vol.50, No.1, Jan. 2012, pp. 23-29.