On Difference between the Provisions for Seismic Hydrodynamic Pressure on bridge pier in Japanese code and Euro code 8

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Abstract. The the provisions on hydrodynamic pressure in two main seismic design codes of bridges in the world, Japanese code and Euro code, are reviewed. The difference on their theoretical bases, and numerical values are dealt with in this paper. In general, the effect of the pressure from Japanese code is larger than that from Euro code, and they are reaching similar at deep water situation. The latter could be considered as the upper bound of the former. A suggestion is contributed to the on going improvement of the Guidelines for seismic design of highway bridges of China, which consists of an equation for added mass and a set of values of pier section shape coefficients from the both codes.

1. Introduction

The effect of hydrodynamic pressure on bridge pier is required to combined with those from ground motion, dead load, earth pressure and so on in seismic design, while there is quite large difference among provisions on the pressure in seismic design codes for bridges in earthquake countries. The difference means that the knowledge on the pressure is now not enough, but it must be taken into account in the code. Therefore, the difference could be a starting point of the further study. The corresponding provisions in two main seismic design codes for highway bridges in the world, Design specifications for highway bridges of Japan (in brief, called as Japanese code below) [1] and Euro code 8 [2], are reviewed in this paper. The difference between the provisions, theoretical bases, and numerical values are compared, then a suggestion is contributed to the on going improvement of the Guidelines for seismic design of highway bridges of China [3].

2. The provisions for seismic hydrodynamic pressure in the two codes

2.1 In Japanese code. To determine the effects of earthquakes, the inertia force due to the dead weight of the structure, earth pressure, effects of liquefaction and liquefaction induced ground flow, and ground displacement should be taken into account with hydrodynamic pressure during an earthquake. The seismic hydrodynamic pressure is determined with consideration of water level, shape and size of the section of pier and design ground motion. It can be assumed to act in the same direction of the inertia force of the pier. The formulas for the pressure on pier completely surrounded by water in Japanese code are as follows [1].

$$p=\begin{cases}\frac{3}{4}k_h w_0 A_0 h\frac{b}{a}(1.0-\frac{b}{4h}), & if \quad \frac{b}{h}\leq 2.0\\ \frac{3}{4}k_h w_0 A_0 h\frac{b}{a}(0.7-\frac{b}{10h}), & if \quad 2.0<\frac{b}{h}\leq 4.0\\ \frac{9}{40}k_h w_0 A_0 h\frac{b}{a}, & if \quad 4.0<\frac{b}{h}\end{cases} \tag{1}$$

where P is the resultant force of total seismic hydrodynamic pressure acted on the pier at height of $3h/7$, k_h is the design lateral seismic coefficient defined as the ratio of design horizontal basic acceleration to gravity acceleration, w_0 is unit weight of water (kN/m^3), A_0 is the area of the pier section at the height of $3h/7$, h is the water depth (m), b is the pier width in the direction perpendicular to the direction of hydrodynamic pressure (m), a is the length of the other side of rectangular section of the pier.

For dynamic analysis, an added mass is suggested for the pressure effect with a cubic expression with pier height as in Eq. 8 and in the form with water depth is similar as in Eq. 1.

2.2 In Euro code 8. The effect of hydrodynamic interaction may be estimated by taking into account an added mass of entrained water from Euro code 8 [2]. That effect is assumed in the horizontal directions per unit length of the immersed pier. Therefore, the total horizontal effective mass in seismic response analysis should be taken as the sum of the actual mass of the pier, the mass of water possibly enclosed within the pier and the added mass m_a of externally entrained water per unit length of immersed pier. The m_a depends on the shape of section of the pier.

It is obvious that the provisions on hydrodynamic interaction during earthquake are quite different in the two codes. The action is considered as an additional static force in Japanese code. The key term $k_h w_0 A_0 h$ is in form of product of an acceleration and a mass, the mass is defined by the product of water density and the volume of immersed pier. The latter is the same as the added mass m_a in Euro code. The difference is mainly on the considerations with water depth and the shape of section of pier. Firstly we would like to deal with why there is a relative complicated coefficient on water depth in Japan code, while it always keep a same value of 1.0 in Euro code.

3. The difference between the theoretical bases of the two provisions

3.1 In Japanese code. According the commentary of Japanese design specifications for highway bridges, Part V seismic design [1, 4, 5], the Eq. 1 comes from the suggestion by Goto and Toki (1965) [6]. From the following integrating equation on velocity potential in cylindrical coordinate system, Eq. 2, and the boundary conditions in Eq. 3, Eq. 4, Eq. 5 and Eq. 6, dynamic pressure per unit length on a vertical rigid cylinder surface in horizontal y direction can be described by Eq. 7, with neglecting effect of surface wave and compressibility of water.

$$\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2}+\frac{\partial^2\phi}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2}=0 \tag{2}$$

$$\left(\frac{\partial\phi}{\partial r}\right)_{r=a}=-\frac{\partial y}{\partial t}\cos\theta \tag{3}$$

$$\left(\frac{\partial\phi}{r\partial\theta}\right)_{\theta=0}=\left(\frac{\partial\phi}{r\partial\theta}\right)_{\theta=\pi}=0 \tag{4}$$

$$\left(\frac{\partial\phi}{\partial z}\right)_{z=0} = 0 \tag{5}$$

$$\left(g\frac{\partial\phi}{\partial z} + \frac{\partial^2\phi}{\partial t^2}\right)_{z=h} = 0 \tag{6}$$

$$P_y = k_h\gamma_w\pi a^2\sum_{m=1}^{\infty}\frac{(-1)^{m-1}}{\alpha_m h}\frac{4}{\alpha_m a}\frac{K_1(\alpha_m a)}{K_0(\alpha_m a)+K_z(\alpha_m a)}\cos\alpha_m z \tag{7}$$

In Eq.7, k_h, and h are the same as in Eq.1, a is the radius of the cylindrical pier, z is height along the pier from 0 at bottom to h at water surface, other coefficients and functions can be found in [5] and will not be illustrated here.

In simplification, a cubic expression and a modification are taken for distribution of the hydrodynamic pressure with the ordinate z, and with water depth h respectively, in the case of the cylinder moving in finite mass of water, the following formula is then derived.

$$P_y = k_h\gamma_w\pi a^2(1.0-\frac{a}{2h})\sqrt[3]{1.0-\frac{z}{h}} \tag{8}$$

One can see that the P_y value should reach $k_h\gamma_w\pi a^2$, the same as in Euro code. Integral of the term containing z from 0 to h, can be obtained as

$$\int_0^h\sqrt[3]{1.0-\frac{z}{h}}dz = \frac{3}{4}h \tag{9}$$

Substitute Eq. 8 into Eq. 9, with considering the fact that a, a^2 and γ_w here equal to $b/2=a/2$, $A_0=ab$ and w_0 in Eq.1 respectively, one can see that the result must be the same as Eq. 1, for $b/h \leq 2.0$. So the static force for hydrodynamic pressure in Japanese code is a result of simplification from three dimensional dynamic analysis.

3.2 In Euro code. The added mass in Euro code is the result in the case of infinitely long cylinder moving perpendicularly to its length in an infinite mass of water. The effective mass is convenient to be adopted in dynamic analysis, while it must be conservative compared with the term in parentheses at right side of Eq. 1. The force from the equation changes with water depth, and it reaches to those from added mass in Euro code, if water depth is large enough. In cases the seismic action in transverse direction of bridge is resisted mainly by piers, without significant interaction between adjacent piers, the seismic action effect may be approximated by an equivalent static force [2]. In such case, the forces from the two codes can be compared as in Fig. 1 [6]. In the figure, the ordinate represents the ratio of the dynamic water pressure at the pier bottom to the inertia force of the excluded mass of water, and the abscissa is for the ratio of radius of cylinder to water depth.

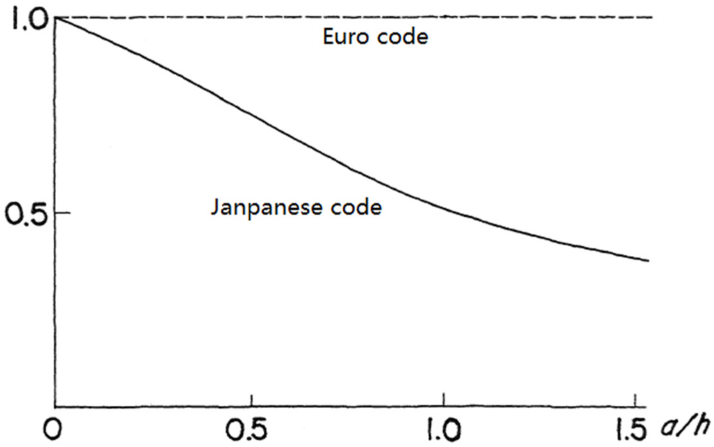


Fig 1 Comparison of normalized hydrodynamic pressures from the previsions of the two codes

One can find from the figure that the formula in Japanese code applies bridge pier especially in shallow water, and the resultant additional effect by hydrodynamic pressure from Euro code is similar with it if water depth is more than 10 times of the pier radius.

4. The difference between the pier section shape coefficients in the two codes

4.1 In Japanese code. Section shape coefficients of bridge pier for hydrodynamic pressure in the existing Japanese code is 1.0 for all situations, and is a factor with value 1.0 for rectangular section, 0.8 for circular, 0.9~1.0 and 0.8 along longitudinal or transverse the bridge direction respectively for section with two circular ends as shown in Fig. 2, in a previous edition [4].

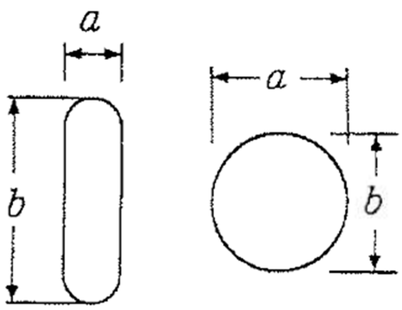
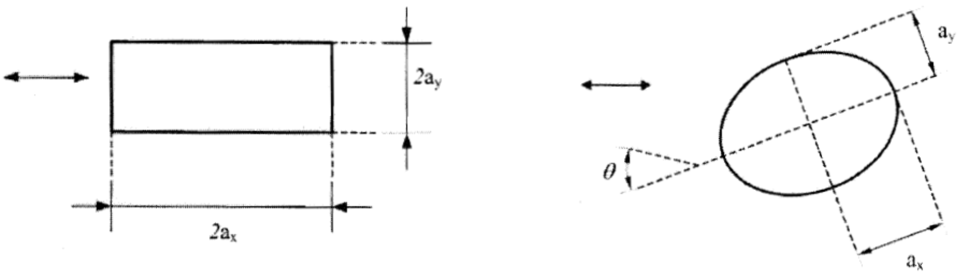


Fig 2 Definition of dimensions of pier section in Japanese code [4]

4.2 In Euro code. The section shape coefficient in Euro code is defined for three kinds sections. The added mass is provided by $m_a = \rho\pi R^2$ for circular section, means that the value of shape coefficient equals to 1.0. For elliptical section as shown in Fig. 2, and horizontal seismic action at an angle θ to the x-axis of the section, it is provided as $m_a = \rho\pi(a_y^2\cos^2\theta + a_x^2\sin^2\theta)$, the value of shape coefficient is that in parenthesis. For rectangular section as shown in Fig. 2, the mass $m_a = k\rho\pi a_y^2$ is provided with values of the shape coefficient k listed in table 1.



Rectangular Elliptical

Fig. 3 Definition of dimensions of pier section in Euro code

Table 1 Values of shape coefficient for rectangular pier section in Euro code

a_y/a_x	0.1	0.2	0.5	1.0	2.0	5.0	10.0	∞
k	2.23	1.98	1.70	1.51	1.36	1.21	1.14	1.00

The values of the shape coefficients from the two codes are listed in table 2 for the pier section of rectangular, circular ends and elliptical respectively. The value ranges for elliptical section are calculated with 5 values of a_y/a_x and 5 values of θ, i. e. 0, 30, 45, 60 and 90 respectively. One can see from the table that the values from Euro code is about 1.2~2.0 times of those from Japanese code for rectangular and circular sections, but a quarter to 6 times for elliptical or circular ends section, since the angle to the x-axis is just considered for this kind of section. The authors believe the difference between shape coefficient values is two large, especially for elliptical section, comparing with the difference shown in Fig.1.

Table 2 Comparison of values of shape coefficient for various sections from the two codes

Code	Section	a_y/a_x				
		0.2	0.5	1.0	2.0	5.0
Euro	Rectangular	1.98	1.70	1.15	1.36	1.21
	Circular	1.0	1.0	1.0	1.0	1.0
	Elliptical	0.2~5.0	0.5~2.0	1.0	0.5~2.0	0.2~5.0
Japanese	Rectangular	1.0	1.0	1.0	1.0	1.0
	Circular	0.8	0.8	0.8	0.8	0.8
	Circular ends	0.8		0.8	0.9~1.0	

5. Conclusions

The difference between the provisions on hydrodynamic pressure in the two seismic design codes of bridges in the world, Japanese code and Euro code, and their theoretical bases, and numerical values are deal with. In Japanese code, a static force in stipulated for the pressure from a simplification of three dimensional dynamic analysis, it is described in a form changing with water depth and also the height of pier. In Euro code, a added mass is stipulated for the pressure in dynamic analysis without changing with water depth or height of pier. The effect of the latter is larger than that of the former, and they are similar for deep water situation. Therefore, in the on going improvement of the Guidelines for seismic design of highway bridges of China, added mass from both codes could be adopted for dynamic analysis in seismic design of bridges, if deep water situation is going to be taken into account in the improvement, e. g. the following equation would be suggested for the added mass in unit height of pier at z with coefficients as same as in Eq.7.

$$m_a = \begin{cases} \gamma_w \pi a^2 \sqrt[3]{1.0 - \frac{z}{h}}, & if \quad \frac{a}{h} \le 0.1 \\ \gamma_w \pi a^2 (1.0 - \frac{a}{2h}) \sqrt[3]{1.0 - \frac{z}{h}}, & if \quad 0.1 < \frac{a}{h} \le 1.0 \\ \gamma_w \pi a^2 (0.7 - \frac{a}{5h}) \sqrt[3]{1.0 - \frac{z}{h}}, & if \quad 1.0 < \frac{a}{h} \le 2.0 \\ 0.3 \gamma_w \pi a^2 \sqrt[3]{1.0 - \frac{z}{h}}, & if \quad 2.0 < \frac{a}{h} \end{cases} \tag{10}$$

The shape coefficients from the two codes are not very different for circular and rectangular section of bridge pier, but quite different for elliptical section. The values of shape coefficient for the new version of Chinese code, would be suggested as 1.0 for circular section of bridge pier, 1.25 for rectangular section, and 1.0 and 1.25 for section with circular ends respectively along longitudinal or transverse direction of bridge.

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