Influence of the pier heights on the seismic response of large rigid frame bridges in mountain regions

Xiaoqiong LI*, Louis Chi Hung LAM

1 Department of Civil Engineering, Chu Hai College of Higher Education, Hong Kong, China

*Corresponding author’s e-mail: natalieli@chuhai.edu.hk

Abstract. In recent years, several large rigid frame bridges with piers over 100 meters have been built in mountain regions in China. However, few studies are focused on the influence of the height of piers on the seismic performance of these bridges. Based on the sizes of piers of the existing large continuous rigid frame bridge in the world, finite element models with different pier heights of the bridges are established and dynamic analysis are conducted subjected to three-dimensional multi-support excitation. The seismic response of the structures is studied with the change of pier heights and natural periods. The results show that in actual engineering designs, it is strongly recommended that the adjacent piers with similar heights or very different heights should be avoided. The conclusion also provides suggestion to the design of large rigid frame bridges afterwards.

1. Introduction

Recently many high-pier, long-span continuous rigid frame bridges are under rapid construction in mountainous areas such as Western China and South America, because these bridges are suitable and economical to surmount the difficulties of transportation through deep valleys or gorges[1, 2]. The current trend of continuous rigid frame bridges is to be higher and longer, which on the other hand brings new challenge to the seismic design of bridges. However, there are limited studies about the influence of design parameters on the seismic performance of high-pier bridges. Ignoring the influence of design parameters on the seismic performance of large bridges could lead to potential risks[3-4].

Current research on the design parameters of bridges are focused on the cross section of components, such as the thickness and height of the webs, slenderness ratio of panel, reinforcement ratio, etc[5-9]. Most of them are based on bridges with piers no more than 100 metres high, so they cannot provide significant reference to the design of high-pier continuous rigid frame bridges. The spatial variability of ground motion inputs is also ignored despite that the length of the continuous deck exceeds an appropriate limit[10-12]. In this study, the main variables concerned are the heights of piers, so the variability of other parameters of the bridge and environment is necessarily minimized. Besides, the dimensions of cross sections of the piers are rather small compared to their height, so it is reasonable to assume that the cross sections of components have less influence than the pier height on the performance of the whole bridge, and they will remain consistent in this study.

According to the heights of piers of the existing high-pier continuous rigid frame bridge in the world, finite element models with different pier heights of the bridges are established. Based on original spectral representation method [13-14], non-stationary spatially variable ground motions are simulated including wave passage, coherency and site amplification effects. Three-dimensional multi-support
Excitation is then applied to these bridge models for nonlinear dynamic time history analysis. The seismic responses of the bridges are studied with the change of pier heights and natural periods.

2. High-pier, long-span continuous rigid frame bridge models

The overview of the existing high-pier, long-span continuous rigid frame bridges all over the world is shown in Table 1. The last column indicates the length ratio of the adjacent pier and the main girder based on the height of the highest pier in each bridge. Therefore the ratio range of the existing high-pier, long-span continuous rigid frame bridge is: short pier: high pier = 0.319:1~1:1; main girder: high pier = 0.865:1~2.178:1. The average length of the main girder is about 180 metres.

| Name of Bridge      | Highest Pier (m) | Main Girder (m) | Short pier:Tall pier:Main girder (length ratio) |
|---------------------|------------------|-----------------|-------------------------------------------------|
| San Macos Bridge    | 208              | 180             | 0.754(0.516):1:0.865                            |
| Hezhang Bridge      | 195              | 180             | 0.431(0.349):1:0.923                            |
| Sanshuine Bridge    | 183              | 185             | 0.984(0.967):1:1.011                            |
| Labajin Bridge      | 182.5            | 200             | 0.488(0.767):1:1.096                            |
| Longtanhe Bridge    | 178              | 200             | 0.978(0.393):1:1.124                            |
| Tongzihe Bridge     | 172              | 200             | 0.523(0.756):1:1.163                            |
| Mengjiedu Bridge    | 168              | 220             | 1:1:1.310                                       |
| Erlanghe Bridge     | 166              | 200             | 0.982:1:1.205                                   |
| Shuanghekou Bridge  | 163              | 170             | 0.485(0.773):1:1.043                            |
| Zhegaohou Bridge    | 158              | 215             | 0.5(0.615):1:1.53(1.246)                        |
| Tangxihe Bridge     | 157              | 230             | 0.962:1:1.465                                   |
| Hutiaohou Bridge    | 150              | 225             | 0.493(0.693):1:1.5                             |
| Tianqiao Bridge     | 150              | 200             | 0.68:1:1.33                                     |
| Luohe Bridge        | 144              | 160             | 0.889(0.319):1:1.111                            |
| Mashuihe Bridge     | 142              | 200             | 0.95(0.789):1:1.408                             |
| Beipanjiang Bridge  | 141              | 290             | 0.624(0.482):1:2.057(1.560)                     |
| Juhe Bridge         | 140.5            | 160             | 0.5(0.88):1:1.139                               |
| Huluohe Bridge      | 138              | 160             | 0.942(0.420):1:1.159                            |
| Houzihe Bridge      | 135              | 220             | 0.978:1:1.630                                   |
| Datiegou Bridge     | 120              | 160             | 1:1:1.333                                      |
| Niujiaoping Bridge  | 120              | 192             | 0.633:1:1.6                                    |
| Yesanhe Bridge      | 120              | 200             | 0.721:1:1.667                                  |
| Xixihe Bridge       | 118              | 190             | 0.771(0.653):1:1.610(0.860)                     |
| Wujiang Bridge      | 115              | 168             | 0.957:1:1.461                                   |
| Qingshuihe Bridge   | 110              | 128             | 0.872:1:1.164                                  |
| Weijiazhou Bridge   | 108              | 200             | 1:1:1.852                                      |
| Lizigou Bridge      | 107              | 128             | 0.963(0.883):1:1.196                           |
| Furongjiang Bridge  | 106              | 230             | 0.514:1:2.170                                  |
| Xiaotiegou Bridge   | 102              | 160             | 1:1:1.569                                      |
| Shintabiashi Bridge | 101              | 220             | 0.926:1:2.178                                  |

The parameter study in this paper is based on single-span rigid frame bridges with two main piers because 14 of 35 bridges shown in Table 1 have single span. This study is mainly focused on the height variation of the piers, so all the material properties and other geometrical dimensions remain consistent. The C50/60 concrete adopted in the whole bridge is simulated through a uniaxial nonlinear constant confinement model[15], and the S400 reinforcement is arranged based on the design code GB-50011-2010[16]. The finite element model and cross sections are shown in figure 1.
The main girder is assumed to remain consistent as 180m and both side spans are 90m as shown in figure 1(a). The height ratio between two main piers (Pier 1# and Pier 2# in figure 1(a)) varies from 0.3:1 to 1:1 based on Table 1. Meanwhile the height range of the high pier (Pier 2#) is 100m-200m. All the 48 groups of different pier heights are indicated in Table 2.

Table 2. Different height groups of two main piers

| The height of Pier 2# (m) | The height of Pier 1# (m) |
|-------------------------|-------------------------|
| 100                     | 30                      |
| 120                     | 40                      |
| 140                     | 50                      |
| 160                     | 60                      |
| 180                     | 70                      |
| 200                     | 80                      |

48 finite element models of rigid frame bridge with different pier heights are established based on table 2. There are three critical points as indicated in figure 1(a), namely the top of the short pier Point 1#, the top of the high pier Point 2#, and the middle of the main girder Point 3#. Multiple support excitation is applied to the four supports of bridge (both ends of the side spans and bottoms of two piers) in three directions. The site condition is assumed as medium soil, with wave passage and coherency effects considered. The PGA of the spatially variable ground motions is about 0.2g [17, 18], and the simulated non-stationary ground motion acceleration time histories are shown in Fig. 2.

3. Numerical results

3.1. Influence of pier height on relative displacement
Relative displacements of the three critical points 1#, 2# and 3# (as shown in figure 1(a)) considerably reflect the influence of pier height variation. The relative displacements of 1# and 2# are based on the bottom of Pier 1 and Pier 2, respectively, and that of 3# is based on the average of two pier bottoms.
Figure 3 shows how the relative displacements of the three points vary with the natural vibration period of the whole bridge. The natural vibration period of each model is obtained from the first ten modes. In the x direction, the relative displacements of Point 1# and 3# (x1 and x3) both increase about 50%, while x2 remains stable after about 30% decrease, with the increasing period. They all level out after the vibration period reaches 1s, when x1 and x3 (more than 0.09m) remain approximately 3 times of x2. In the y direction, the relative displacement of Point 2# (y2) obviously keeps about 20% larger than y1 and y3, and they show more fluctuation than relative displacements in x direction. Overall, x1, x3 and y2 are relatively larger responses, so they are defined as “critical response variables” in this study. Therefore, the 3D plots of x1, x3 and y2 and corresponding contour plots are shown in figure 4, taking the heights of the high pier and the short pier as x axis and y axis, respectively.

Looking at the relative displacements presented in figure 4: when the short pier is taller than 80 metres, the peak values of x1 and x3 occur in the bridges whose two piers have similar heights; the relative in x direction are generally related to the height of short piers, x1 and x3 positive while x2 negative correlated; y2 increases with the height of the high pier, but is rarely related to the short pier; the relative displacements of two piers are positive correlated to their own height respectively.

(a) 3D plot and contour plot of x1

(b) 3D plot and contour plot of x3
Overall, the relative displacements $x_1$, $x_3$ and $y_2$ (0.1m, 0.094m and 0.102m) are critical response variables. The peak values of $x_1$ and $x_3$ are achieved when the heights of both piers are 120m, while $y_2$ reach a plateau at the pier heights group of (60m, 200m). Therefore, the longitudinal displacement response of the short pier should be noticed when the pier heights are close, while the lateral displacement response of the high pier should receive more attention when the height difference of piers is large.

3.2. Influence of pier height on relative displacement

The total support forces/moments[19] consist of two horizontal shearing force responses $F_x$ and $F_y$, and three bending moment responses $M_x$, $M_y$ and $M_z$. Figure 5 shows how the peak values of these variables vary with the natural vibration period of the whole bridge.

![Graph showing total support forces/moments vs. natural vibration period.](image)

(a) Shearing forces
(b) Bending moments

Figure 5. Total support forces/moments with the natural vibration period

The peak shearing force responses increase with the natural vibration period, and $F_x$ is always larger than $F_y$. $F_x$ is about twice of $F_y$ (40.372 kN and 21.547 kN) at short vibration periods. When the size of bridge as well as the vibration period gets longer, $F_x$ increases more than $F_y$ (eventually up to 94.330 kN and 35.845 kN). On the other hand, the peak moment responses decline with the natural vibration period, and $M_y$ remains the largest. $M_y$ is about 10 to 20 times of $M_x$ and $M_z$ (7214.668 kN-m, 743.835 kN-m and 346.364 kN-m) at short vibration periods. It decreases and then goes stabilized with the growth of the period, and is eventually about twice of $M_x$ and $M_z$ (463.33 kN-m, 282.09 kN-m and 200.87 kN-m). Thus the 3D plots and contour plots of $F_x$ and $M_y$ (critical response variables) with the height of the piers are shown as figure 6.

There is significant difference between the variation pattern of $F_x$ and $M_y$. The peak value of shearing forces appears when the height of the high pier is large (180m or 200m), while the bending moments reach the peak at small height of the high pier (100m or 120m). The shearing force is relatively large when two piers are close to each other’s height. When both piers are 180m high, $F_x$ obtains its maximum value. The other critical response variable $M_y$ reaches the peak when the height ratio of two piers is 0.3:1, among which the maximum $M_y$ is 7214.67kN-m at the pier heights group of (30m, 100m).

Therefore, the support of the bridge suffers more from shearing failure when the heights of two piers are close and large (180m, 180m). On the other hand, the support, especially the bottom of the high pier, tends to fail in bending moment when the height difference of two piers is large.
Figure 6. 3D plot and contour plot of total support forces/moments with the height of the piers

4. Conclusions
Finite element models with different pier heights (high pier’s height 100m to 200m) of the bridges are established and dynamic analysis are conducted subjected to three-dimensional multi-support excitation. The seismic response of the structures are studied with the change of pier heights and natural periods. Results show that there are some critical response variables significantly larger than others, including the longitudinal displacement of the short pier $x_1$ and mid-span $x_3$, the lateral displacement of the high pier $y_2$, the total support force $F_x$ and moment $M_y$. When the piers have similar heights, $x_1$, $x_3$ and $F_x$ are of concern; when there is significant height difference between piers, $y_2$ and $M_y$ are more crucial to the seismic study of the rigid frame bridge.

The study in this paper is not only based on the real sizes of existing rigid frame bridges, but also with spatially variable ground motions due to complex mountainous site conditions considered. Thus the conclusions are adequately reliable and instructive. In practical engineering designs, the adjacent piers with similar heights or very different heights should be avoided. The conclusion is based on two adjacent piers and the girder of rigid frame bridges, so it is also of great significance and reference to the relationship of any adjacent piers in continuous rigid frame bridges with multiple spans.

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