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DAMAGE ANALYSIS OF BRIDGES AFFECTED BY TSUNAMI DUE TO GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The Great East Japan Earthquake and the resulting tsunami hit the coastal areas of Japan. It is found that the outflow of steel and steel truss bridges is more serious than concrete bridges. By the use of videos, the tsunami velocities in 5 severely affected areas were estimated and the overall average is about 6.0m/s. In Rikuzentakata, 30% RC buildings suffered structural damage and 40% bridges flowed out. Besides, it is found that the outflow of superstructure is able to be judged by the level of ratio β between superstructure resistance and wave horizontal force primarily.

Key Words: tsunami, bridge damage, tsunami velocity, building damage

INTRODUCTION

During the Great East Earthquake, the outflow of superstructure and excessive scour occurred to more than 300 bridges in East Japan. Fig. 1 illustrate the bridges which suffered damage Rank A (bridge seriously damaged and could not be used). Among the 300 bridges, 9 national way bridges, 14 prefectural road bridges and 101 railway bridges, suffered serious losses. Despite a lack of official data about the damage to city and village roads, by the use of Google Earth, it is noted that at least 200 bridges suffered serious losses.

Furthermore, the damage extent of bridges in East Japan is compared with the damage to bridges caused by Sumatra Earthquake. Before comparison, we define the damage level in Table 1, focusing on the outflow condition of bridge superstructure. The damage level of 29 different bridge superstructures affected by tsunami in Great East Japan Earthquake is plotted in Fig. 2-A and the damage level of 26 bridge superstructures affected by tsunami in Sumatra Earthquake is illustrated in Fig. 2-B. From the 2 figures, it is found that the bridges constructed by steel or steel truss suffered more serious damage than concrete bridges. All the 6 survey steel and steel truss bridges flowed out by tsunami. For the concrete bridges, during the 2 tsunami disaster, about half PC superstructures belong to Rank A while about 2/3 RC superstructures belong to Rank A.

EVALUATION OF TSUNAMI VELOCITY

Based on former research, in order to analyze the tsunami action on bridge superstructures, it is necessary to estimate the tsunami flow velocity. In this chapter, we apply the videos recording the

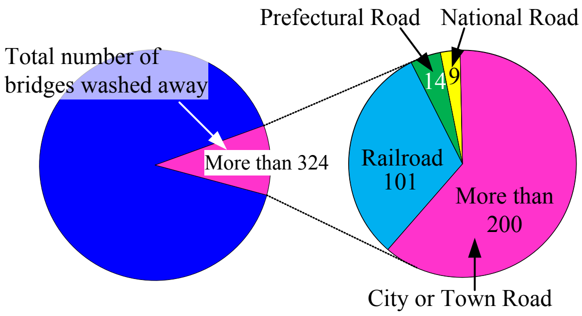
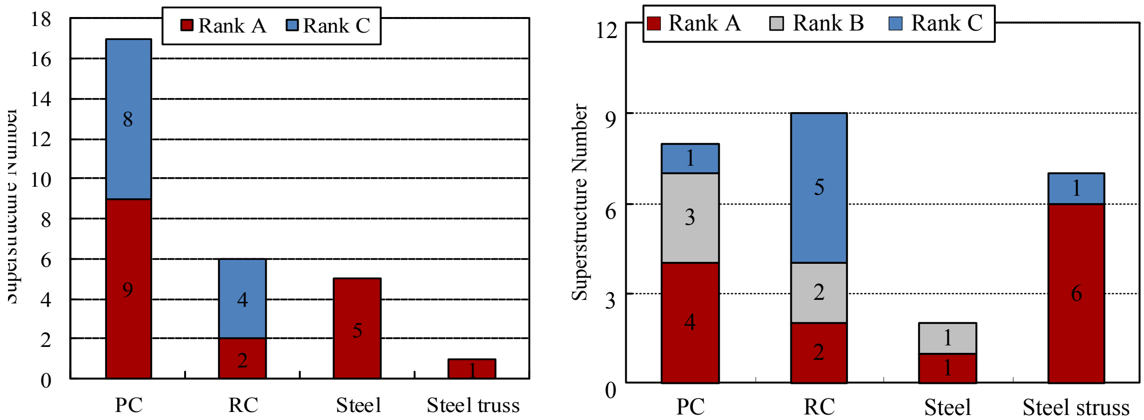


Fig. 1 Amount of bridges washed away

Table 1 Definition of damage level

Damage level	Outflow condition of superstructure
Rank A	Flowed out completely
Rank B	Moved but not divorced from abutment
Rank C	Slight damage



A. Damage in East Japan

B. Damage in Sumatra

Fig. 2 Comparison of tsunami damage

tsunami flood on land, to estimate the tsunami velocity comprehensively. And in order to exclude the accidental case, 5 typical tsunami affecting areas are selected to carry out velocity measurement.

Method of Velocity Estimation

During tsunami landing, some videos were shot. It is possible to apply the videos to estimate 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 piece 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.

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

in which, 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).

Velocity Result

Herein, the detailed measurement in Shizugawa town of Minamisanriku city is described as an

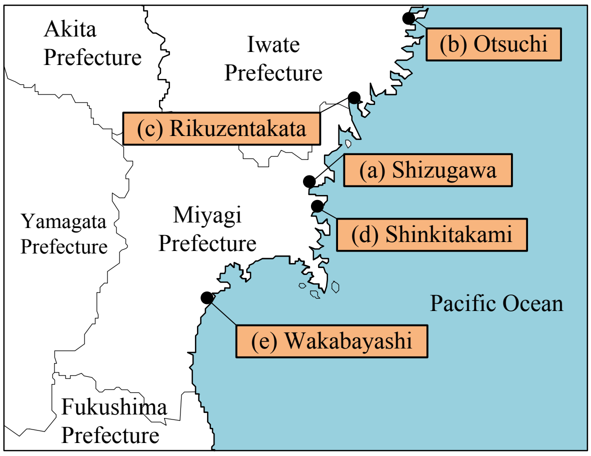
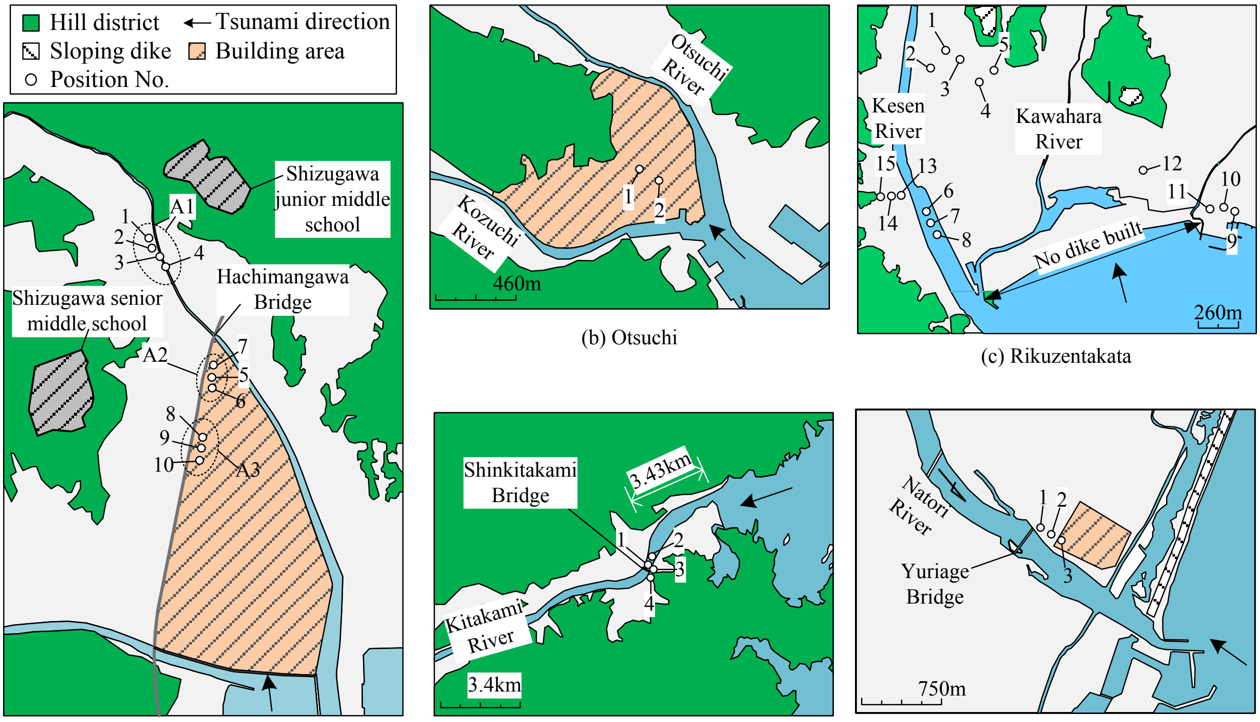


Fig. 3 Tsunami velocity estimate positions

Table 2 Tsunami velocity in Shizugawa

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



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

Fig. 4 Velocity result

example.

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 last section, the velocity is measured by 10 times at different positions, which are plotted in Fig. 4-(a). Among the 10 positions, No.1~4, No.5~7 and No.8~10 locate at A1, A2 and A3 areas respectively. Table 2 plots the debris types and velocity result in Shizugawa. The average velocity in Shizugawa is 5.8m/s.

By the same process, the tsunami velocities in Otsuchi, Rikuzentakata, Shinkitakami and Wakabayashi have been estimated and the measure positions are illustrated in Fig. 4-(b) to (e). The velocities of each measure position and the maximum, minimum and average velocities in each area

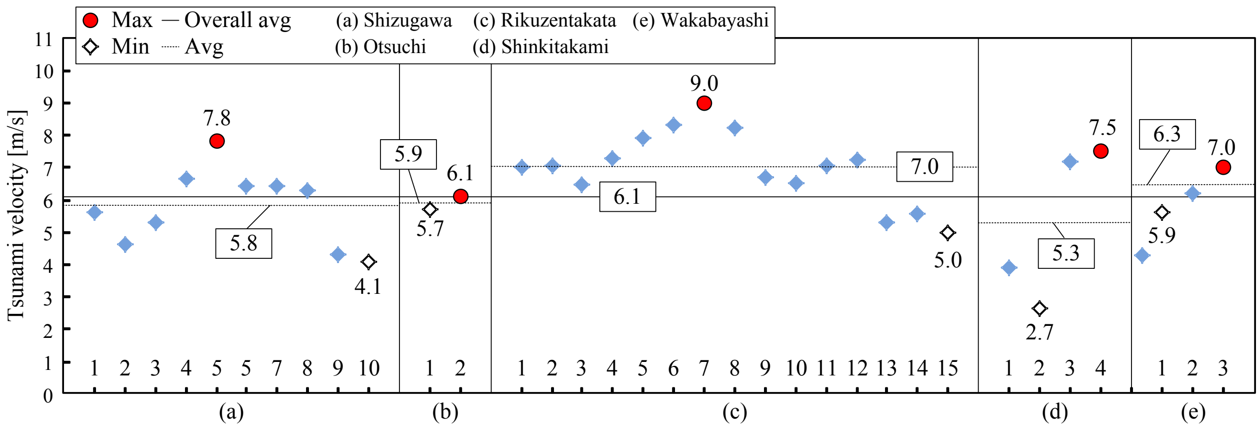


Fig. 5 Maximum, minimum and average velocities

are given in Fig. 5. The overall average is 6.1m/s. It is obvious that the average velocities in Shizugawa, 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 the overall average.

DAMAGE TO STRUCTURES

Soon after the great earthquake, the authors conducted several field investigations to the disaster areas of Japan. In this chapter, as a specific example, the authors will analyze the damage conditions of structures including residential 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 (Japan Institute of Construction Engineering 2011) is illustrated in Fig. 6. Total 26 bridges over the main rivers and original 628 residential buildings in one central area (circled with long dash line) will be analyzed for their damage conditions in detail.

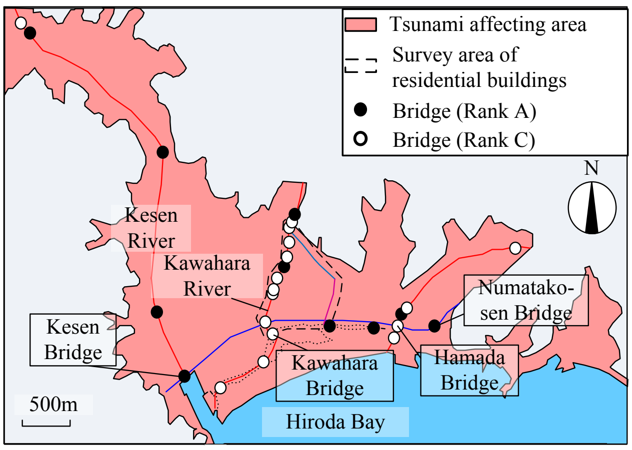


Fig. 6 Research region of Rikuzentakata

Table 3 Damage extent of buildings

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

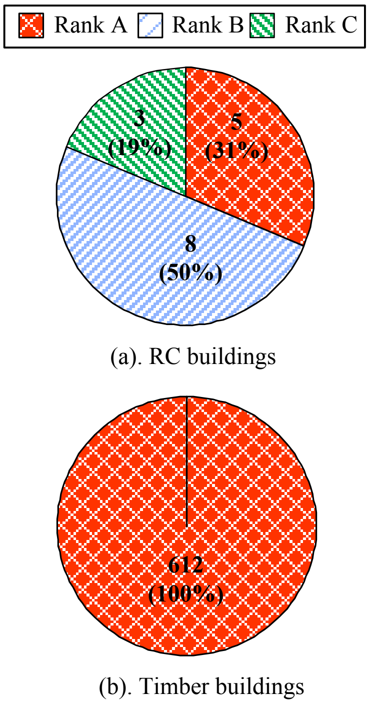


Fig. 7 Investigation result of buildings

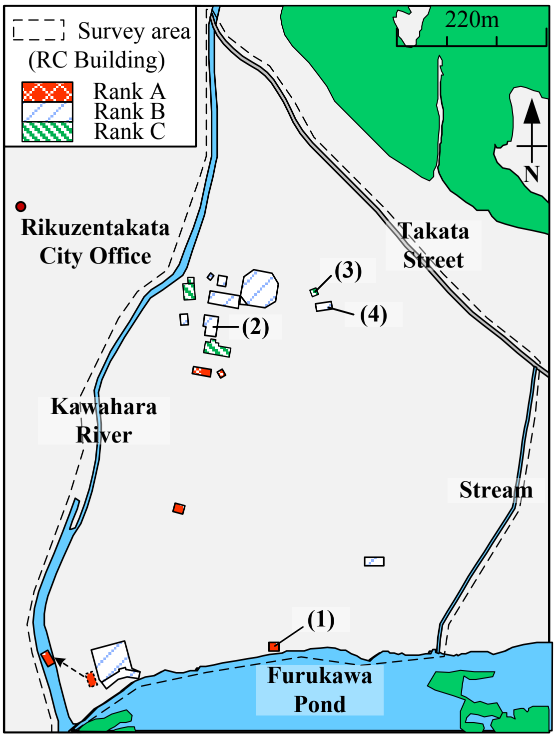


Fig. 8 Survey area to buildings

Damage to residential buildings

Authors decided the survey area for residential buildings as illustrated in Fig. 6 and enlarged in Fig. 8. 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: reinforced concrete building (RC building for short, including steel-frame building) and timber building.

Authors defined the damage extents of residential buildings as presented in Table 3. In Fig. 7, 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. 8 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 stiffness 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 Photo 1 and Photo 2. Positions can be referred from Fig. 8. Typical Rank A building is a two-floor, steel-frame structure with its structural members seriously damaged. Main 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 size. Since building (4) (Fig. 8) with greater size in front of it worked as barrier and weakened

Rank A

Rank B

Photo 1 Damage performance of buildings (Rank A, Rank B)

Rank C

Photo 2 Damage performance of buildings (Rank C)

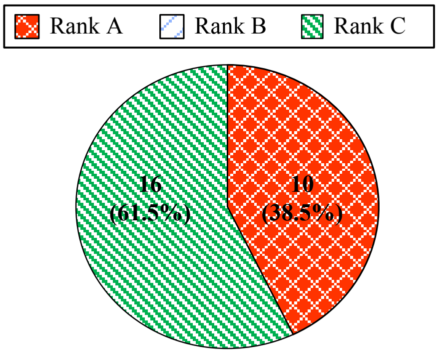


Fig. 9 Investigation result of bridges

the impact, building (3) did not suffer great damage.

Damage to bridges

Damage to bridge is also analyzed by the authors. Same with the former description, 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. 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. 6.

From Fig. 6, 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. 9, 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).

Table 4 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

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 4 and Fig. 6) 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. 2 and Eq. 3:

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

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

in which, 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 (Japan Road Association 2002); v is tsunami velocity and A_h is effective projected area of the superstructure in horizontal direction; S is resistance of superstructure; μ is friction coefficient used as 0.6 (Rabbat, et al. 1985); W is dead load of the superstructure.

Thus, an indicator is defined as Eq. 4:

$$\beta = \frac{S}{F} \quad (4)$$

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. 2, based on measured results described previously, the average value for entire Tohoku area is around 6.0m/s. 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 horizontal force.

Fig. 10 illustrates the relationship between the computed β ratios (from bridge details in Table 4) with the damage conditions. In terms with the two Rank C 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 (total 29 bridges, Rikuzentakata area included) are presented in Fig. 11. Average β ratio of Rank A bridges with their superstructures outflowed is 0.87. Average β ratio of Rank C bridges with their superstructures survived is 1.91 (2.20 times of Rank A).

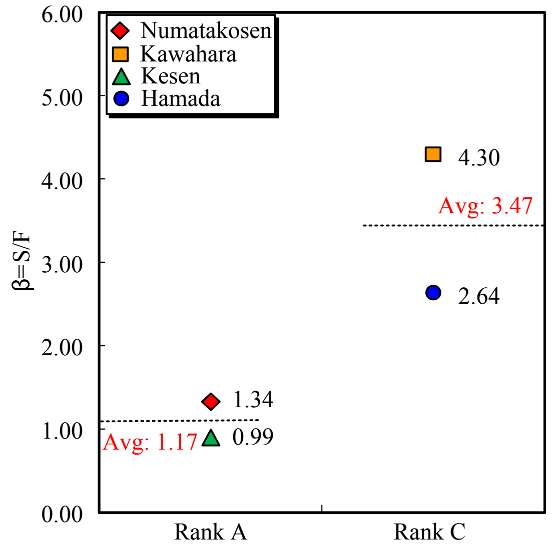


Fig. 10 β Ratios for Rikuzentakata area

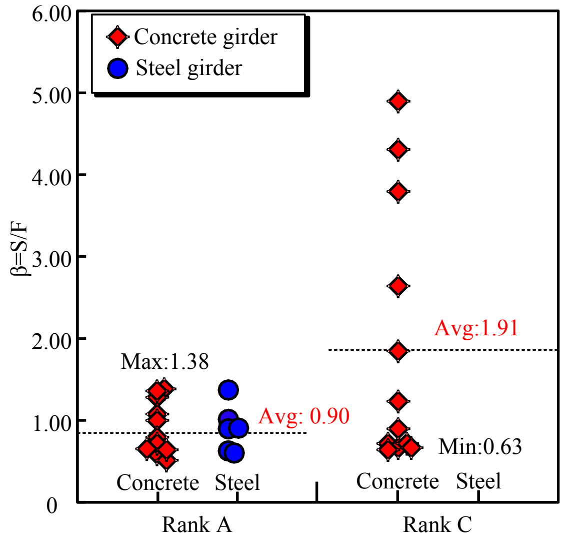


Fig. 11 β Ratios for Tohoku area

With respect to β ratios of different girder types (simply divide into concrete girder and steel girder, Fig. 11), concrete girders have relatively great β ratios and 53% of them have survived (12 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. 10) while some of Rank C bridges are smaller than 1.0.

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.

Same with what have been explained in the former content, first method is based on the recorded videos. Based on possessed materials, three videos shot in Rikuzentakata region is considered suitable to evaluate.

The evaluation positions are plotted in Fig. 13. Table 5 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.

With respect to the second evaluation method, the following equations which are based on the former research (Matsutomi, H. 1998).

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

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

Table 5 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	

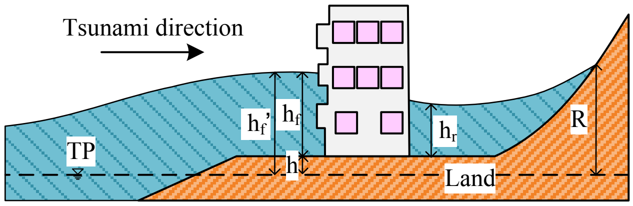


Fig. 12 Factors for equation

Table 6 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

in which, 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. 12.

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 (Matsutomi, H. 1998), while F_r number is given as 0.65 for the Rikuzentakata region by the investigation report (Institute of Industrial Science 2011). Thus, based on Eq. 5, the available equation for computing tsunami velocity is derived to be Eq. 6.

As illustrated in Fig. 12, 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 (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2011). Thus, based on the inundation depth h_f (difference of h_f' and h), velocities near four buildings (positions shown in Fig. 13) can be calculated from Eq. 6. Table 6 shows calculation parameters and results. From Fig. 13, evaluated tsunami velocities from equation can roughly coincide with those in neighboring areas from videos. (A B with (d), C D with (c), Fig. 13)

Thus, focus on evaluated results from videos as illustrated in Table 5 and Fig. 13, the average tsunami velocity for Rikuzentakata is about 7.0m/s, being greater than 6.0m/s of entire Tohoku area.

RECALCULATION OF β RATIOS BY DETAILED VELOCITIES

As explained in the former chapter, tsunami velocities in all areas were not uniform to be 6.0m/s as the authors assumed. Some β ratios of Rank A bridges are relatively great while some of Rank C bridges are small. Thus, based on the detailed tsunami velocities obtained in the previous chapters, the β ratios for four bridges in Rikuzentakata and another eight bridges of other velocity measured areas were recalculated.

Recalculation for Rikuzentakata area

Based on the distribution of measured tsunami velocities as shown in Fig. 13, the detailed velocity near each bridge is used for recalculation. For Kesen Bridge, the average velocity 8.50m/s in (b) river area is applied; for Kawahara Bridge, the average velocity 7.28m/s of A and B points is applied; for Hamada Bridge, the average velocity 6.10m/s of C and D points is used; and for Numatakosen Bridge, the average velocity 6.76m/s in the (c) area is used.

Thus, using the same calculation methods and the detailed velocities, the β ratios for Rikuzentakata area are recalculated and illustrated in Fig. 14.

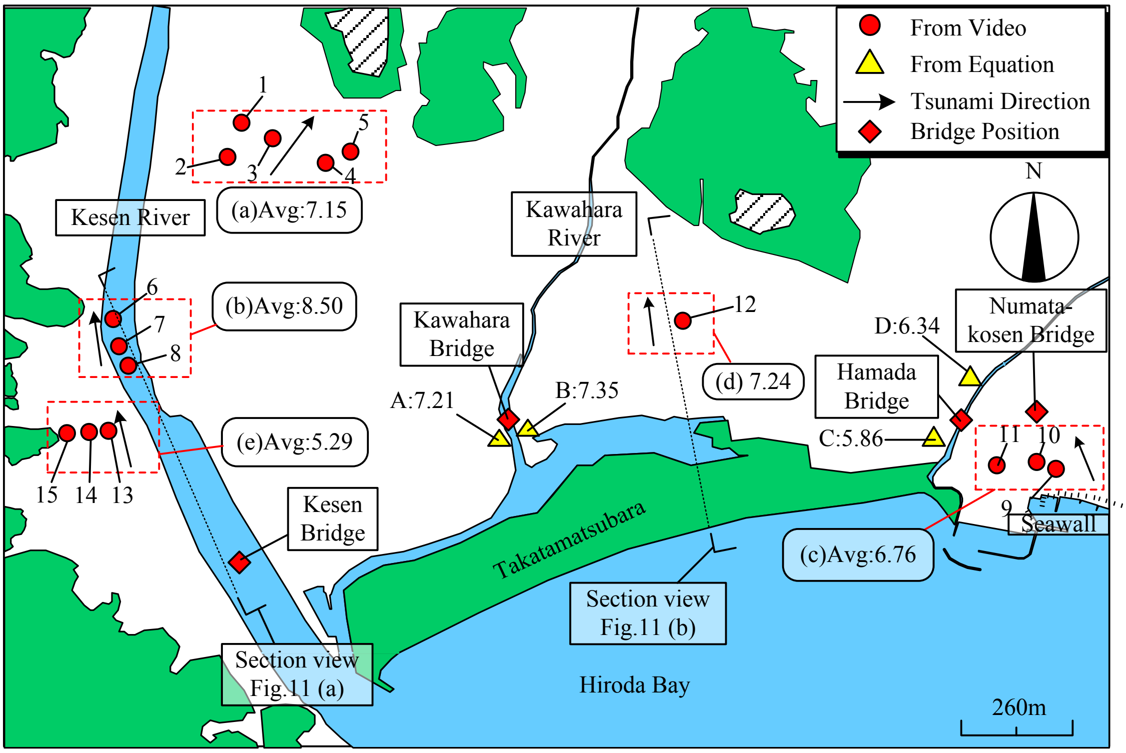


Fig. 13 Distribution of tsunami velocity

For the Numatakosen Bridge (Rank A damage), which originally has relatively greater β ratio (1.34), the β ratio reduces to be 1.06, indicating the smaller girder resistance. For the Kesen Bridge, as the greater tsunami velocity in the river area, the β ratio decreases to be 0.50, adequately explaining the outflows of its girders. For the Kawahara Bridge, the β ratio becomes 2.92 as the greater tsunami velocities nearby. For the Hamada Bridge, as the tsunami velocity (6.1m/s) is relatively close with what we assumed previously, the β ratio is not changed obviously.

Recalculation for Entire Areas

Based on the average velocities measured from videos, the authors recalculated the β ratios for total 12 bridge girders in the velocity measured areas (Rikuzentakata, Shinkitagami, Shizukawa and Otsuchi, Wakabayashi is not included as no bridges are calculated in there). The calculation parameters and results are shown in Table 7 and Fig. 15, respectively.

Compared with the summary results of former β ratios (velocity assumed as 6.0m/s) in different areas (Fig. 16), we get to know the following phenomenon. For Rikuzentakata area, as the increasing of velocity (6.0m/s vary to be 7.0m/s), the β ratios have reduced entirely. The β ratio of girders for Numatakosen Bridge (Rank A, Mark A of Fig. 15) reduced to be smaller than 1.0, reflecting outflow

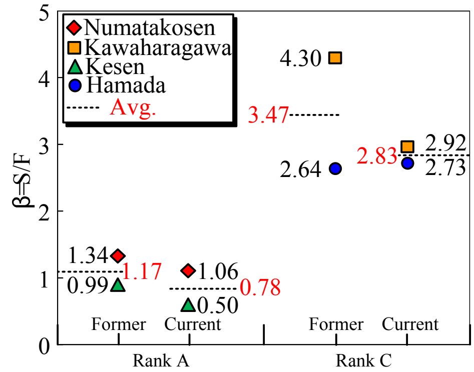


Fig. 14 Recalculated β Ratios for Rikuzentakata

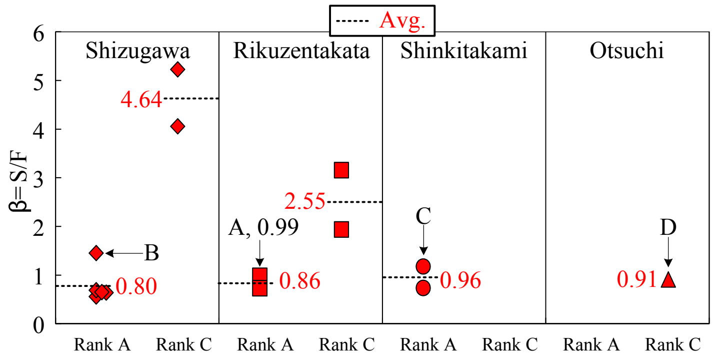


Fig. 15 Recalculated β ratios for entire area

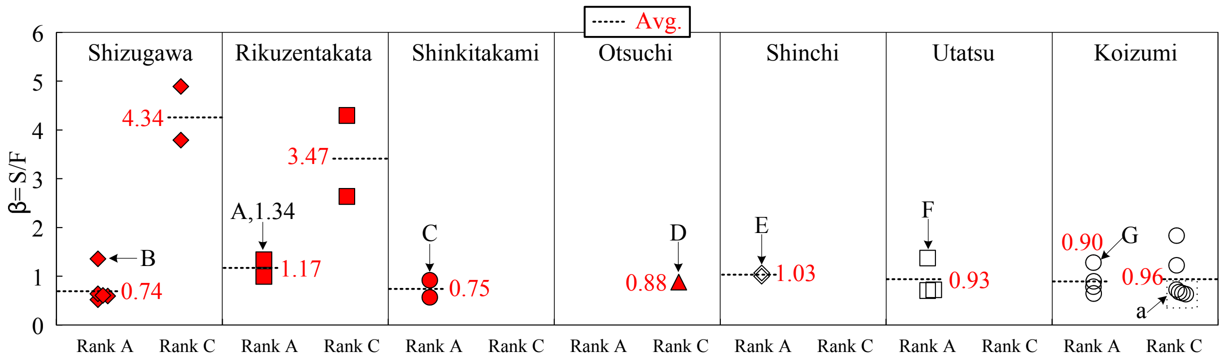


Fig. 16 Former β ratios for entire area

Table 7 Recalculated β Ratios for entire area

Location	Bridge	Span	Span type	Damage Rank	Avg. v [m/s]	β (6.0m/s) S/F	β (avg. v) S/F
Rikuzen-takata	Hamadagawa	1	PC-T	C	7	2.64	1.94
	Kawaharagawa	1	PC-hollow	C		4.30	3.16
	Numata-kosen	2	PC-T	A		1.34	0.99
	Kesen	1～5	Steel plate	A		0.99	0.73
Shinkita-kami	Shiaikawa	1	Steel box	A	5.3	0.57	0.74
	Shikitagami	1,2	Steel truss	A		0.92	1.18
Shizu-gawa	Hachiman	3	PC-I	C	5.8	4.88	5.22
	Shiomi	3	PC-I	C		3.79	4.06
	Mizujirigawa	3th	PC-I	A		0.59	0.63
		1st	RC-I	A		0.52	0.56
	Hachimangawa	2～3	RC-I	A		0.64	0.69
		4th	Steel-H	A		1.36	1.45
	Mizujiri	3	Steel-H	A		0.61	0.65
Otsuchi	Namiita	1	PC-T	C	5.9	0.88	0.91

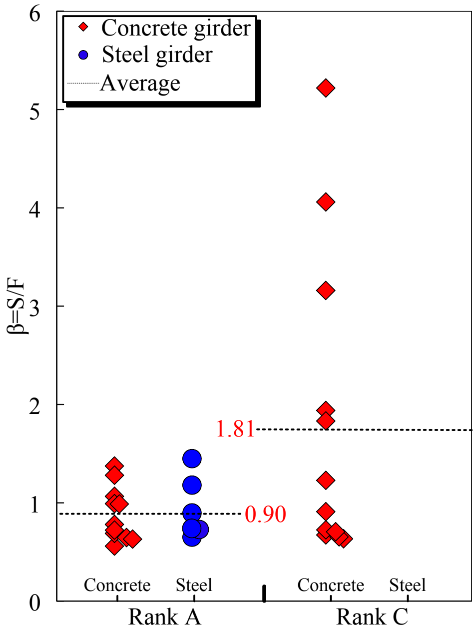


Fig. 17 β Ratios for entire area

condition more accurately. For other three areas, as the slight variation of tsunami velocities, the β ratios do not have significant change.

As a result, after recalculations by using the detailed tsunami velocities for four velocity measured areas, the β ratios do not have great variations. Differences of β ratios between Rank C and Rank A bridges are also obvious. Trend of β ratios can fit the damage conditions well.

However, after recalculations, there are still some β ratios of Rank A bridges greater than 1.0 (Mark B, Mark C, Fig. 15) while some of Rank C bridges are smaller than 1.0 (Mark D, Fig. 15). Further, for the areas without measurement of velocities, some β ratios also can not coincide with their outflow conditions (Mark E, F, G and Section a, Fig. 16). A series of numerical analysis for getting more detailed and precise velocities will be conducted later. After that, more precise β ratios will be obtained and the evaluations will be continued. Besides that, the average β of Rank A and C bridges after modifications is plotted in Fig. 17. Compared to the average β before modification (Fig. 11), it is found that the β of Rank C become smaller which is 1.81.

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:

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.

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.

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

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