- Technical Paper -

EVALUATION OF BRIDGE OUTFLOWS DUE TO GREAT TSUNAMI

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ABSTRACT

Triggered tsunami from the Great East Japan Earthquake caused outflows of many bridges. β ratios (ratio of girder resistance to tsunami impact) of 38 girders were evaluated. There is great difference between β of girders flowed and survived. From modifications using average drag coefficient, β have 20% increase. After revising, flowed bridges with β greater than 1.0 are located in smaller distance to coastal line inducing greater velocities and decrease of β. As representative, β of Koizumi Bridge was modified by velocity (7.3m/s) from numerical analysis and becomes sufficient to explain the outflow.

Keywords: tsunami, bridge outflow, drag coefficient, ratio β

1. INTRODUCTION

Triggered tsunami from the Great East Japan Earthquake caused tremendous destructions in eastern Japan. Soon after the great tsunami, to study the outflow mechanism of bridges, the authors conducted several field investigations to the disaster areas of Japan. As shown in Fig. 1, the outflows of 24 bridges (38 bridge girders) with their positions close to the coastline have been studied. Firstly, the former evaluation results of bridge outflow by β ratio (ratio of girder resistance to tsunami impact) will be introduced. Secondly, the basis and modification of drag coefficient, which is very influential on the tsunami impact, will be discussed. In this part, the authors will also study the variation of β ratio due to the modification of drag coefficient. After the modification, the bridges with their β ratios not coinciding with the outflow conditions will be evaluated. Further, Koizumi Bridge will be selected as a representative to check the reason combined with results from numerical analysis.

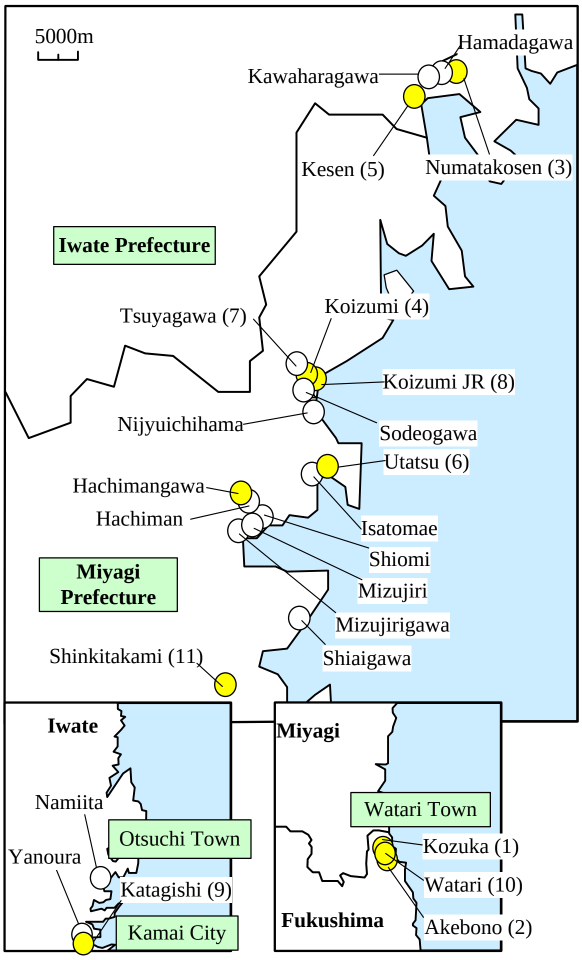

Fig. 1 Positions of studied bridges

2. FORMER EVALUATION RESULTS OF GIRDER OUTFLOW

In this chapter, the authors will introduce the evaluation methods and the former evaluation results of bridge outflows by β ratios. Combined with the results, the insufficient points in the evaluation method will be proposed.

Damage ranks for bridges are divided by the outflow conditions of girders as illustrated in Table 1.

For evaluating bridge outflow, tsunami impact force (F) and resistance of girder (S) are concentrated. The impact force is based on the drag force of tsunami, as illustrated in Eq. 1:

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Table 1 Damage ranks of bridges

Damage Ranks	Bridge Girders
A	Flowed out completely
B	Moved but not dropped
C	Slight damage (concrete spall)

$$F = \frac{1}{2}\rho_w C_d A v^2 \qquad (1)$$

where, ρ_w is density of water (1030kg/m^3); C_d is drag coefficient based on the specification of the Honshu-Shikoku Bridge Authority [1]; v is tsunami velocity; A is projected area of girder onto the vertical plane (m^2).

The girder resistance is evaluated by Eq. 2:

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

where, μ is the friction coefficient (0.6 is assumed based on the former research [2]); W is the dead weight of the girder (kN).

Thus, an indicator β is defined as Eq. 3:

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

in which, if β ratio is smaller (greater) than 1.0, girder resistance is smaller (greater) than tsunami impact force, which means girder is easy (difficult) to flow out. For the tsunami velocity (v) in Eq. 1, based on the analysis of many recorded videos in the entire Tohoku area, the average value is estimated to be 6.0m/s, which is used for evaluating the tsunami impact force.

Fig. 2 illustrates the relationship between β ratios and the damage ranks. Average β ratio of Rank A bridges with their girders flowed out is 0.84. Average β ratio of Rank C bridges with their girders survived is 1.52 (1.81 times of Rank A). Differences of β ratios between Rank C and Rank A are obvious. Further, as to the detailed numerical values, when β is greater than 1.41 (Max. of β for Rank A), bridges can be confirmed to survive; when β is smaller than 0.63 (Min. of β for Rank C), bridges can be confirmed to flow out. However, when β is located in the section between 0.63 and 1.41, the Rank A and Rank C bridges are mixed together and the β ratios cannot reflect the damage ranks.

Two possible reasons have been considered for this un-coinciding area of β ratios. First one is the inappropriate use of drag coefficient and another one is the not uniform tsunami velocity as 6.0m/s. Both these two factors will be discussed in detail in subsequent chapters.

3. EVALUATION OF DRAG COEFFICIENT

In this chapter, the authors will introduce the

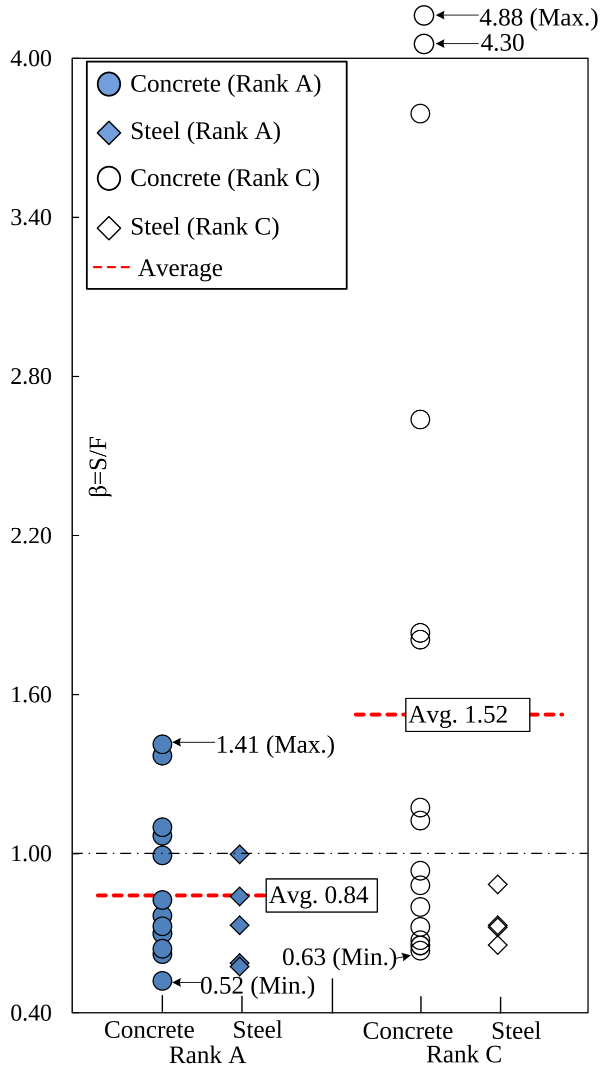

Fig. 2 Evaluation results

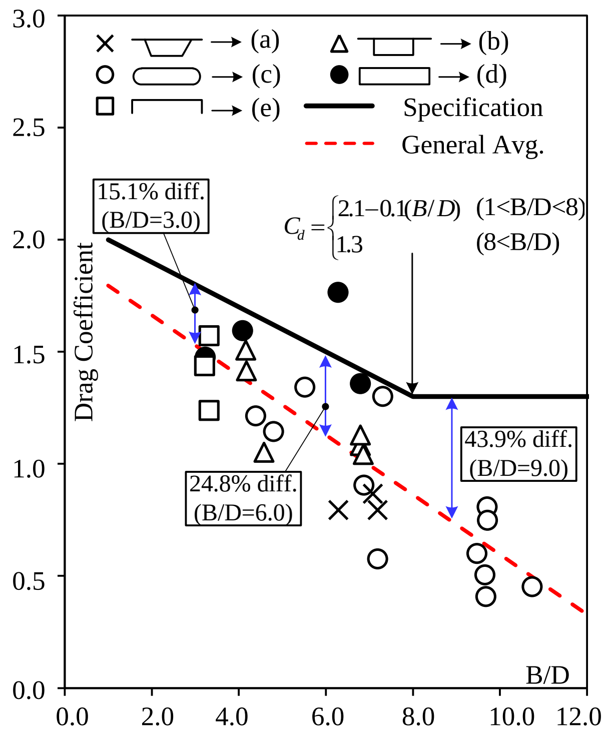

Fig. 3 Basis of drag coefficients

basis for equation of drag coefficient given by the specification [1]. After that, for precise evaluations, two different modifications of the equation will be conducted.

Fig. 3 presents the basis for equation of drag coefficient given by the specification. The data for different girder types are got from the wind tunnel tests conducted by the Public Works Institute of Japan. The bridge models are based on the Honshu-Shikoku Bridges. As presented in the Fig. 3, the specification proposed the equation as a decreasing line before the B/D (Bridge width/height) as 8.0, by considering the safety factors; continually, for agreement with the equation from British Standard, a constant line was proposed after the B/D as 8.0. The proposed equation is shown in Eq. 4.

$$C_d = \begin{cases} 2.1\text{-}0.1(B/D), & 1 \le B/D < 8 \\ 1.3, & 8 \le B/D \end{cases} \tag{4}$$

where, C_d is the drag coefficient; B is the bridge width (m); D is the bridge height (m). The evaluation results of β in Chap. 2 are evaluated based on this equation.

To prevent the overestimations of drag coefficient and then the tsunami impact force, the following two different modifications of the equation are conducted.

First one is modifying the evaluation equation based on the general average (Fig. 3). By calculating the approximate line based on the average, the following Eq. 5 is proposed:

$$C_d = 1.929 - 0.133(B/D) \tag{5}$$

The coefficient of variation is 35% which means that the experimental data have a relatively great deviation. Referring to Fig. 3, the differences of change after modification are 15.1%, 24.8% and 43.9% when B/D are 3.0, 6.0 and 9.0. It is found that greater change occurs with the greater B/D.

The other modification will be discussed in the following. As presented in the Fig. 4, girder type (a) and (b) have the stretching parts in the girder ends. As assumed in the former research [2], girders with stretching part have the possibility to possess greater drag coefficient because vortex might occur in the stretching part. To check whether this assumption is proper, the authors attempted to classify the drag coefficients for girders with and without stretching part. Based on the related materials to the wind tunnel tests, type (b) is considered to be similar to girders with stretching parts in the studied bridges. The type (c), (d) and (e) are assumed to be the girders without stretching part. Thus, based on the average values, the evaluation equations of the girders with and without stretching part are proposed as the following Eq. 6 and Eq. 7:

$$C_d = 1.795 - 0.107(B/D) \tag{6}$$

$$C_d = 1.960 - 0.134(B/D) \tag{7}$$

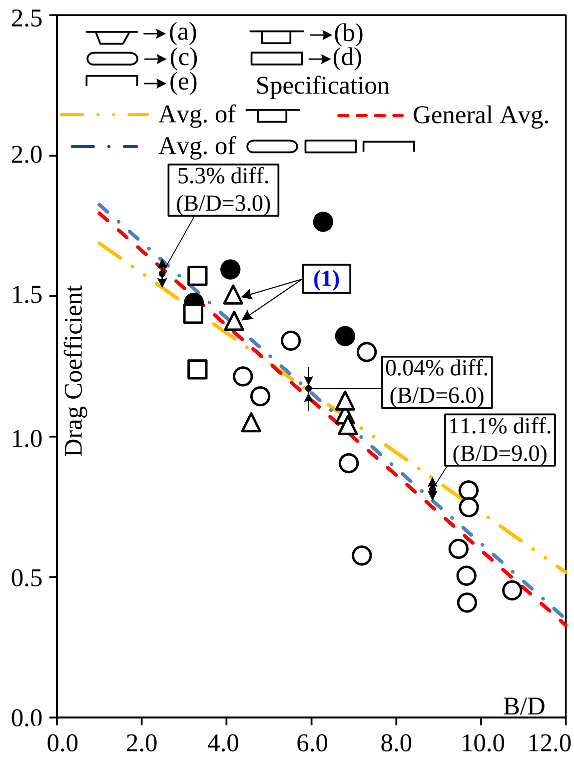

Fig. 4 Drag coefficients for different girder types

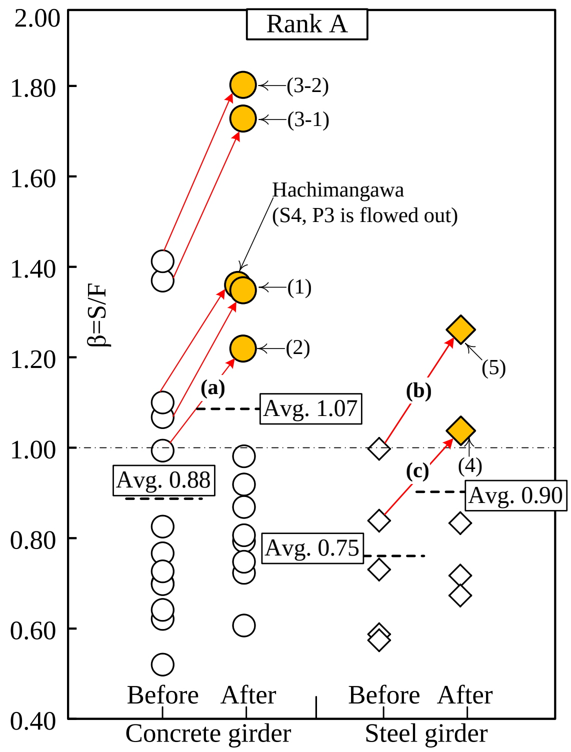

Fig. 5 Modification of β by drag coefficient (Rank A)

From Fig. 4, the difference between the drag coefficients of girders with and without stretching part is 5.3%, 0.04% and 11.1% when B/D is 3.0, 6.0 and 9.0. It is known that no great difference has occurred. Similarly, no great difference generates compared with the general average values. One possible reason can be referred from the Fig. 10 of next chapter, which illustrates the section view of Koizumi Bridge (representative for the girders with stretching in our study). The length (b) and height (d) of stretching part is 1300mm and 1500mm with the ratio (b/d) as 0.87; while for the representative girder (Ishikarigawakakou Bridge) with stretching in the wind test as shown in (1) of Fig. 4, this ratio is 0.40 (b as 1000mm and d as 2500mm). The ratio of Koizumi Bridge is about 2 times of that for the bridges in wind test, because the Honshu-Shikoku Bridges are long-span bridges which have differences with the normal bridges the authors studied. It is considered that the smaller stretching ratio decrease the vortex influence on the drag coefficient. More detailed data should be collected for studying this influence from stretching of girder in future. As a result, due to the smaller differences, the authors will use the general average Eq. 5 for revising the β ratios in the next chapter.

4. EVALUATION OF RESULTS AFTER REVISING

Herein, based on the modified equation of drag coefficient in the last chapter, β ratios will be revised firstly. Secondly, the un-coinciding β (Rank A bridges with β greater than 1.0 and Rank C bridges with β smaller than 1.0) after revising will be explained.

4.1 Discussion of Revised Results

Fig. 5 and Fig. 6 illustrate the comparison of β before and after the revising for Rank A and Rank C, respectively. The impact forces decreased due to the decrease of drag coefficients (Eq. 1). Thus, the general β ratios have the trend to increase.

For the Rank A bridges (Fig. 5), average of β changes from 0.88 to 1.07 with 21.6% increase for concrete girders; average of β varies from 0.75 to 0.90 with 20% increase for steel girders. For the variation (a), (b) and (c) presented in Fig. 5, β becomes greater than 1.0.

For the Rank C bridges (Fig. 6), β become more reasonable to explain the survival with the increase of β. (average from 1.72 to 2.45 with 42.4% increase for concrete; Average from 0.75 to 0.90 with 20% increase for steel). For the variation (d), (e) and (f) shown in Fig. 6, β becomes greater than 1.0, further verifying the greater girder resistance and the survivals of them.

As shown in Fig. 5 and Fig. 6, there are 7 β of Rank A bridges greater than 1.0 and 9 β of Rank C bridges smaller than 1.0, which are difficult to reflect the outflow tendencies. In the following section, the reasons of these un-coinciding β will be discussed.

4.2 Estimation of Reasons for Un-coinciding β

Table 2 presents the girder types, the distances to coastal line (L') and the corresponding river widths (B') for bridges with un-coinciding β. As to the girder types, there are 4 concrete girders and 3 steel girders for Rank A; while 6 concrete girders and 3 steel girders for Rank C. Before the detailed discussion of distances to coastal line and river widths, a special case (span 4 of

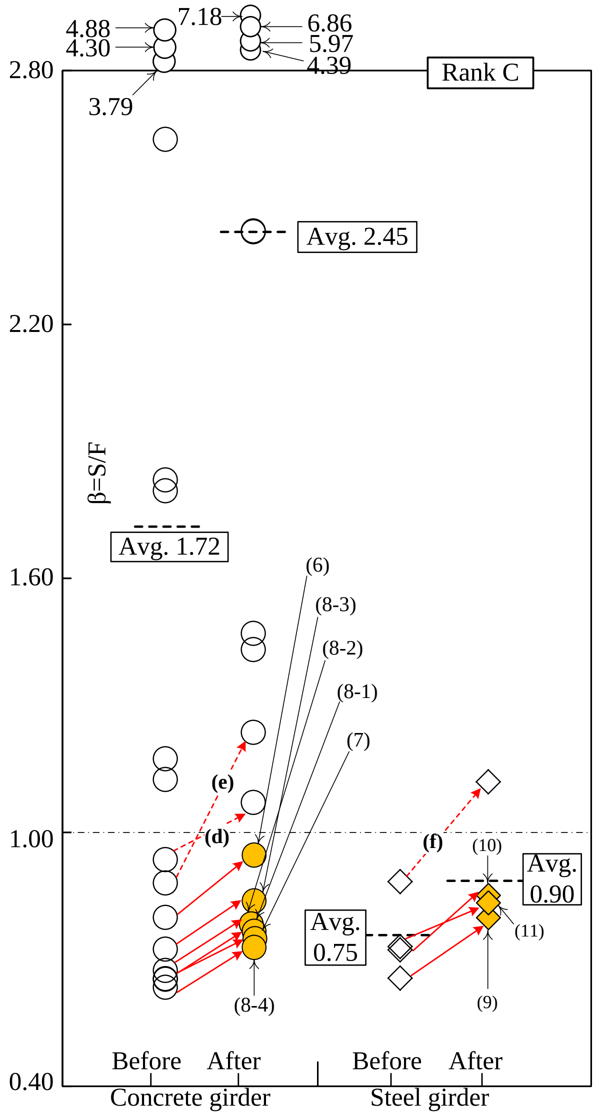

Fig. 6 Modification of β by drag coefficient (Rank C)

Table 2 Details of bridges with un-coinciding β

Rank	No.	Bridge Name	Span No.	Girder Type	L' (m)	B' (m)
A	1	Kozuka	2	PCT	56.0	42.4
	2	Akebono	1	PCT	100.6	26.6
	3-1	Numatakosen	1	PCT	236.6	0.0
	3-2		2~3	PCT	236.6	0.0
	--	Hachimangawa	4	Steel H	976.9	22.4
	4	Koizumi (Road)	1~3	Steel I	716.4	180.4
	5	Kesen	1~3	Steel I	459.4	190.8
C	6	Utatsu	1~2	PCT	55.7	32.8
	7	Tsuyagawa	8~9	PCT	1754.8	26.0
	8-1	Koizumi (JR)	1~2	RC-T	701.8	0.0
	8-2		3	PCI	701.8	0.0
	8-3		9	Underway PC	701.8	0.0
	8-4		15	RC-T	701.8	0.0
	9	Katagishi	1	Steel I	277.0	20.0
	10	Watari	3	Steel Box	1734.3	630.0
	11	Shinkitakami	5~7	Steel Truss	4275.7	567.7

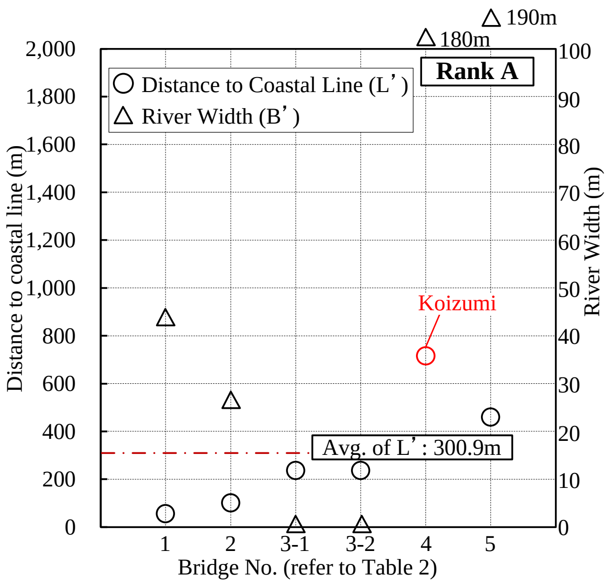

Fig. 7 Distance to coastal line & river width (Rank A)

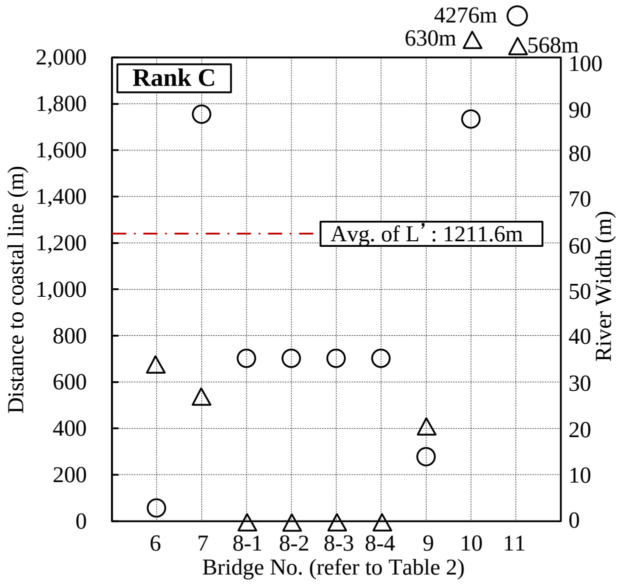

Fig. 8 Distance to coastal line & river width (Rank C)

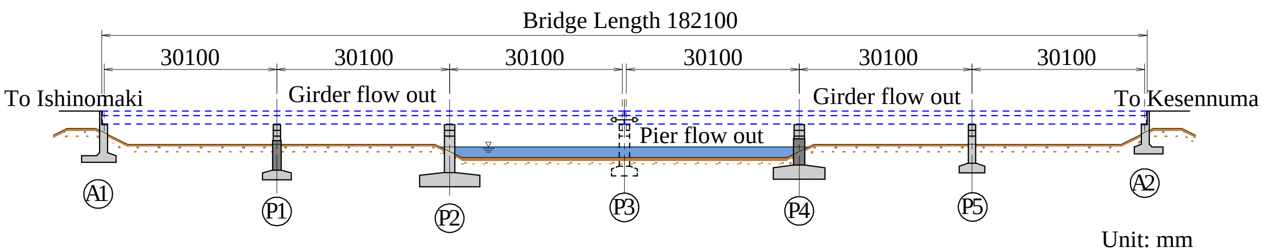

Fig. 9 Side view of Koizumi Bridge

Hachimangawa Bridge) will be explained. The pier 3 of Hachimangawa Bridge which was supporting the span 4 is evaluated to be very weak in the former research. Pier 3 was also confirmed to flow out by tsunami impact. It is considered that the previous outflow of the pier 3 caused the outflow of the span 4. Due to that, the β of span 4 cannot coincide with the outflow. Thus, this β will not be discussed in the following. As illustrated in Table 2, the other un-coinciding β are named from (1) to (11) (positions can be referred from Fig. 1).

Firstly, the β of Rank A bridges will be discussed. Fig. 7 presents the distributions of the distance to coastal line and the river width near the bridges. For the general trend, the distance is relatively small with the average as 300.9m. As illustrated in the references [3] and [4], tsunami velocity will be decreased together with the tsunami propagation because of the dissipation of tsunami energy. Thus, due to the smaller distances to coastal line of the Rank A bridges, greater velocities were estimated. For the No. 4 and No. 5 bridges, although the distances are in medium level around 600m, the river widths are relatively great, which make the tsunami propagation to be more easily and thus greater velocities might be occurred.

Therefore, because of the possible greater velocities for Rank A bridges, the tsunami impacts may be in greater level which will decrease the β ratios.

Secondly, the un-coinciding β of Rank C bridges will be discussed (Fig. 8). For the general trend, the distance is in relatively great level with the average as 1211.6m. Most of the distances are greater than 600m. Smaller velocities are estimated to occur. Thus, the tsunami impacts may be in smaller level which will increase the β ratios.

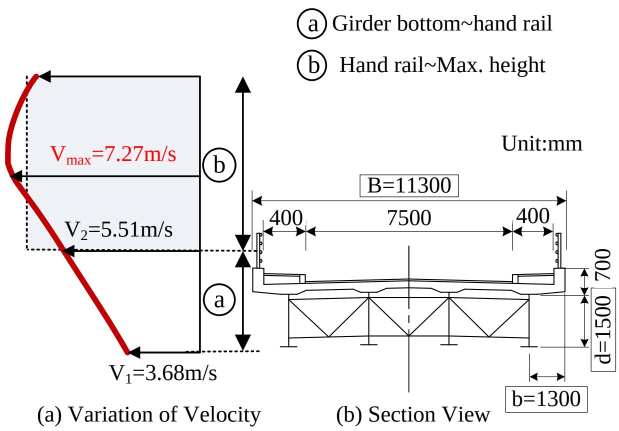

Fig. 10 Velocity variations near Koizumi Bridge

As a result, due to the different positions and terrains, the bridges with un-coinciding β might have different velocities with the assumed 6.0m/s. Among these bridges, the authors selected the Koizumi Bridge (No. 4 of Table 2, Rank A) as a representative to discuss the velocity based on the results from numerical analysis.

Fig. 9 presents the side view and damage conditions of Koizumi Bridge, which is a roadway bridge in the National Route 45 (section view in Fig. 10). It is formed by 2 Continuous Steel-Composite Girders with 6 spans (30.1m long). Due to the tsunami impact, all spans and the P3 have flowed out.

For the simulation, the tsunami propagation is based on the similar method explained in the former research [5]. The nonlinear long wave theory is applied. The Fujii•Satake Model (Ver.4.6) is used as the seismic wave source and the mesh size 5m of terrain data is applied.

As illustrated in Fig. 10, combined to the relative relations between the variations of tsunami height with the position of bridge girder, the velocity variations in the Koizumi Bridge is plotted. Two stages have been divided. Stage (a) represents the velocities when the tsunami height varies from the girder bottom to the girder top (400mm from the wheel guard). Stage (b) refers the velocities when tsunami height varies from the girder top to the maximum. The maximum velocity is found to occur in the stage (b) with the value near 7.3m/s, which is greater than the assumed 6m/s. Fig. 11 shows the velocity distributions near the Koizumi Bridge when the maximum velocity occurred. Tsunami is considered to collect together in the river mouth from the sea side. Due to the narrow terrain near the Koizumi Bridge, great velocity occurred. Thus, the β changed from 1.04 (velocity as 6.0m/s) to 0.70 (velocity as 7.3m/s). Therefore, the Koizumi Bridge flowed out by tsunami impact.

As a result, similar to the Koizumi Bridge, Rank A bridges with β greater than 1.0 have the probable tendencies to have greater velocities; while the Rank C bridges with β smaller than 1.0 might have smaller velocities. Through numerical analyses, more studies for the velocities near these bridges should be conducted in future.

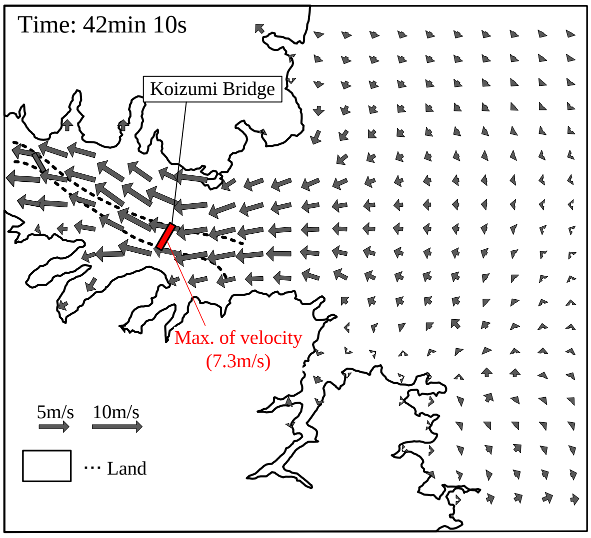

Fig. 11 Velocity Distributions near Koizumi Bridge

5. CONCLUSIONS

In this paper, β using the drag coefficient from specification [1] is evaluated; then, the revising of β by the average drag coefficients are conducted; at last, the un-coinciding β are explained from the discussion of distance to coastal line and the tsunami velocity from numerical analysis. From these studies, the following conclusions can be drawn:

(1) Based on evaluations using drag coefficients from specification [1], average β (ratio of girder resistance to tsunami impact) of Rank A bridges with girders flowed out is 0.84. Average β of Rank C bridges with girders survived is 1.52 (1.81 times of Rank A). Great difference occurred between the different damage ranks. β ratios is efficient for evaluating girder outflows.

(2) Through analyses from the wind tunnel test, great difference of drag coefficients between girders with and without stretching part is not found. By revising β using the general average drag coefficient, about 20% increase of β occurred.

(3) After revising β by drag coefficients, 7 β of Rank A bridges are greater than 1.0. From the discussion, these bridges are discovered to mainly locate in smaller distance to coastal line, which would produce greater velocities. The β will also be decreased.

(4) As a representative for Rank A bridges with β greater than 1.0, numerical analysis of Koizumi Bridge is conducted. The maximum velocity is estimated to be 7.3m/s which is in great level. The modified β by velocity becomes sufficient to explain the outflow of it.

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