SEISMIC RESPONSE ANALYSIS OF LONG-SPAN CONTINUOUS RIGID-FRAMED BRIDG

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ABSTRACT:

Highway crossing mountain valley, continuous rigid-framed bridge with high piers and long spans is constructed. In this paper, for this type of bridge, the dynamic time-history analysis method is used to analyze the seismic response of bridge under uniform excitation and traveling-wave effect. The focus is on a three-span highway bridge with unequal height piers crossing a mountain valley. Group pile effect and soil-structure interaction being taken into account, the bridge and its foundation system, including the surrounding soil, are modeled by finite elements. The analyses show that traveling-wave has strong influence on response of earthquake, and the relative displacement of top and bottom of low pier is less sensitive to traveling-wave velocity than that of high pier. Due to traveling-wave effect, the maximal moment at top of low pier is much larger than that of high pier, but its variation is less than that of high pier with the change of wave velocity. The effect of soil-structure interaction being taken into account, decrease of whole stiffness of structure results in that the frequency of vibration reduces and relative displacement of top and bottom of pier increases.

KEYWORDS: Continuous rigid-frame bridge, Time history analysis method, Traveling-wave effect, Soil-structure interaction, Group pile effect

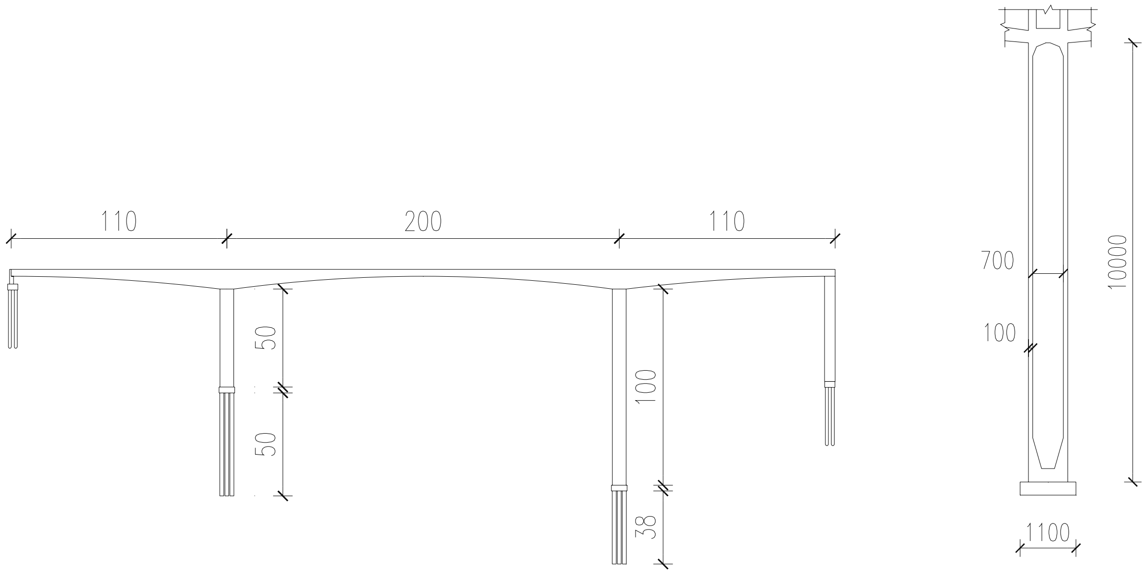
1. INTRODUCTION

Highway crossing mountain valley, continuous rigid-framed bridge with high piers and long spans is constructed. Its scale is far over the range regulated by Specifications of Earthquake Resistant Design for Highway Engineering in China [1]. In seismic design of the bridge, it is necessary to understand dynamic responses of bridge under earthquake-induced loadings, especially the responses of bridge with high piers or long spans. Because the difference of height of piers is great, the earthquake behavior of high piers is quite different from that of low piers, so the dynamic time-history analysis method is adopted to carry out the anti-seismic performance of continuous rigid-framed bridge.
The presence of soil plays a key role in shaping the dynamic responses of both aboveground and underground structures and should be taken into account in any realistic structural analysis procedure [2]. According to soil-structure interaction and traveling-wave effect of earthquake wave, finite element model of a three-span continuous rigid-frame bridge with high piers is set up.

2. CONFIGURATION OF BRIDGE

The particular highway bridge investigated has three-span irregular configuration (110m + 200m + 110m) in length，with hollow box-like construction, as shown in Figure 1. The deck is 10m in width (6m at the bottom) and rests on the abutments and two piers of unequal height (50 and 100 m) with two thin-walled shape, which is representative of piers constructed across valley in seismic mountainous terrain. Furthermore, Figure 1 shows cross-section details of high pier(every thin wall is 600cm×100cm), as well as the deck-to-abutment support system and the deck-to-pier connections,. The prestressed reinforced concrete deck has single room and

its cross-section varies in longitudinal direction, the height of beam (3.5~10m) and thickness of bottom plate (30~ 120cm) change in second-degree parabola. The height of deck is 10m at top of piers and 3.5m at abutments as well as the middle of span. Thickness of web is 50~80cm, top plate is 28 cm.
The foundation of a pier consists of 9 cast-in-place piles, which are founded on medium decomposed rock. The diameter of piles is 2 m. The boundary condition of piers can be taken as full fixity.
In terms of material properties, box beam is C60, pier is C50 and bearing platform is C30.



(a) View of the bridge (unit: m) (b) Cross-section of high pier (unit: cm)

Figure 1 Configuration of bridge

3. THE DYNAMIC TIME-HISTORY ANALYSIS METHOD

For long span bridges, the difference of earthquake wave at supporting points is taken into account using large mass method and analogy static displacement, in which response of ground displacement and internal force are truly reflected by horizontal moving effect of ground.
Adding a suppositional large mass M_{ll} to structure mass M_{ss} in excitation direction at supporting points, Response of structure is attained, which is called Large mass method. In this bridge, the ratio between M_{ll} and M_{ss} is equal to 10^6, so structure mass is neglected. When earthquake wave is added. Movement equation [3] [6] of bridge structure system at time *t* is as follows.

$$M\ddot{u}(t)+C\dot{u}(t)+Ku(t)=F(t) \tag{3.1}$$

In the above, $\ddot{u}(t)$ is the acceleration vector of node, $\dot{u}(t)$ is the velocity vector, M is mass matrix, C is damp matrix, K is stiffness matrix, and F(t) is load vector of node. Every matrix and vector is integrated by response matrix of pile, soil and superstructure units, so Equation （3.1） can be rewrote in Equation （3.2）.

$$\begin{bmatrix} M_{ss} & 0 \\ 0 & M_{bb}+M_{II} \end{bmatrix}\begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_b \end{Bmatrix}+\begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{bmatrix}\begin{Bmatrix} \dot{u}_s \\ \dot{u}_b \end{Bmatrix}+\begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} \end{bmatrix}\begin{Bmatrix} u_s \\ u_b \end{Bmatrix}=\begin{Bmatrix} 0 \\ F_b \end{Bmatrix} \tag{3.2}$$

If damp function caused by moving velocity of supporting points is neglected, due to exist of large mass M_{ll}, the first item of left of Equation is especially larger than others. The second and third item of left of equation and the effect of M_{bb} being neglected, Equation （3.2）can be predigested in Equation （3.3）.

$$M_{II}\left\{\ddot{u}_b\right\}=\left\{F_b\right\} \qquad (3.3)$$

Absolute displacement of structure is resolved into analogy static displacement Y_s and analogy dynamic displacement Y_d. Assuming that damp force of structure is direct proportion to dynamic relative velocity, $\left\{\dot{u}_s,\dot{u}_b\right\}^T$ is replaced by $\left\{\dot{Y}_d,0\right\}$, then

$$[M_{ss}]\left\{\ddot{Y}_d\right\}+[C_{ss}]\left\{\dot{Y}_d\right\}+[K_{ss}]\left\{Y_d\right\}=-[M_{ss}][\alpha][M_{II}]^{-1}\left\{F_b\right\} \qquad (3.4)$$

When excitation takes place at every supporting points, lager mass is added. The constraint is relaxed in excitation direction; the moving acceleration of ground $\ddot{u}_b$ is attained under function of F_b. When excitation of traveling wave is only taken into account, F_b is attained according to acceleration value of same earthquake wave with certain phase.

4. FINITE ELEMENT MODEL FOR BRIDGE

Based on characteristics of soil and structure, the bridge deck and the piers are modeled using the software Midas/Civil2006, box beam and piers were simulated in beam elements. It is assumed that boundary restriction is joined elastically with nodes. Weight of box beam and transverse clapboard is considered as deadweight. See Figure 2.

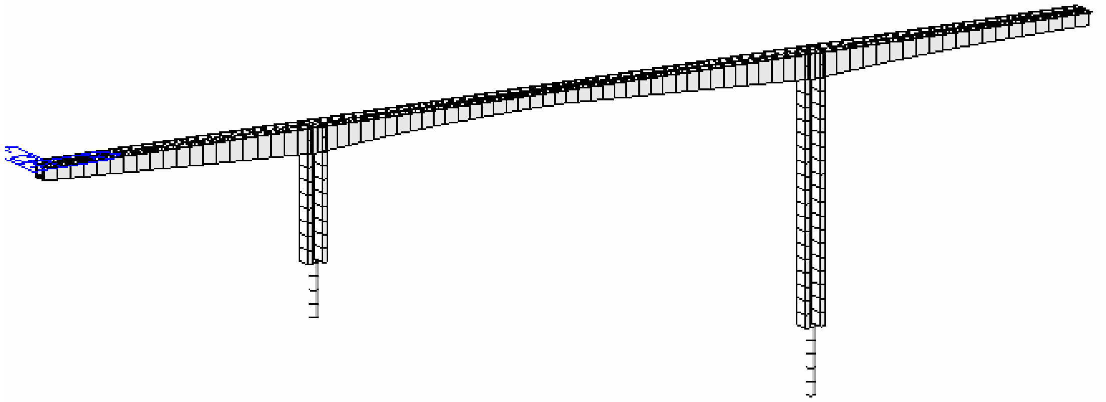


Figure 2 Beam finite element model for the bridge

For earthquake wave, the dynamic time-history is analyzed using El-Centro wave, earthquake intensity recorded is 7 degree, peak value of horizontal acceleration recorded is 1.458 m/s^2, and that of vertical acceleration recorded is 0.7314 m/s^2. Soil-structure interaction being considered or neglected, the dynamic time-history is analyzed, in which the longitudinal and transverse earthquake wave is local horizontal wave and the vertical wave is vertical local wave.

5. THE EFFECT OF TRAVELING-WAVE ON RESPONSE OF EARTHQUAKE

In order to analyze the effect of traveling-wave on response of earthquake wave, two suppositions are

considered in this work [4]. Firstly, earthquake wave travels in longitudinal direction. In the second option, frictions between deck and sliding bearings at bridge ends is equal to zero.
The earthquake wave velocity is 200~1400 m/s in ground. The value of longitudinal wave velocity is as follows: 200m/s, 300m/s, 400m/s, 500m/s, 600m/s, 800m/s, 1000m/s, 1200m/s and 1400m/s, accordingly, the difference of time when wave arrive to two piers is calculated. Response of pier includes relative displacement of top and bottom of pier, moment at top of pier and center of spans. The results are shown in Figure 3 and Table 1.

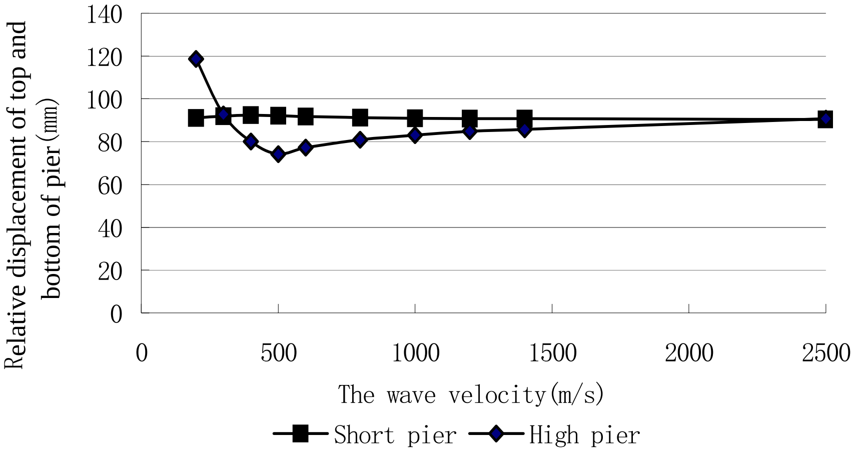


Figure 3 The relation of relative displacement and the wave velocity

Table 1 The relation of maximal moment at top of pier and the wave velocity

Wave velocity (m/s)	Maximal moment at top of low pier (kN.m)	Maximal moment at top of high pier(kN.m)
200	-15585.76	-5195.66
300	-15835.93	-5916.11
400	-15588.53	-6016.07
500	-15798.39	-6099.35
600	-16034.92	-6299.4
800	-16119.71	-6436.41
1000	-16048	-6588.99
1200	-15946.54	-6715
1400	-15884.57	-6772.47
2500	-15622.54	-7000.56

Under the function of uniform excitation, relative displacement of top and bottom of low pier and high pier is 90.732mm and 91.117mm, while relative displacement is 91.000mm and 118.628mm when wave velocity is 200m/s, therefore, effect of traveling-wave being taken into account, relative displacement increases by 0.29% and 30.19%, which is because that the stiffness of low pier is larger than that of high pier.
For internal force, maximal moment at top of low pier is far larger than that of high pier, but with the change of wave velocity, the variation of maximal moment at top of high pier changes a lot. Furthermore, on the basis of time-history analysis, with the quickening of wave velocity，the moment at center of middle span increases and that at center of side span reduces.

6. ANALYSIS OF THE BRIDGE WITH SOIL -STRUCTURE INTERACTION

For piers shown as Figure 1, group pier effect is taken into account. In calculation, piers are converted into

stiffness in x, y and z directions on the principle of equivalent stiffness. In order to simulate the piers function each other due to common vibration of ground among piers, group pier effect is simulated as special rigid-frame, and ground among piers is simulated as two forces staff to connect piers in longitudinal and transverse direction.
For seismic calculation of bridge, it is usually assumed that mechanics model is set up on absolute rigid foundation, In fact, deformation of soil around pile has effect on vibration of pier, soil-structure interaction will change dynamic property of structure, damp and response of earthquake. It is assumed that soil medium is liner elastic and continuous, restriction function is described as double direction liner spring with damp, its equivalent element stiffness K of foundation spring is calculated using “m” method[5] in Equation （6.1）.

$$\sigma_{zx} = mzx_z \qquad (6.1)$$

In above, σ_{zx} is transverse resistant stress of soil layer on pile, *m* is resistant stress coefficient of soil layer, *z* is depth of soil layer, x_z is transverse displacement, so equivalent stiffness k_s of foundation spring is described as:

$$k_s = \frac{p_s}{x_z} = \frac{A\sigma_{zx}}{x_z} = \frac{(a \cdot b_p)(m \cdot z \cdot x_z)}{x_z} = ab_p mz \qquad (6.2)$$

In above, *a* is the thickness of soil layer replaced by foundation spring, *b* is calculating width of pile.
Group pier effect and soil-structure interaction being taken into account in different mode, relative displacement of top and bottom of pier, the moment at top of pier are shown in Table 2.

Table 2 The effect of soil-structure interaction on relative displacement and moment

Item	Position	Taking no account of soil-structure interaction	Taking account of soil-structure interaction
Displacement (mm)	Low pier	90.732	91.774
Displacement (mm)	High pier	91.117	92.026
Axial force (kN)	Center of side span	-165.300	-166.160
Axial force (kN)	Center of middle span	1060.430	1188.120
Moment (kN.m)	Center of side span	-34114.240	-37466.640
Moment (kN.m)	Center of middle span	-15420.710	-15645.890
Moment (kN.m)	Top of low pier	-15468.560	-15356.540
Moment (kN.m)	Top of high pier	-6842.600	-6940.700

The effect of soil-structure interaction being taken into account, vibration frequency of the first mode reduces by 6.1%, which is because that whole stiffness of structure reduces. Relative displacement of top and bottom of pier increase, while internal force increase or decrease occasionally.

7. CONCLUSIONS

The analyses demonstrate that effect of traveling-wave has strong influence on response of earthquake, so this effect should be taken into account in seismic calculation of bridge. The analyses show that traveling-wave has stronger influence on relative displacement of top and bottom of high pier than that of low pier, the slower the wave velocity is, the larger the difference is. Due to traveling-wave effect, the maximal moment at top of low pier is much larger than that of high pier, but its variation is less than that of high pier with the change of wave velocity. Furthermore, on the basis of time-history analysis, with the quickening of wave velocity， the moment at center of middle span increases and that at center of side span reduces. The effect of soil-structure interaction being taken into account, decrease of whole stiffness of structure results in that the frequency of vibration reduces and relative displacement of top and bottom of pier increases.

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