Seismic Analysis for Concrete Continuous Beam Bridges in Transverse Direction

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ABSTRACT :
According to the bridge layout scheme and the linear rigidity ratio of the beam to piers, a theoretical calculation method for the laws of the transverse seismic response is deduced through simplifying a three-span concrete continuous beam bridge structure as a elastic support continuous beam model. The effects of the distribution laws of transverse seismic response is analyzed with Finite Element Methods (FEM) considering the following three different situations: changing the linear rigidity ratio of beam to piers on condition of equal pier height, changing the ratio of piers height on condition of symmetrical and asymmetrical side-span. By comparison of the finite element analysis results and theoretical analysis results, the validity of the simplified theoretical calculation method is verified. Theoretical analysis and numerical simulation show that: the linear rigidity ratio of the beam to piers can influence anti- push rigidity of the pier. If the linear rigidity ratio of beam to pier increases, the anti-push rigidity of the pier will increase. The shear and moment partition coefficient of each pier is related to the anti-push rigidity of the pier, and the more anti-push rigidity of the pier, the more internal force partition coefficient of the pier; otherwise it decreased. Pier height ratio changed the linear rigidity ratio of the beam to piers, thus the internal force partition coefficient of the pier has been changed. According to the above parameter analysis,a reference method to optimization the design of continuous concrete bridges seismic design in transverse direction is given in this paper.

KEYWORDS: Concrete continuous beam bridge, Transverse seismic response, Linear rigidity ratio, Anti-push rigidity

1. INTRODUCTION

With implementation of china great western development strategy, the western bridge construction obtains great development in china. Because of the characteristic of terrain and landform in west, muti-span concrete continuous beam bridges are commonly used. Due to the particularity of various bridges terrain, landform and geological hydrology condition, the pier height and the span of bridges are different, which leads to the difference of those dynamic characteristics. Earthquake often occurred in western area, where earthquake fortification level is high. So studying on the law of dynamic characteristics with different bridge layout scheme, which is essential to grasp characteristic of the seismic response and take necessary earthquake proof measures. In seismic response analysis of continuous beam bridge, the author find that longitudinal seismic response is often based on the rigidity variations of piers distribution because the beam can be assumed as a rigid body in longitudinal. But the transverse seismic response is more complex. Along with the different bridge layout scheme, seismic force distribution has great difference [1-2]. Therefore, how to grasp the characteristic of the continuous beam bridge's transverse seismic response is also an important research subject.

In present research on the bridge's transverse seismic response, methods often used are: considered the beam as a rigid rod, calculating bridge's transverse seismic response through the method of structural mechanics [3]; basing on the response spectrum theory to calculate bridge's transverse natural vibration characteristics, suggesting that the seismic force of continuous beam bridge's the first-order transverse vibration mode can be used to estimate the structure's transverse seismic force[4]; basing on time history analysis theory to simplify calculation of the continuous beam bridge's transverse seismic response[5]. In fact, the linear rigidity ratio of the beam to piers has great influence on bridge's transverse seismic response. In this paper, a simplified theoretical calculation method, in which the linear rigidity ratio of the beam to piers is taken into consideration, is proposed to calculate the concrete continuous beam bridge's transverse seismic response. It will be useful to guide continuous beam bridge's preliminary seismic design.

2. THEORETICAL ANALYSIS OF DISTRIBUTION IN TRANSVERSE SEISMIC FORCE

By the assumption that the transverse bending rigidity of bridge is invariable, a three-span continuous beam concrete bridge structure can be simplified as an elastic support continuous beam model theoretically as Figure1 shows Because the rigidity of lateral restraint of the abutment on both sides is comparatively very large, the beam can be assumed as articulated at both ends. And the rigidity of the middle elastic supports are determined by the transverse anti-push rigidity of each pier. Without considered seismic traveling wave effect, seismic force on bridge is simplified as equivalent uniform load 'q'. Thus the dynamic problem can be simplified static force problem in this analysis[6].

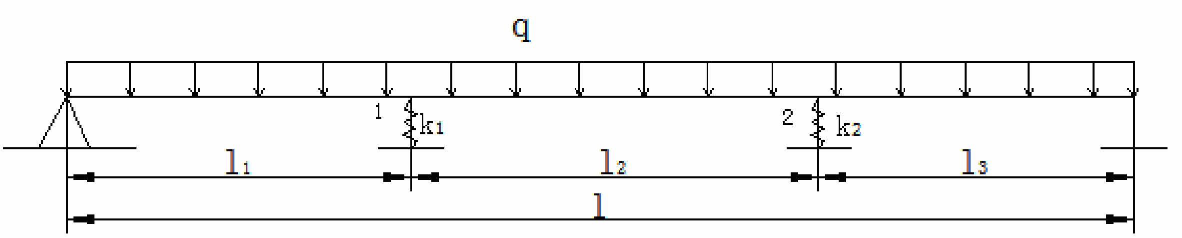

Figure 1 Transverse simplified analysis model of continuous beam bridge

Simplified as a statically indeterminate structure, analysis method of structural mechanics can be used. Assume the transverse force at support 1 and 2 are X_1 and X_2 respectively. So the basic equation is as Eqn.2.1.

$$\begin{cases} \delta_{11}X_1+\delta_{12}X_2+\Delta_{1p}=-\dfrac{X_1}{k_1} \\ \delta_{22}X_2+\delta_{21}X_1+\Delta_{2p}=-\dfrac{X_2}{k_2} \end{cases} \tag{2.1}$$

Solving above equation, then X_1 and X_2 can expressed as Eqn.2.2.

$$\begin{cases} X_1=\dfrac{\Delta_{1p}(\delta_{22}+\frac{1}{k_2}-\delta_{21})}{(\delta_{11}+\frac{1}{k_1})(\delta_{22}+\frac{1}{k_2})-\delta_{12}\delta_{21}} \\ X_2=\dfrac{\Delta_{2p}(\delta_{11}+\frac{1}{k_1}-\delta_{12})}{(\delta_{11}+\frac{1}{k_1})(\delta_{22}+\frac{1}{k_2})-\delta_{12}\delta_{21}} \end{cases} \tag{2.2}$$

Where:

$$\delta_{11}=\frac{l_1^2(l_2+l_3)^2}{3EIl}, \quad \delta_{22}=\frac{l_3^2(l_1+l_2)^2}{3EIl},$$

$$\delta_{12}=\delta_{21}=\frac{l_1l_3}{6EIl^2}\left[l_1(l_2+l_3)(2l_1+3l_2)+l_3(l_1+l_2)(2l_3+3l_2)+l_2^3\right]$$

$$\Delta_{1p}=\frac{1}{24EIl}ql_1^3(l_2+l_3)(l_1+4l_2+4l_3)+\frac{1}{24EIl}ql_1l_3^3(4l_1+4l_2+l_3)+\frac{1}{48EIl}ql_1l_2\left[12l_1(l_2+l_3)(2l_1+l_2)+2l_2(l_3-l_1)(3l_3+l_2)+l_2^2(2l_1+l_2)\right]$$

$$\Delta_{2p}=\frac{1}{24EIl}ql_3^3(l_1+l_2)(4l_1+4l_2+l_3)+\frac{1}{24EIl}ql_1^3l_3(l_1+4l_2+4l_3)+\frac{1}{48EIl}ql_2l_3\left[12l_3(l_1+l_2)(l_2+2l_3)+2l_2(l_1-l_3)(3l_1+l_2)+l_2^2(l_2+2l_3)\right]$$

EI is the transverse bending rigidity of the beam, k_1、k_2 are transverse anti-push rigidity of the piers at support 1 and support 2 respectively. δ_{11} is the displacement at support 1 when the unit force acts on support 1; δ_{21} is the displacement at support 2 when the unit force acts on support 1; δ_{22} is the displacement at support 2 when the unit force acts on support 2; δ_{12} is the displacement at support 1 when the unit force acts on support 2; Δ_{1p} and Δ_{2p} are the displacement at support 1 and support 2 respectively when the uniform load 'q' acts on the beam.

The pier under seismic exciting often brings bending deformation and shear deformation, so the anti-push rigidity of the pier can be confirmed as Eqn.2.3.

$$k = \frac{1}{\dfrac{1}{k_v} + \dfrac{1}{k_b}} \tag{2.3}$$

Where:

k_b is the bending rigidity of the pier, $k_b = \alpha \dfrac{E_p I_p}{h^3}$; k_v is the shear rigidity of the pier, $k_v = \dfrac{G_p A_p}{h}$; E_p is the elastic modulus of the pier; I_p is the cross-section inertia moment of the pier; h is the height of the pier; G_p is the shear modulus of the pier, $G_p = \dfrac{E_p}{2(1+\upsilon)}$; A_p is the shear area of the cross section of the pier, υ is the poisson ratio; α is a parameter related to boundary condition.

As all know, when the top of the pier is completely consolidated, $\alpha = 12$; when the top of the pier is completely free, $\alpha = 3$. In this model, because of the change of the side-span and the pier height, the constraint condition of the pier has been changed. So the selection of α is adopting D-value method [7]. Assumed $K = \dfrac{i_1 + i_2}{i_p}$, then $\alpha = 12 \times \dfrac{0.5 + K}{2 + K}$. i_1 and i_2 are the linear rigidity of the beam on both sides, i_p is the linear rigidity of the pier. So the change of linear rigidity ratio of beam to piers affects anti-push rigidity of the pier, and also affects shear force distribution between piers.

Shear partition coefficient on the top of pier can be expressed as $c_i = \dfrac{X_i}{\sum_{i=1}^{n} X_i}$. So it can be known that the shear partition coefficient of three-span bridge's pier top is $c_1 = \dfrac{X_1}{X_1 + X_2}$ and $c_2 = \dfrac{X_2}{X_1 + X_2}$.

As the analysis above the shear partition coefficient can be expressed as Eqn.2.4.

$$c_1 = \frac{\Delta_{1p}(\delta_{22} + \dfrac{1}{k_2}) - \Delta_{2p}\delta_{21}}{\Delta_{1p}(\delta_{22} + \dfrac{1}{k_2} - \delta_{21}) + \Delta_{2p}(\delta_{11} + \dfrac{1}{k_1} - \delta_{12})}, c_2 = \frac{\Delta_{2p}(\delta_{11} + \dfrac{1}{k_1}) - \delta_{12}\Delta_{1p}}{\Delta_{1p}(\delta_{22} + \dfrac{1}{k_2} - \delta_{21}) + \Delta_{2p}(\delta_{11} + \dfrac{1}{k_1} - \delta_{12})} \tag{2.4}$$

So the shear partition coefficient on the top of pier is relating to layout scheme of the bridge and the anti-push rigidity of the pier.

Considered the effect of the height of pier, the moment distribution coefficients on the bottom of the pier can be expressed as $d_1 = \dfrac{X_1 \times h_1}{X_1 \times h_1 + X_2 \times h_2}$ and $d_2 = \dfrac{X_2 \times h_2}{X_1 \times h_1 + X_2 \times h_2}$.

In the same way, four-span, five-span and more span bridges can be analyzed. Thus the shear and the moment distribution coefficients of each pier can be simplified calculated.

3 . PARAMETER ANALYSIS AND VERIFICANTION OF REAL BRIDGE STRUCTURES

Based on analysis above, layout scheme of bridge has a great influence on distribution of transverse seismic response. In order to analysis the distribution law of transverse force, the below continuous beam model is choose as shown in Figure.2. This model is based on a certain overpass bridge of freeway from Xiaogan to Xiangfan Hubei province of china.

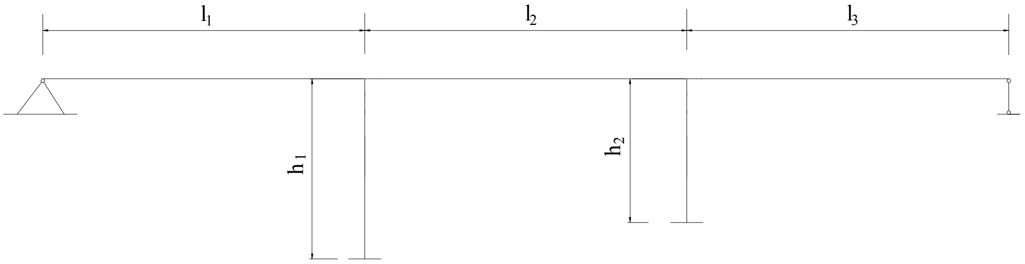

Figure.2 The diagram of the real continuous beam bridge

The beam and piers use the same concrete material (C50), the elastic modulus is $E = 34.5Mpa$. Beam section is single cell and single box sections, pier sections are double-column. Sectional characteristic of the real bridge is shown in Table.1. The finite element model of the bridge is shown as Figure.3.

Table.1 Sectional characteristic of the real bridge

Sectional characteristic	Beam	Pier
Area A （m^2）	7.35	4.5
Moment of inertia I_{xx} （m^4）	2.84	0.84
Moment of inertia I_{yy} （m^4）	104.06	23.66

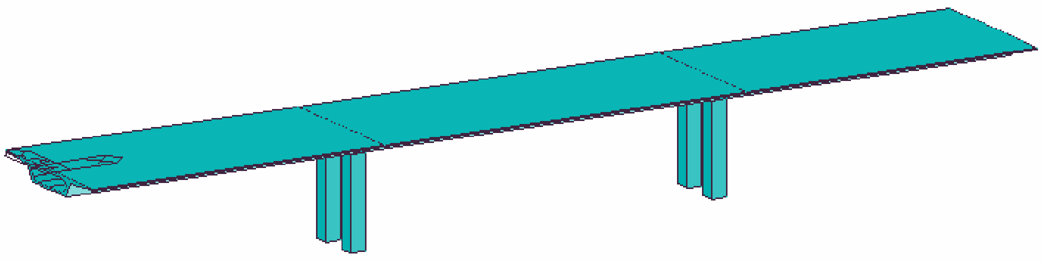

Figure.3 The finite element model of the real bridge

3.1 The Influence of Transverse Seismic Response with Different Side-span Ratio

Take three-span continuous beam bridge for example, holding mid-span l_2=40m and left side span l_1=30m, through changing right side span length l_3, in order to change side-span ratio. At same time, remaining the height of the pier constant, respectively h_1=9m and h_2=9m. Under this condition, the influence of the linear rigidity ratio of beam to piers on transverse internal force partition coefficient of each pier can be discussed. The influence of transverse seismic response with different side-span ratio is shown as Figure.4.

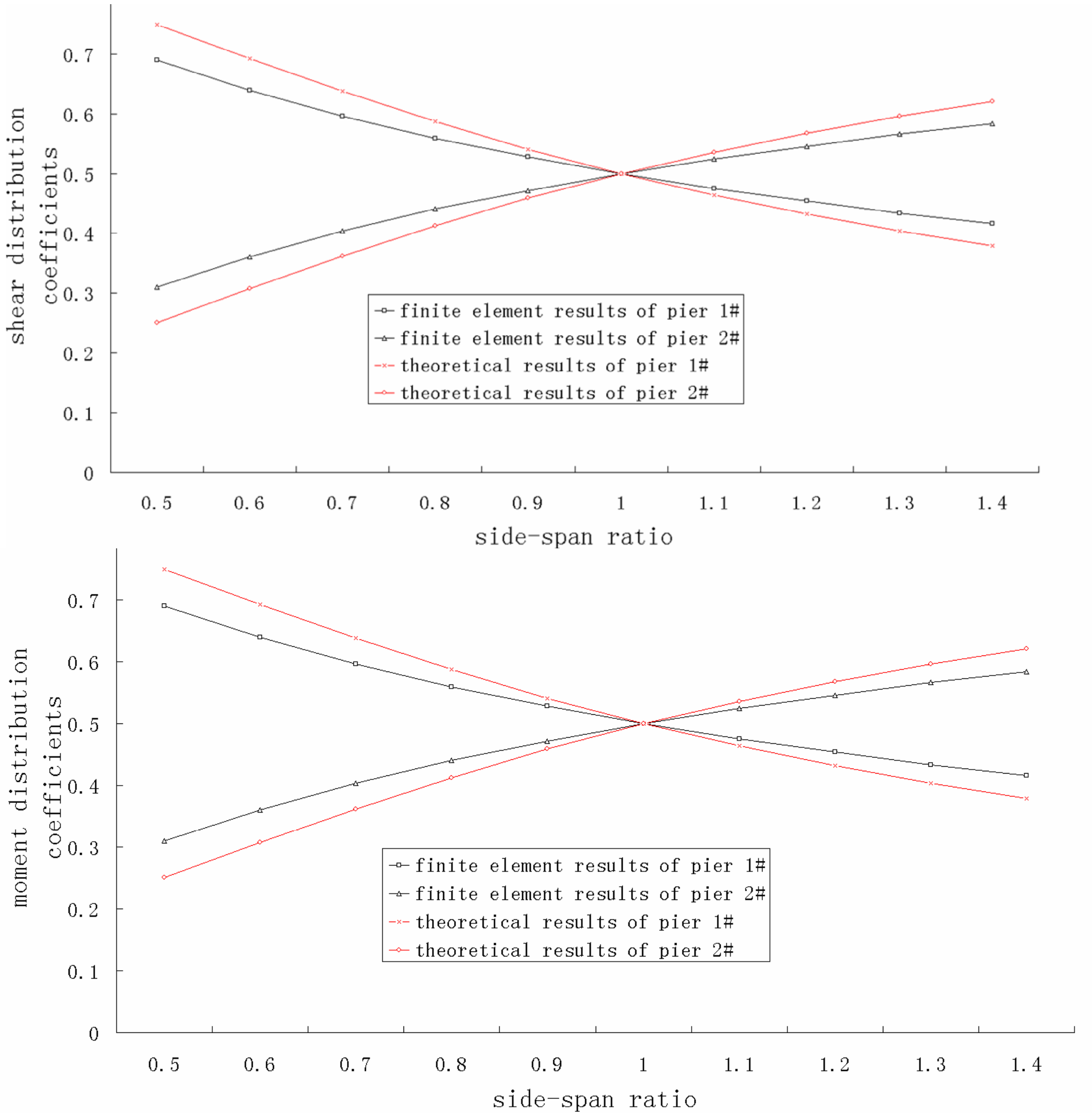

Figure.4 The influence of transverse seismic response with different side-span ratio

The Figure 4 shows that the change of side-span ratio will influence the linear rigidity ratio of beam to piers even the pier height constant, so as to influence the transverse anti- push rigidity of the pier. When the side span increased, the linear rigidity ratio of beam to pier on this side is decreased; the anti-push rigidity is increased, so the internal force partition coefficients are increased. The tendency of finite element analysis results and theoretical analysis results are consistent.

If the beam is considered as a rigid rod, the anti- push rigidity of the pier only relate to the height of pier. Under the condition that the height of piers is equal, the partition coefficientof internal force is equal, and the value is

0.5. So the linear rigidity ratio of beam to piers has a great influence on the internal force partition coefficient of the pier.

3. 2 Influence of Different Pier Height Ration on Transverse Seismic Response

3.2.1 Influence of different pier height ration on symmetrical side span continuous beam bridge

Take three-span continuous beam bridge for example, keeping the bridge span at 30+40+30m and h_2=9m, change h_1 to increase or decrease the pier height ratio. The influence of the transverse seismic response with different pier height ration for the symmetrical side-span bridge is shown as Figure.5.

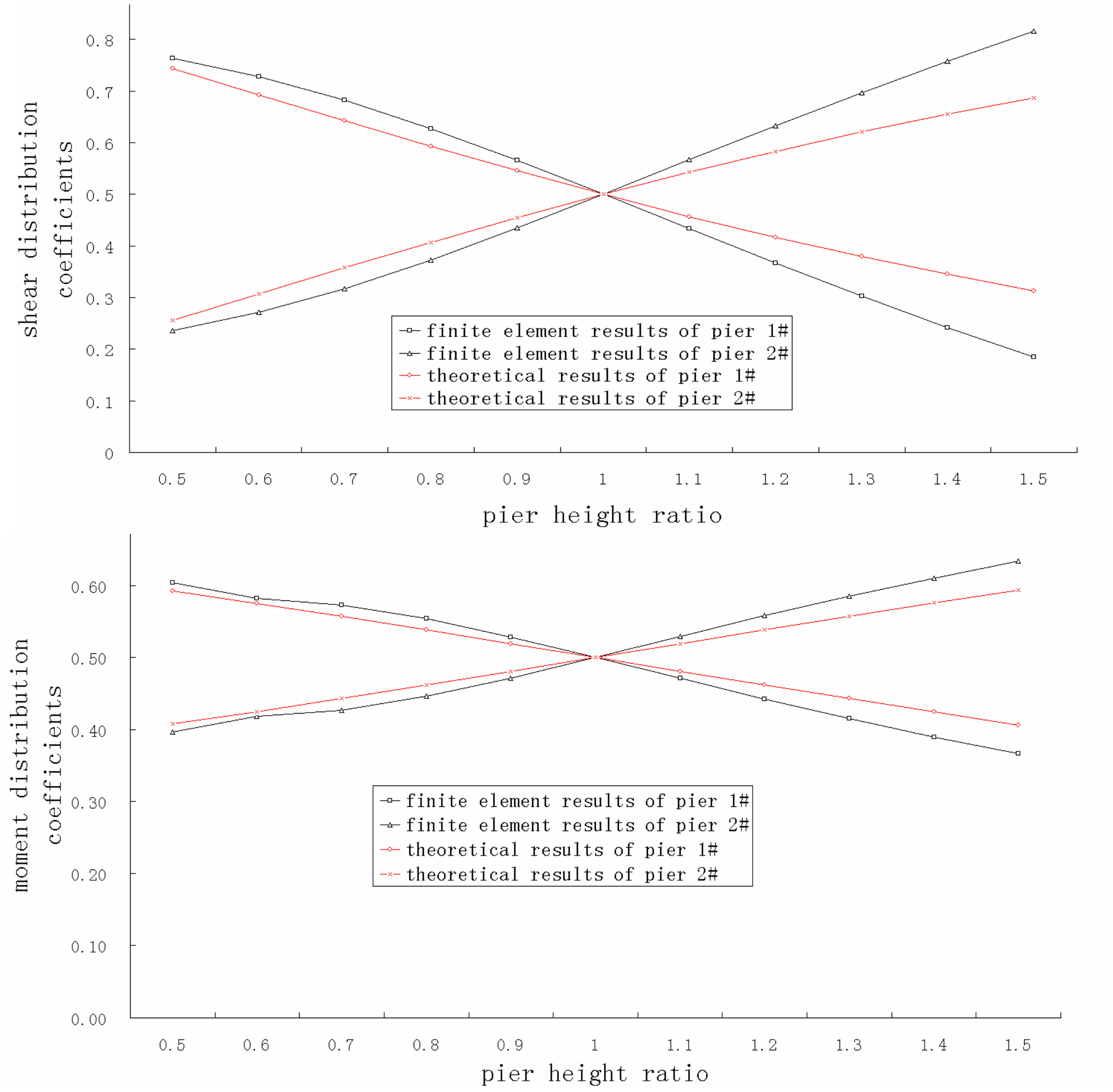

Figure.5 The influence of the transverse seismic response with different pier height ration for the symmetrical side-span bridge

The Figure 5 shows that the height of pier 1# increased gradually with the increase of pier height ratio, the partition coefficient of internal force decreased gradually. When the two piers reached same height, their partition coefficient of internal force is equal, and the value is 0.5. So we can get the result that to the change of pier height ratio of symmetrical side span continuous beam bridge, change the linear rigidity ratio of beam to piers, so as to change the anti- push rigidity of the pier, which leads to the change of the pier’s partition coefficient of internal force. The tendency of finite element analysis results and theoretical analysis results are consistent.

3.2.2 Influence of Different Pier Height Ration on Asymmetrical Side-span Continuous Beam Bridge

Take three-span continuous beam bridge for example, keeping the bridge span at 30+40+24m, h_2=9m,change h_1 to increase or decrease the pier height ratio. The influence of the transverse seismic response with different pier height ration for the asymmetrical side-span bridge is shown as Figure.6.

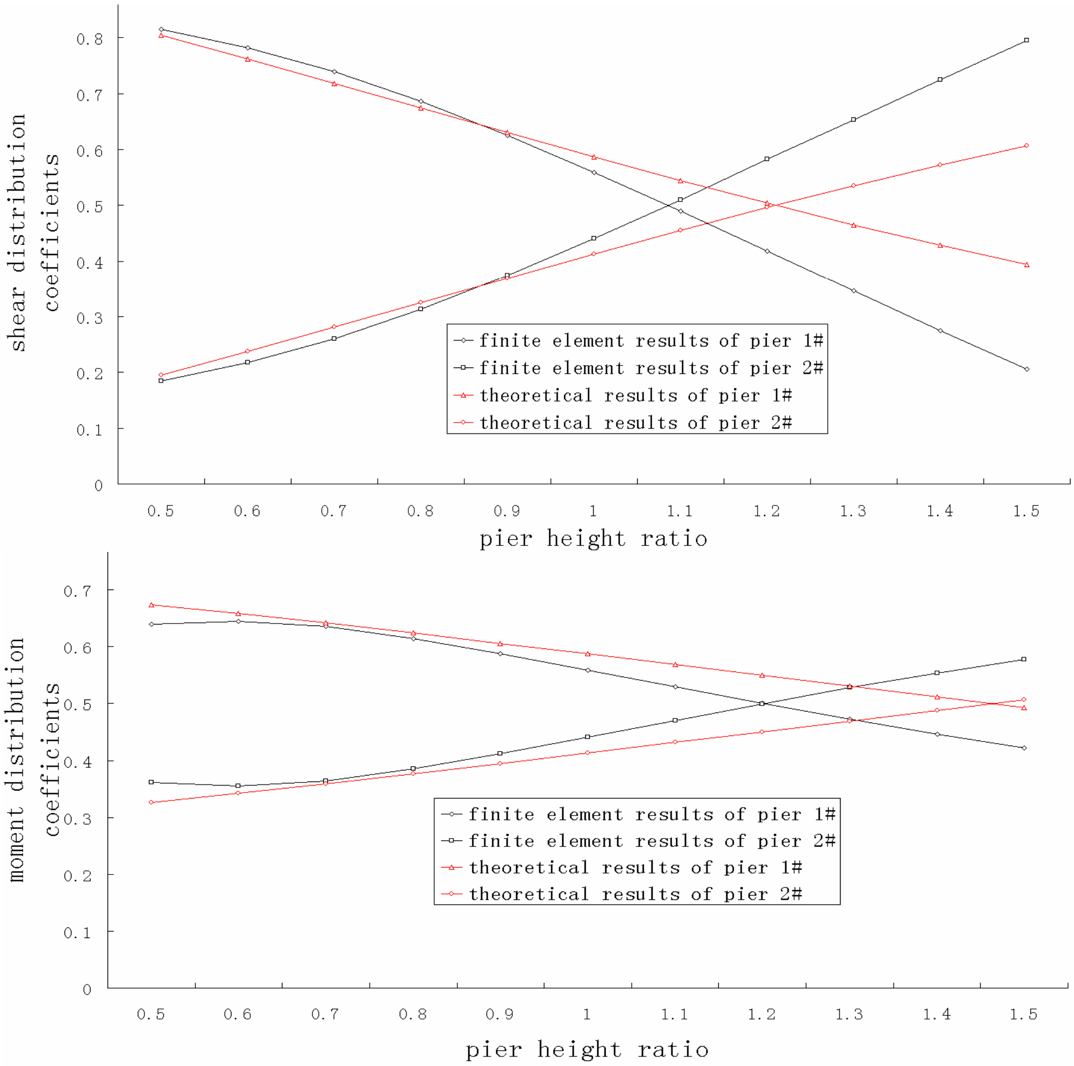

Figure.6 Influence of the transverse seismic response with different pier height ration for the asymmetrical side-span bridge

The Figure 6 shows the same trends as the symmetrical side span continuous beam bridge. With the increase of pier height, internal force partition coefficient of pier 1# decreased gradually, and internal force partition coefficient of pier 2# increased gradually. But when the height of two piers is same, because the side span is different, the linear rigidity ratio of beam to pier of pier 1# and pier 2# is different, so as the anti pushing rigidity of the two piers is different, so their partition coefficient of internal forceis different too. The pier height ratio to make two piers' force distribution coefficient same is related to their side span. The tendency of finite element analysis result and theoretical analysis result are consistent. But with the increase of pier height, the participation coefficient of high order vibration mode increases, and the difference between uniform load 'q' and realistically seismic force becomes larger, thus the discreteness of comparison becomes larger.

The above three situation show that: the linear rigidity ratio of the beam to piers will influence by the span of the beam, transverse bending rigidity of the beam, the height of the pier , transverse bending rigidity of the pier and the layout scheme of the pier. So in practical bridge design, the optimal design of transverse seismic response should consider all the factors mentioned above. In the specific bridge design, the transverse bending rigidity of piers can be adjusted according to the above influence laws of the linear rigidity ratio of beam to piers.

4. CONCLUSION

Following conclusions can be draw through the comparison between theoretical analysis and finite element analysis.

1. A simplified calculation method of transverse seismic internal forces partition coefficient for each pier of the concrete continuous beam bridge are proposed. The method can estimate the transverse seismic internal forces partition coefficient of the pier accuratally and provide reference for preliminary transverse seismic design.
2. The theoretical analysis and numerical simulation show that: the linear rigidity ratio of beam to piers influences anti- push rigidity of the pier. The linear rigidity ratio of beam to piers increases, the anti-push rigidity of pier increases. So the bridge layout scheme has great effect to the transverse seismic response of the concrete continuous beam bridge.
3. In practical bridge design, if the bridge's pier height and side span is different, the influence of linear rigidity ratio of beam to piers should be taken into consideration and exercise optimal design of pier's rigidity. The influence of the size of the span, the pier height and the linear rigidity ratio of beam to piers should be considered in optimal design. Owning to the limitation of the scope, it will be discussed in other paper.

REFERENCES

[1] Wang Jun-wen, Li Jian-zhong, Fan Li-chu.(2005). Parametric study of longitudinal seismic pounding response for continuous girder bridges. China Journal of Highway and Transport **18:4,**42-47.
[2] Huang Jian-wen. Zhu Xi, Zhang Jing.(2004). Simplified response analysis and research on design parameters of seismically isolated bridges. Journal of Northern Jiaotong University **28:1**,17-22.
[3] Yan Dong, Yuan Wan-cheng.(2003). Conceptual design of earthquake-resistance for multi-span continuous bridges in transverse direction. Journal of Tongji University **31:11**,1275-1279.
[4] Zhang Peijun, Hu Shi-de.(2005). Discussion for simplified calculation method of seismic load to piers of continuous bridges. Structural Engineers **21:4**,16-21.
[5] Meng-Hao Tsai.(2007). Transverse earthquake response analysis of a seismically isolated regular bridge with partial restraint. Engineering Structures **29:4** 1-11
[6] Li Lian-kun. (2002). Structural Mechanics. Beijing: Higher Education Press.
[7] Southeast University, Tianjin University, Tongji University.(2003). Concrete building structural design principle. China Building Industry Press.