DAMAGE ANALYSIS OF BRIDGES DUE TO TSUNAMI

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Abstract：Triggered tsunami from the Great East Japan Earthquake hit coastal areas of eastern Japan. 33 bridge superstructures are evaluated for the outflow conditions by β ratio (between bridge resistance and tsunami impact force). It is confirmed that β is an effective indicator. The great drag coefficient of the steel truss bridge caused the smaller β and outflow of it. Bridge width and height give influence on β corporately. Greater width and smaller height, like PC hollow bridges or bridges with many girders, are considered to produce greater β value and thus the greater resistant ability.

Key words：Bridge outflow, β ratios, Drag coefficient, PC hollow

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.

Soon after the great earthquake, the authors conducted several field investigations to the disaster areas of Japan. As shown in **Fig. 1**, 24 bridges with their positions near the coastline will be the study objects in this paper. Firstly, the evaluation of bridge outflow by β ratio (ratio between girder resistance with lateral load of tsunami) will be conducted, from which, the characteristics for the bridges with greater or smaller β ratios will be talked about. Secondly, distribution for the drag coefficient as an influential parameter to β ratio will be investigated. Further, the relations between β ratio with bridge width and height will be discussed.

2. Evaluation of Bridge Outflow by β Ratios:

In this chapter, the authors will firstly evaluate the outflow of bridges by β ratios in section 2.1. Secondly, the analysis of characteristics for the disaccording bridges and bridges with greater (smaller) β will be discussed.

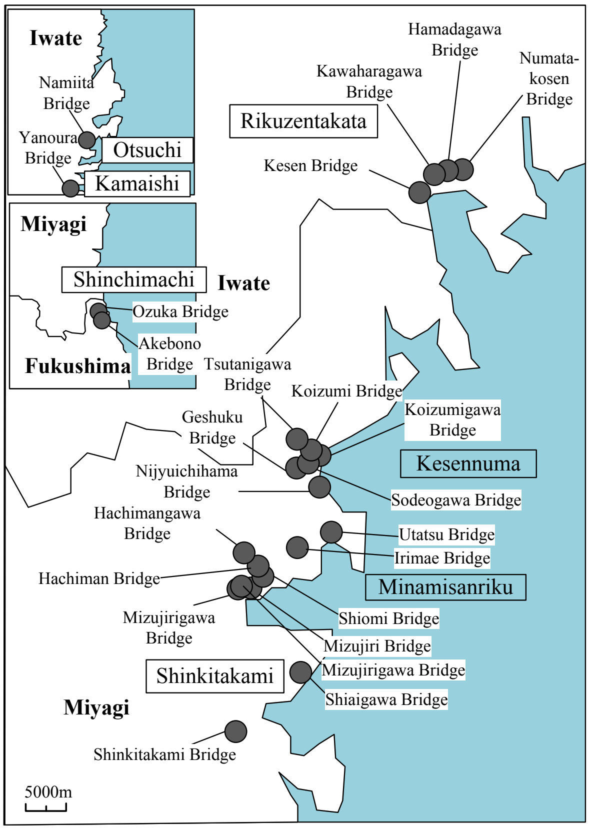


Fig. 1 General Tohoku Area

2.1 Evaluation of bridge outflow:

As bridge superstructure is of great significance to keep the traffic running, damage extents for bridges are divided by the outflow conditions of superstructure as illustrated in **Table 1**. However, based on the investigation this time, no Rank B bridge was found.

For evaluating bridge outflow conditions, tsunami impact force (F) and resistance of superstructure (S) is concentrated. F and S can be calculated by **Eq. 1** and **Eq. 2**:

$$F = \frac{1}{2}\rho_w C_d v^2 A_h \tag{1}$$

$$S = \mu W \tag{2}$$

where, ρ_w is density of water (1030kg/m^3); C_d is drag coefficient with its value decided from reference [1]; v is tsunami velocity and A_h is projected area of the superstructure in horizontal direction; μ is friction coefficient (0.6, based on research of Rabbat [2]); W is dead load of the superstructure.

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

$$\beta = \frac{S}{F} \tag{3}$$

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 [3]. Thus, v as 6.0m/s is used as a constant to all bridges, for only concentrating on the relationship between damage conditions with impact force.

Table 1 Definition for Damage Ranks

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

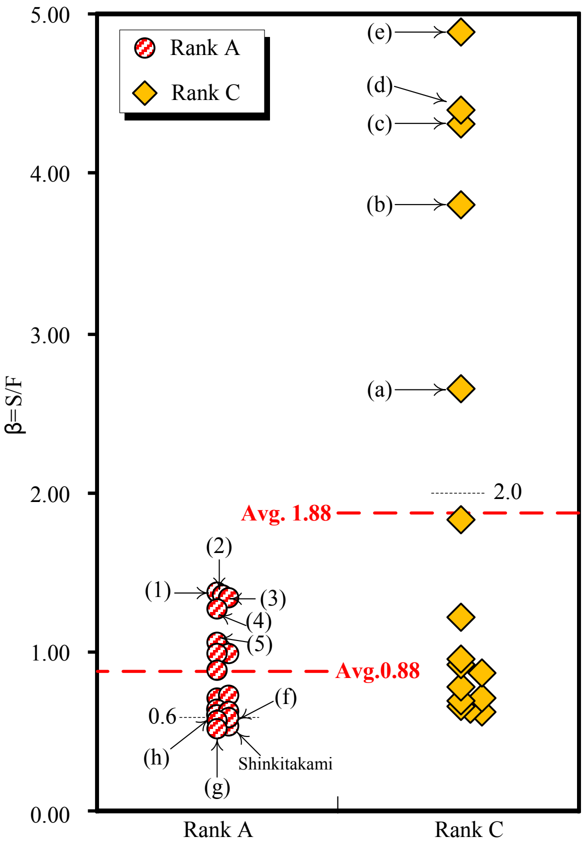


Fig. 2 β Ratios for Entire Tohoku

Table 2 Rank A Bridges with β Greater than 1.0

Rank A Bridges with β greater than 1.0				
No.	Area	Name	β	Girder Type
(1)	Utatsu	Utatsu	1.38	PC-T
(2)	Shizugawa	Hachimangawa (4th Span)	1.36	Steel-H
(3)	Rikuzentakata	Numatakosen	1.34	PC-T
(4)	Tsutanigawa	Geshuku	1.28	PC-T
(5)	Shinchimati	Ozuka	1.07	PC-T

Fig. 2 illustrates the relationship between the computed β ratios with the damage extent. Average β ratio of Rank A bridges with their superstructures outflowed is 0.88. Average β ratio of Rank C bridges with their superstructures survived is 1.88 (2.14 times of Rank A). Difference of β ratios between Rank C and Rank A bridges are obvious. β ratios are considered to be reasonable to evaluate the outflow condition well, which is also been proved in the former research [4].

2.2 Bridge characteristics with special β Ratios:

As illustrated in **Fig. 2**, there are 5 Rank A bridges with their β greater than 1.0 (mark (1) to (5)). The β ratios cannot coincide with their damage ranks. **Table 2** shows the bridge details. 4 of the total 5 bridges

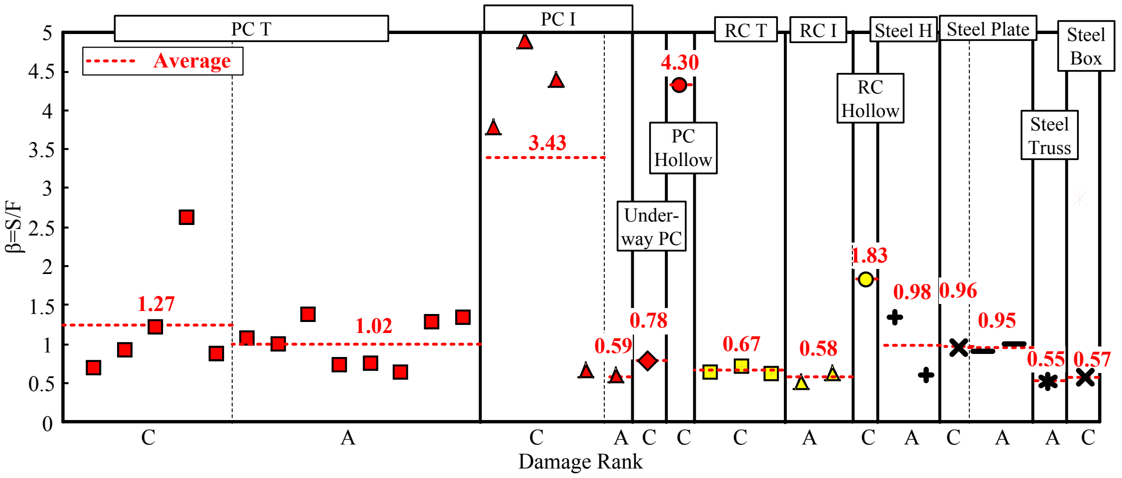


Fig. 3 Classification of β by Different Girder Type

are made of PC-T type girders. **Fig. 3** presents the β distributions calssified by girder type. The authors found that compared with the β ratios of other types for Rank A bridges, PC-T girders of Rank A bridges have greater β ratios with the average as 1.02. Though with greater β ratios, bridges are outflowed. There are two reasons. First one is considered to be the different velocities. As shown in **Table 2**, 4 PC-T bridges are distributing in different areas. Through the influence from landforms, the velocities in these areas maybe not consistent as 6.0m/s, which is assumed in this paper. For example, Rikuzentakata was confirmed to have greater velocity in the former research, which will make the β ratio of Numatakosen Bridge to be smaller. Thus, probably caused by the smaller assumed velocity, greater β ratios are obtained. The second reason is considered to be the influence from drag coefficient. Except for the steel-truss type bridges, the specification [1] gives the same calculation equation (**Eq. 4**, disscussed in Section 3.1) of drag coefficient for different type of bridges. From **Fig. 7** (studied in Section 3.1) which shows the distritbuion of drage coefficients for different girder type, the average of PC-T girder is 1.66 which is almost in the same level with that for PC-I girder. **Fig. 4** shows the representative girder shapes of PC-T and PC-I bridges. Compared with PC-I type, the groove part in the tsunami impacting area (A in **Fig. 4**) may cause the PC-T girder with greater drag coefficient, which will decrease the β ratios. Thus, the smaller calculated drag coefficient for PC-T bridges may also be the reason for the greater evaluated β ratios.

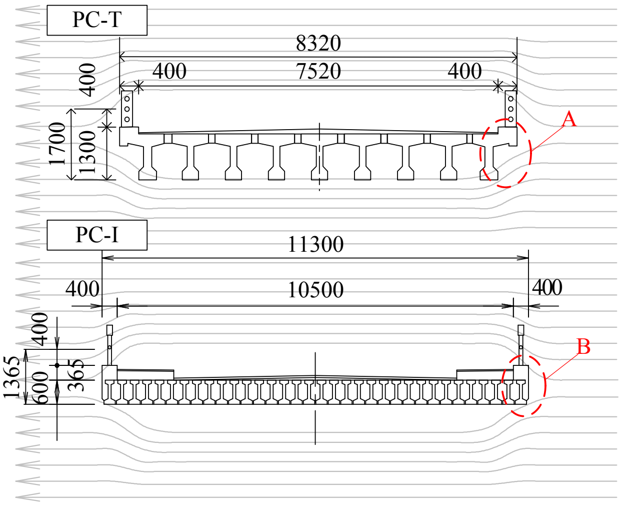
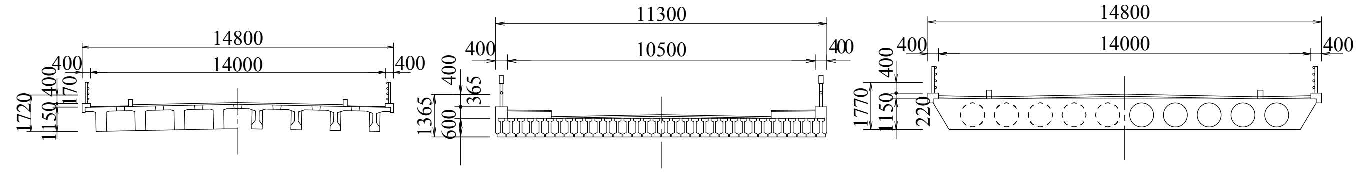
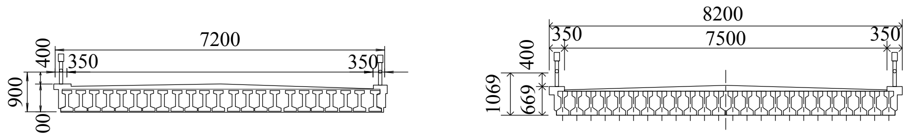


Fig. 4 Influence from Different Girder Types

Further, for checking the characteristics of easily outflowed and difficultly outflowed bridges, the section views of difficultly outflowed bridges with β ratios greater than 2.0 (closer to average β, 1.88 for Rank C) are shown in **Fig. 5**. While the section views of easily outflowed bridges with β ratios smaller than 0.60 (closer to minimum β, 0.63 of Rank C) are illustrated in **Fig. 6** (Shinkitakami as a truss bridge with β as 0.55 is discussed in Section 3.1). It is found that the girders of difficultly outflowed bridges are all belong to the PC type. 3 of 5 bridges are made by PC-I girder, which infers the greater resistant ability. Further, it is easily discovered that the superstructure of difficultly outflowed bridges are relatively in flat

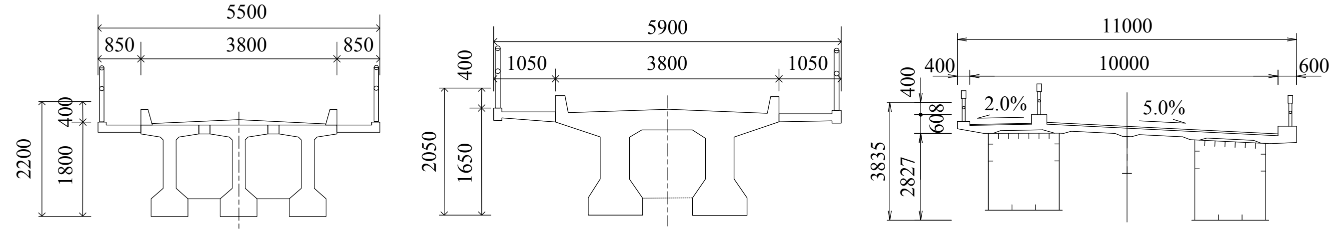


(a). Hamadagawa Bridge (PC-T)　(b). Shiomi Bridge (PC-I)　(c). Kawaharagawa Bridge (PC-hollow)



(d). Irimae Bridge (PC-I)　(e). Hachiman Bridge (PC-I)

Fig. 5 Section View of Bridges with β Ratios Greater than 2.0



(f). Mizujirigawa Bridge (PC-I)　(g). Hachimangawa Bridge (RC-I)　(h). Shiaigawa Bridge (Steel-box)

Fig. 6 Section View of Bridges with β Ratios Smaller than 0.6

shape. As to the difficultly outflowed bridges, the overall bridge length is in greater level and bridge height is in smaller level compared with those for the easily outflowed bridges.

If the bridge height is smaller, the tsunami impacting area per unit superstructure length will have the trend to be smaller. While, if the bridge width is greater, the superstructure weight per unit length will have the trend to be greater. Thus, greater β ratios will occur. As a result, the authors consider that greater bridge width and smaller bridge height will cause the bridges to have greater β and further the greater resistant ability.

3. Analysis of Influential Parameters for β Ratios:

In this chapter, characteristics of distributions for drag coefficient will be talked firstly. Secondly, based on the derivation of β ratio, the influential bridge parameters will be investigated in Section 3.2.

3.1 Distribution of drag coefficient:

From the definition of β ratio (**Eq. 3**), the drag coefficient as an influential parameter for the tsunami impact force, will affect the value of β. The calculation of drag coefficient is given by the specification [1] as shown in **Eq. 4** and **Eq. 5**: (**Eq. 5** is for calculation of truss type bridge, while **Eq. 4** is for other types)

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

$$C_d=1.35/\sqrt{\phi}\quad(0.1\leq\phi\leq0.6) \tag{5}$$

where, C_d is the drag coefficient; B is the bridge width (m); D is the bridge height (m); ϕ is the fill rate as the ratio between the area of truss and the area of external contour for the truss.

Based on the equations above, the drag coefficients for different type of girders have been calculated and presented in **Fig. 7**. The authors found that the maximum value occurs to the steel truss girder as 3.34 (point (1)). The minimum value is located in the PC hollow girder as 1.30 (point (2)). The drag coefficients for the other girder types have relatively smaller variations with the average values changed from 1.51 to 1.85.

In order to investigate the reason for the maximum and minimum values, **Fig. 8** illustrates the section view of the steel truss bridge and the PC hollow bridge. As to the steel truss bridge (**Fig. 8 (1)**), the truss area and the external contour area is calculated as 15.24m^2 and 93.33m^2 for each unit span between two joints. Thus, the fill rate ϕ is 0.1633 and the drag coefficient is 3.34 based on **Eq. 5**. The drag coefficient is in greater level. It is known that when fluid such as wind flow past an object, the opposite side to the impact area will promote the impacting forces in the flowing direction. With respect to the truss girder, these promoting effects will be relatively in greater level. Thus, greater drag coefficient is obtained, which decrease β ratio (0.55, **Fig. 3**) and cause the outflow of the bridge. The bridge with minimum drag coefficient (**Fig. 8 (2)**) is PC hollow type with relatively flat shape. As disscussed in Section 2.2, this type of bridge has relatively greater bridge length and smaller bridge width, which makes the ratio *B/D* to be great (8.36). Hence, the lower limit value 1.30 is obtained from **Eq. 4**. Smaller drag coefficient makes greater β ratio (4.30, **Fig. 3**) and the survival of the bridge.

3.2 Relation between β and *B*, *D*:

Further simplification of β is conducted as **Eq. 6**: (*L*: Bridge length, *γ*: weight per unit volume)

$$\beta = \frac{S}{F} = \frac{\mu \cdot W}{\frac{1}{2}\rho_w \cdot C_d \cdot v^2 \cdot A_h} = \frac{\mu \cdot \gamma \cdot B \cdot D \cdot L}{\frac{1}{2}\rho_w \cdot v^2 \cdot C_d \cdot D \cdot L} \tag{6}$$

From **Eq. 6**, the authors found that bridge length *L* and height *D* are included in both resistance *S* and impact force *F*, which can be offset. Then, the influential parameters to β are considered to be *B* (included in *S*) and *D* (included in C_d and give influence on *F*). Herein, bridge width and height are considered to be the independent parameters to influence the β ratio. **Fig. 9** and **Fig. 10** show the relations between β with *B* and *D*, respectively. As the irregular distributions, it is considered that no apparent relations can be found if considering *B* and *D* separately. However, considering for the greater β ratios (like point (7), (13) and (14)), the *B* values are in greater level and *D* values are relatively in smaller level. While for the smaller β values (as point (31) and point (32)), the *B* is in smaller level and the *D* is in greater level. Further, for the medium

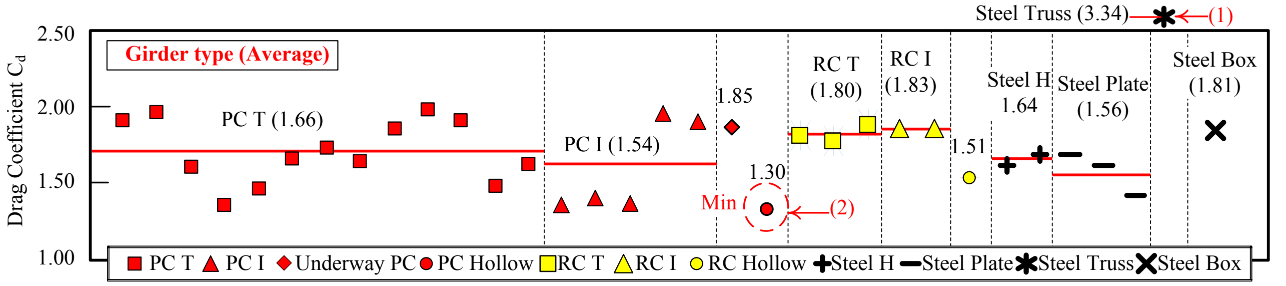
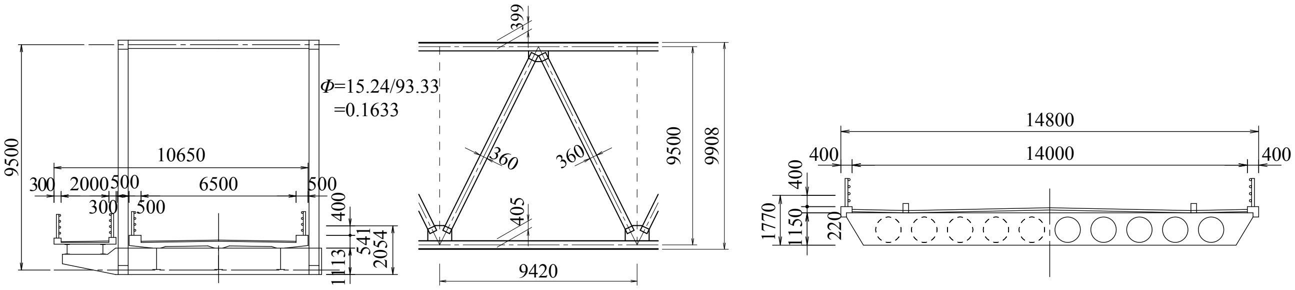


Fig. 7 Drag Coefficients Classified by Girder Types



(1). Shinkitakami Bridge (Steel-truss)　　(2). Kawaharagawa Bridge (PC-hollow)

Fig. 8 Section View for Bridges with Maximum and Minimum C_d

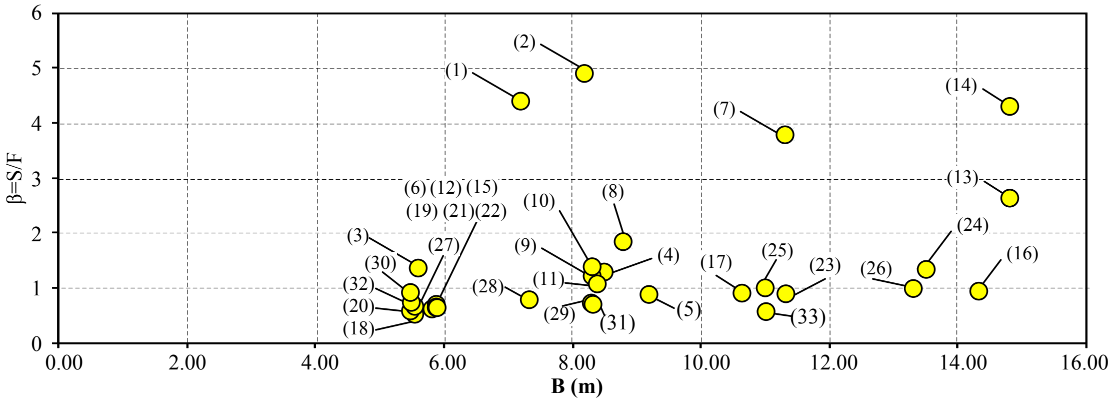


Fig. 9 Relations between β and *B*

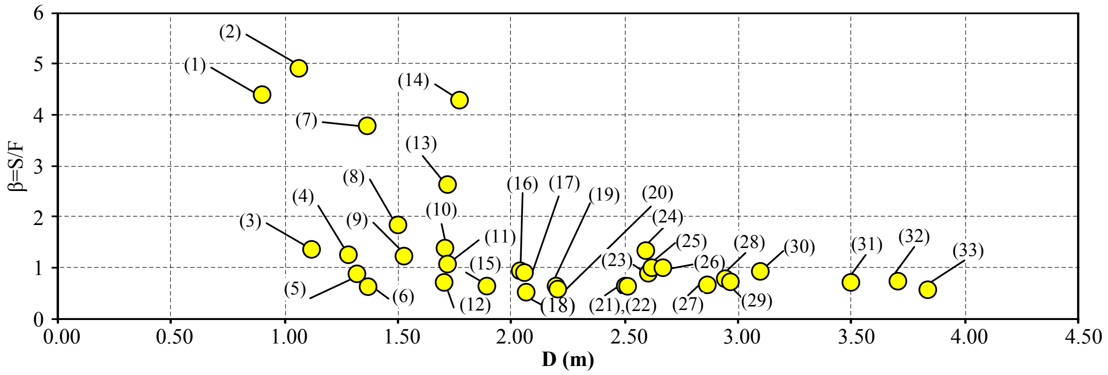


Fig. 10 Relations between β and *D*

β ratios (point (9) and (10)), both the values of *B* and *D* are in the medium level. Thus, the authors consider that the bridge width and bridge height give influence on β ratios corporately. The greater width and smaller height (like PC hollow bridge or bridges with many girders) will cause greater β value and thus the greater resistant ability of bridges.

4. Conclusions:

(1). From evaluation of the 33 bridge superstructures, average β ratio of Rank C superstructures is 1.88 as 2.14 times of that for Rank A. Difference of β ratios between Rank C and Rank A is obvious. β is considered as an effective indicator for the evaluation of bridge outflow.

(2). The Rank A bridges with β ratios greater than 1.0 are mainly made of PC-T girders. The different velocities in different area and the smaller evaluated drag coefficient for the PC-T girders are considered the reasons for the greater β ratios.

(3). The greater drag coefficient of the truss bridge caused the smaller β and thus the outflow of the bridge.

(4). The bridge width and bridge height give influence on β ratios corporately. Greater width and smaller height (like PC hollow bridge or bridges with many girders) would produce greater β value and thus the greater resistant ability of bridges.

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