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Seismic Response of High Pier Continuous Rigid Bridge Subjected to Multiple Support Excitation

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***Abstract*—To study the influence of the spatial variability of ground motion on the dynamic response of high pier and long-span bridges, the numerical model of a high pier and long-span railway bridge respectively subjected to longitudinal and transversal earthquake excitations and located at western mountain of China is established to study its dynamic response based on the principle of multiple support excitation. The results show that the bottom and the top sections with longitudinal ground motion excitations are dangerous, especially the bottom section of high pier; the internal forces at the top of pier are smaller, while the bottom sections are still at adverse conditions; compared with the uniform excitation, the dynamic response of the structural design control points may be increased and also may be reduced, especially in the internal forces of the main pier. These phenomena indicate that the influence of the traveling wave effect on the structural response is related to the structural characteristics and the location of interest of the bridge structures. Comprehensive consideration should be given to seismic design of long-span bridges with high piers.**

***Index Terms*—seismic, high pier, continuous rigid, railway bridge**

I. Introduction

There are so many high pier and long-span continuous rigid frame railway bridges, beyond the requirements of specification, in the west of china with high seismic intensity, so it has important signification to develop seismic analysis of high pier bridges. [1]

The variability of ground motion mainly includes local site effect, arbitrary coherency and traveling wave effect. Qin Wei [2] and Xiao-guo Hang [3] found that traveling wave effect has significant influence on the vibration response of the continuous rigid frame bridge. Shi-xiong Zheng [4] have compiled program to calculate and analyze the prestressed concrete continuous rigid frame bridge in 1997, founding that the traveling wave effect has great influence on the seismic response. The spatial variability of ground motion can be considered in ground motion input mode. Many scholars have carried out a lot of research on it and the results showed that in the seismic analysis of long-span bridge structures, the uniform ground motion input mode can not be adopted simply and the spatial input characteristics of ground motion should be taken into account [5]. At present, it has become a hot topic in anti-seismic research to study dynamic response of long-span bridge structures under multi support seismic excitation [6]. To solve problem, multi point ground motion input models generally adopt the Pseudo-static Displacement Method, the large stiffness method, the Lagrange multiplier method, the large mass method [7], the displacement input method [8]. This paper based on ANSYS finite element analysis platform, establishes numerical model of high pier and long-span railway bridge, adopts the large mass method to analyze its dynamic time history response under consistent ground motion excitation and traveling wave effect, in order to provide basis and reference for the selection of anti-seismic calculation method of high pier and long span bridge in mountainous area.

II. Engineering Situation

This paper is based on a high pier and long-span continuous rigid frame bridge located at western mountain of China. Its total length is 466 meters and its bridge span structure is (88m+168m+88) prestressed concrete continuous rigid frame + (33m+56m+33m) prestressed concrete continuous beam. The highest bridge pier is No. 2 with the pier height of 103m. No. 1 The bridge layout is shown in Fig. 1.

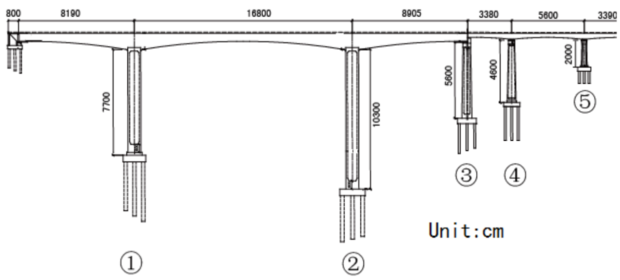

Figure 1. General layout of bridge

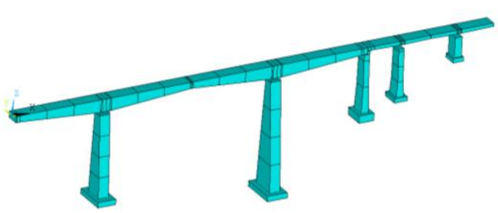

Figure 2. Three dimensional finite element model of bridge

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This paper establishes 3D finite element model as shown in Fig. 2. On the No.1 pier and the No. 2 pier, degrees of freedom of the pier top and the beam bottom are fully coupled. On the No. 3 pier, the No. 4 pier and the No. 5 pier, degrees of freedom, except longitudinal degree of freedom, are fully coupled.

III. Seismic Response Analysis Based on the Large Mass Method

A. Principle of the Large Mass Method

For long-span bridge, the dynamic analysis should be considered the influence of different ground motion .The dynamic equation of the structure in the multi points ground motion can be expressed by the block matrix.

$$\begin{bmatrix} \boldsymbol{M}_{ss} & \boldsymbol{M}_{sb} \\ \boldsymbol{M}_{bs} & \boldsymbol{M}_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{u}}_s(t) \\ \ddot{\boldsymbol{u}}_b(t) \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_{ss} & \boldsymbol{C}_{sb} \\ \boldsymbol{C}_{bs} & \boldsymbol{C}_{bb} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{u}}_s(t) \\ \dot{\boldsymbol{u}}_b(t) \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ss} & \boldsymbol{K}_{sb} \\ \boldsymbol{K}_{bs} & \boldsymbol{K}_{bb} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_s(t) \\ \boldsymbol{u}_b(t) \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{p}_b(t) \end{Bmatrix} \quad (1)$$

where, the subscripts b and s refer to the master and slave DoF, respectively; $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ express respectively mass, damping and stiffness matrices, respectively; $\boldsymbol{u}_b(t)$, $\dot{\boldsymbol{u}}_b(t)$ and $\ddot{\boldsymbol{u}}_b(t)$ represent respectively absolute displacement, speed and acceleration of each supporting point under seismic effect; $\boldsymbol{u}_s(t)$, $\dot{\boldsymbol{u}}_s(t)$ and $\ddot{\boldsymbol{u}}_s(t)$ represent respectively absolute displacement, speed and acceleration of each nonsupporting point under seismiceffect; $\boldsymbol{p}_b(t)$ expresses support reaction.

The large mass method by assuming that the structural basis or supporting point is attached to the a sufficiently large concentrated mass. When the structure dynamic analysis is carried out, the corresponding node degree of freedom is not bound, and a set of inertia force is applied to the degree of freedom. Through changing the mass matrix of the original motion equation, Eq. (1) can be rewritten as:

$$\begin{bmatrix} \boldsymbol{M}_{ss} & \boldsymbol{M}_{sb} \\ \boldsymbol{M}_{bs} & \boldsymbol{M}_{bb}+\boldsymbol{M}_0 \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{u}}_s(t) \\ \ddot{\boldsymbol{u}}_b(t) \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_{ss} & \boldsymbol{C}_{sb} \\ \boldsymbol{C}_{bs} & \boldsymbol{C}_{bb} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{u}}_s(t) \\ \dot{\boldsymbol{u}}_b(t) \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ss} & \boldsymbol{K}_{sb} \\ \boldsymbol{K}_{bs} & \boldsymbol{K}_{bb} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_s(t) \\ \boldsymbol{u}_b(t) \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{M}_0 \cdot \ddot{\boldsymbol{u}}_g(t) \end{Bmatrix} \quad (2)$$

$\boldsymbol{M}_0$ is the additional large mass matrix in Eq. (2). Expanding second line of Eq. (2) can be rewritten as:

$$\boldsymbol{M}_{bs}\ddot{\boldsymbol{u}}_s(t) + (\boldsymbol{M}_{bb}+\boldsymbol{M}_0)\ddot{\boldsymbol{u}}_b(t) + \boldsymbol{C}_{bs}\dot{\boldsymbol{u}}_s(t) + \boldsymbol{C}_{bb}\dot{\boldsymbol{u}}_b(t) + \boldsymbol{K}_{bs}\boldsymbol{u}_s(t) + \boldsymbol{K}_{bb}\boldsymbol{u}_b(t) = \boldsymbol{M}_0\ddot{\boldsymbol{u}}_g(t) \quad (3)$$

When $m_0 \to +\infty$,

$$\ddot{\boldsymbol{u}}_b(t) = \ddot{\boldsymbol{u}}_g(t) \quad (4)$$

Each additional mass is generally taken 106 times the total mass of the structure. By avoiding the impact of large number of calculations, Eq. (4) can be approximated as:

$$\ddot{\boldsymbol{u}}_b(t) \approx \ddot{\boldsymbol{u}}_g(t) \quad (5)$$

To solve the problem on using large mass method, Eq. (3) using the direct integral method, the dynamic response of structure can be obtained.

B. The Input of Seismic Wave

Seismic time history analysis in the existing strong earthquake records in the site selection and site conditions similar to the site of the seismic waves, that is, EI -Centro wave. As Fig. 3 shows, time history takes 0.02s as the interval, the number of discrete points is 2903 and the total duration of ground motion is 58.06s.

This paper considers longitudinal and transverse traveling wave effect. The ground motion spreads from the No.1 pier to the No. 5 pier and wave velocity are selected respectively as 100m/s, 400m/s, 800m/s, 1200m/s.

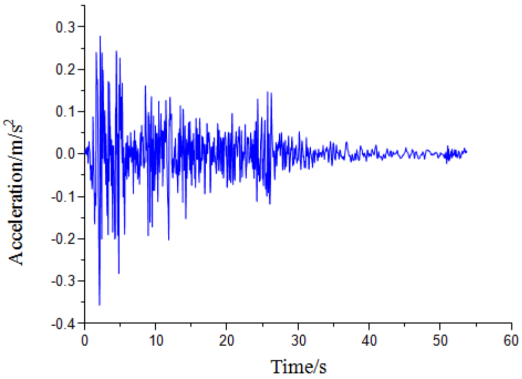

Figure 3. EI-Centro waves

IV. Seismic Response of Railway Bridges under Multi Point Excitation

A. Dynamic Response of Bridge under the Effect of Longitudinal Seismic Wave

As can be seen from the Table I, the shear and moment at the top of the Pier 1 and 2 subjected to different longitudinal seismic wave are substantially larger than those subjected to the uniform excitation,which proves that the traveling wave effect has a negative effect on the structure.

When the apparent wave velocity of seismic wave is 100m/s, relative displacement, shear and moment of pier top are divided respectively by those subjected to uniform excitation and the ratios of the pier 2 are the largest, which are respectively 1.97,2.09,1.85. When the velocity of earthquake wave is 100m / s, moment and shear force of pier bottom are respectively compared with the uniform excitation, ratio of pier 1 is greater than the pier 2. The above datas illustrate that when the apparent wave velocity is low and the phase difference is large, the traveling wave effect has a more unfavorable influence on force condition of the pier top of high pier and the pier bottom of low pier. When the apparent wave velocity increases to 400m/s, 800m/s and 1200m/s, the ratios of displacement on the pier top of the pier 2 decreases to 0.84,0.87 and 0.91 and they are smaller than the ratios of the pier 1,which proves that the traveling wave effect has a beneficial influence on force condition.

In addition, it can be seen from the Fig. 4 that the longitudinal horizontal displacement at the top of Pier 2 is the largest when the apparent wave velocity is 100m/s. With the increase of the apparent wave velocity, the displacement response oscillates firstly in the low velocity segment and then tends to be gentle and approach gradually the structural response of the uniform excitation. The above can show that when the apparent wave velocity is low and the phase difference is large, the traveling wave effect has a negative effect on the top of the high pier. In summary, on the effect of longitudinal earthquake, when the apparent wave velocity is low and less than 400m/s, the traveling wave effect has a more harmful effect on the top of the high pier and the bottom of the low pier. However, when the apparent wave velocity increases, especially after 400m/s, the effect of traveling wave is favorable to the internal force response of high pier.

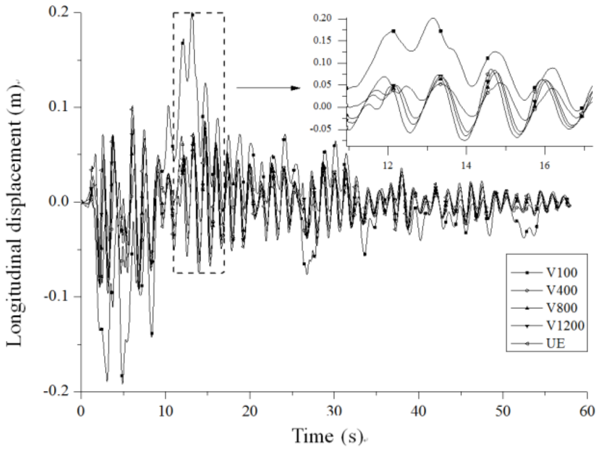

Figure 4. Longitudinal displacement response at the top of Pier 2

TABLE I. COMPARISON OF PEAK INTERNAL FORCE RESPONSE UNDER VERTICAL SEISMIC WAVE ACTION

Section's position	Traveling wave/uniform excitation							
	apparent wave velocity 100m/s		apparent wave velocity 400m/s		apparent wave velocity 800m/s		apparent wave velocity 1200m/s	
	moment	Shear	moment	Shear	moment	Shear	moment	Shear
Pier top of the pier 1	0.95	1.70	1.02	1.03	1.43	1.03	1.46	1.09
Pier top of the pier 2	1.85	2.09	1.03	1.37	1.34	1.26	1.17	1.21
Pier top of the pier 3	1.41	0.72	0.87	0.66	0.75	0.85	0.84	0.87
Pier top of the pier 4	1.02	1.01	1.03	1.04	1.01	1.01	1.02	1.01
Pier top of the pier 5	1.08	0.99	1.06	0.88	0.95	1.05	0.98	0.97
Pier bottom of the pier 1	2.31	1.43	1.33	1.04	1.24	0.92	1.13	0.96
Pier bottom of the pier 2	0.48	1.27	0.50	1.46	0.60	1.31	0.83	1.34
Pier bottom of the pier 3	0.93	0.95	0.83	0.89	0.84	0.88	0.83	0.89
Pier bottom of the pier 4	1.05	1.02	1.02	1.03	1.03	1.01	1.02	1.01
Pier bottom of the pier 5	1.13	0.98	0.96	0.99	1.15	0.98	1.06	0.99

TABLE II. COMPARISON OF INTERNAL FORCE RESPONSE OF BRIDGE PIER UNDER LATERAL SEISMIC WAVE ACTION

Section's position	Traveling wave/uniform excitation							
	apparent wave velocity 100m/s		apparent wave velocity 400m/s		apparent wave velocity 800m/s		apparent wave velocity 1200m/s	
	moment	Shear	moment	Shear	moment	Shear	moment	Shear
top of the pier 1	0.98	0.96	0.95	0.90	0.94	0.96	0.97	0.97
top of the pier 2	1.05	0.73	1.07	0.85	0.71	1.25	0.89	1.30
top of the pier 3	1.00	1.16	0.94	0.82	0.99	0.78	0.94	0.71
top of the pier 4	0.93	1.12	0.99	1.11	1.03	1.05	1.02	0.99
top of the pier 5	0.99	1.01	1.00	1.00	0.99	1.00	1.00	1.00
bottom of the pier 1	0.91	0.84	0.95	0.99	0.91	0.85	0.92	0.91
bottom of the pier 2	0.58	0.77	0.85	1.27	1.24	1.10	1.27	1.31
bottom of the pier 3	0.93	0.90	1.59	1.73	1.28	1.23	0.97	0.83
bottom of the pier 4	1.04	0.96	1.09	1.06	0.98	0.92	0.92	0.87
bottom of the pier 5	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00

B. Dynamic Response of Bridge under the Effect of Transverse Seismic Wave

According to the Table II, subjected to the effect of different transverse seismic waves, the moment on pier top of the pier 1 have no significant change, which are less than those subjected to uniform excitation; when the apparent wave velocity of seismic wave are 100m/s and 400m/s, the moment on pier top of the pier 2 are divided by those under uniform excitation and the ratios are respectively 1.05 and 1.07, which are slightly more than moment under uniform excitation; when the apparent wave velocity of seismic wave are 800m/s and 1200m/s, the moment on pier top of the pier 2 are less than those subjected to uniform excitation. For shear, when the apparent wave velocity of seismic wave are 100m/s and 400m/s, the shear on pier top are all less than those under uniform excitation; when the apparent wave velocity of seismic wave are 800m/s and 1200m/s, the shear on pier top are all more than those under uniform excitation. Therefore, when the apparent wave velocity is low, the traveling wave effect has an unfavorable influence on moment of high pier top and has a favorable influence on shear of high pier top; when the apparent wave velocity is high, the traveling wave effect has a favorable influence on moment of high pier top and has an unfavorable influence on shear of high pier top.

As is shown in the Fig. 5, with the increase of apparent wave velocity, transverse horizontal displacement on pier top of the pier 1 and the pier 2 gradually increase where there is a significant positive correlation. The correlation coefficient of pier 1 is 0.919 and the correlation coefficient of pier 2 is 0.947. For the displacement response of the pier 2,when the apparent wave velocity is low, the displacement response under traveling wave effect are less than those under uniform excitation and it is dangerous to calculate according to the date under uniform excitation; when the apparent wave velocity is high, the displacement response under traveling wave effect are obviously more than those under uniform excitation ,which shows that the high apparent wave velocity has a negative effect on the displacement response of the high pier structure.

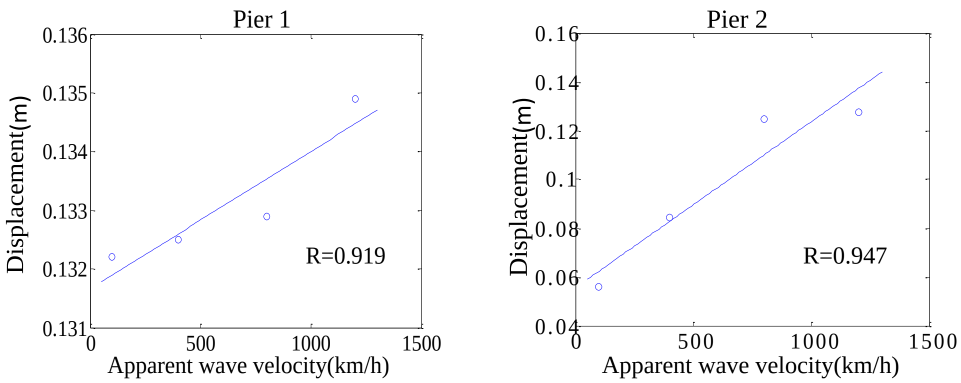

Figure 5. Lateral horizontal displacement response of pier top 1 and 2

V. Conclusion

This paper considers the spatial variability of ground motion and analyzes the influence of traveling wave effect on seismic response of high pier and long span continuous rigid frame railway bridge, and draws the following conclusion:

1. Subjected to the multi point excitation, the dynamic response of the continuous rigid frame bridge is obviously influenced by the seismic wave of different apparent wave velocity. Traveling wave effect has the beneficial or adverse effects on the piers of continuous rigid frame bridge.

2. Subjected to the longitudinal excitation, the bottom and the top of the bridge pier are all dangerous sections. There is a positive correlation between the displacement and moment response of high pier and the apparent wave velocity.

3. When the traveling wave effect of ground motion is considered, by comparison with uniform excitation, the dynamic response of control section may increase, and may also reduce. This trend is particularly evident in the internal force of the main pier, which indicates that the influence of traveling wave effect on the structural response is related to the characteristics of the structure and the location of the structure.

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