SEISMIC RESPONSE OF LARGE-SPAN CABLE-STAYED BRIDGE UNDER MULTI-COMPONENT MULTI-SUPPORT EARTHQUAKE EXCITATION

W. Quan[1], H.N. Li[1] and X.Z. Liu[2]

[1] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian. China*
[2] *Dept. of Road and Bridge Engineering, East China Jiaotong University, Nanchang, China*
Email:bridgeqw@yahoo.com.cn, hnli@dlut.edu.cn, urbwolf@126.com

ABSTRACT :
In this paper, seismic response of large-span cable-stayed bridge under multi-component multi-support earthquake excitations is studied. The emphasis is placed on investigation of the influence of the coherency between different components of same and different supports to the bridge. First, the MSRS method proposed by Kiureghian is extended to account for multi-component multi-support excitations. Then, parametric analyses of coherency to the structural seismic response are performed. The conclusions are drawn as follows: The coherency between different components of same and different supports should be considered in order to guarantee the safety of the bridge. Amplification factors are introduced to account for the influence of coherency, and simple calculation method is obtained to account for the multi-component and multi-support effect.

KEYWORDS: cable-stayed bridge, multi-component multi-support, seismic response, coherency

1 INTRODUCTION

Both theoretical research and earthquake damage analysis indicate that earthquakes are complex multi-component and multi-support movements. Large-span cable-stayed bridges are frequently adopted in the design of large-span bridges. Therefore, it is important to understand deeply the seismic performance of this bridge type under multi-component and multi-support excitations.

Xiang performed an investigation on the seismic response of Tianjin Yonghe Bridge, and the result showed that wave-passage effect is favorable for floating system cable-stayed bridge. On the contrary, Chen conducted influential analysis of wave-passage effect on the same bridge, and the results are different. Under three-component orthogonal earthquake, structural responses, such as tower bottom moments and deck axis forces, increase significantly when considering wave-passage effect. Fan took Nanjing Yangtze Bridge as an example, and studied the response characteristics of long-span cable-stayed bridge under seismic action with spatial variation. The results showed that: the response of cable-stayed bridge under multi-support earthquake excitation can differ from those under uniform excitation up to 40%. Moreover, the large difference at the various supports significantly changes seismic response of the bridge.

Namzy performed linear and non-linear earthquake response analysis of cable-stayed bridge subjected to multi-support as well as uniform seismic excitations. In his study, time histories method was used. Allam presented a response spectrum method for the seismic response of cable-stayed bridge subjected to correlated stationary random ground motion. Although the analysis took into account the partial correlation of ground motion between the supports, the finite propagation effect of the ground motion and the site-response effect were ignored. Soyluk investigated different cable-stayed bridges and pointed out that the displacement and internal forces increased when considering multi-support effect. The extent of increasing depends on the specific structural form, such as span layout and structural stiffness.

The studies before generally considered only multi-support effect, and the parametric analysis of the influential factors are also not sufficient. The studies considering both multi-component and multi-support were meager. And among those considered, the coherency between different components of same and different supports was neglected. The purpose of the paper is to investigate the effects of the coherency between different components of same and different supports in multi-component multi-support seismic analysis.

2. MULTI-COMPONENT MULTI-SUPPORT RESPONSE SPECTRUM METHOD

MSRS(Multiple-Support Response Spectrum) method is based on fundamental principles of stationary random vibration theory. Therefore, the theoretical basis is sufficient, and the method can be treated as the extension of CQC combination rule for structures subjected to incoherent support motions. The method can accurately accounts for the cross-correlations between the support motion as well as the modes of vibration of the structures. The combination rule for the mean of the response is of the form:

$$\mu_{Z\max} = \left[\sum_{k=1}^{m}\sum_{l=1}^{m} a_k a_l \rho_{X_{bk}X_{bl}} X_{bk,\max} X_{bl,\max} + 2\sum_{k=1}^{m}\sum_{l=1}^{m}\sum_{j=1}^{n} a_k b_{lj} \rho_{X_{bk}\delta_{lj}} X_{bk,\max} D_{bl}\left(\omega_j,\xi_j\right) + \sum_{k=1}^{m}\sum_{l=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ki} b_{lj} \rho_{\delta_{ki}\delta_{lj}} D_{bk}\left(\omega_i,\xi_i\right) D_{bl}\left(\omega_j,\xi_j\right) \right]^{1/2} \tag{2.1}$$

in which a_k、b_{ki} are structure-dependent effective influence and modal participation factors, respectively, $X_{bk,\max}$ denotes the peak ground displacement at station k, $D_{bk}\left(\omega_i,\xi_i\right)$ denotes the ordinate of the response spectrum at the support degree of freedom k for the frequency ω_i and damping of mode ξ_i, $\rho_{X_{bk}X_{bl}}$ $\rho_{X_{bk}\delta_{lj}}$ and $\rho_{\delta_{ki}\delta_{lj}}$ are cross-correlation coefficients between the support motions and modes of the structures.

The adopted coherency function is derived from the theoretical model of Luco and Wong, as

$$\gamma_{kl}(\omega,d_{kl}) = \exp\left\{-\left(\frac{\alpha\omega d_{kl}}{v_s}\right)^2\right\}\exp\left\{\mathrm{i}\omega\frac{d_{kl}^{L}}{v_{app}}\right\} \tag{2.2}$$

The first term represents the coherency effect and the second one accounts for the wave-passage effect and the local-soil effect. The first term decays exponentially with the frequency ω, the horizontal separation distance d_{kl} between the two stations k and l and with the inverse of the mechanical characteristics of the soil. The second term depends on the projected horizontal distance along the wave propagation direction and is a measure of the wave-passage delay due to the surface-apparent velocity of waves at the different stations v_{app}.

The incoherence factor α is a measure of the loss of coherency rate with distance and frequency, and its range definition is based on the empirically derived values of the ratio:

$$\frac{\alpha}{v_s} = q\times 10^{-4} \tag{2.3}$$

According to the observation of some field data, Luco and Wong suggested the ratio q as $2\le q\le 3$, which can be assumed as a reasonable value for a medium level of correlation between the ground motions. When

$\alpha/v_s \to 0$, the first term of Eqn.(2.2) tends to be 1 and the incoherence effect results only from wave traveling. If $v_{app} \to \infty$, then the second term of Eqn.(2.2) tends to be 1 and the incoherence is only due to geometric incoherence.

Given the coherency function between the same and different components of the same and different supports, MSRS method can be extended to multi-component multi-support seismic analysis. Therefore, the method is used to the analysis of cable-stayed bridge under multi-component multi-support excitations.

3. EXAMPLE OF CABLE-STAYED BRIDGE

The bridge model used in this study is that of the Quincy Bay-view Bridge crossing the Mississippi River at Quincy, Illinois. The bridge consists of two H-shaped concrete towers, double plane semi-harp type cables and a composite concrete–steel girder bridge deck. A detailed description of the bridge can be found in Wilson and Soneji. A simplified lumped mass finite-element model of the bridge considered for seismic investigations is shown in Fig. 1. The bridge is symmetrical about the vertical centroidal axes. The bridge has a central span of 274 m flanked by two side spans of 134 m each. The height of the towers above and below the deck is 53.7 m and 17 m, respectively. For the purpose of analysis, the deck is divided into 29 members, and each tower is divided into 11 members. Depending on the geometry, the towers are divided into three parts. The finite-element model of the towers is shown separately in Fig. 2. There are 28 cable members: 14 supporting the main span and 7 supporting each side span. The cable members are spaced at 2.75 m at the upper part of the towers and are equally spaced at deck level on the side spans as well as the main spans. The relevant properties of the bridge deck (for equivalent steel area) and towers are given in Table 1, while those of the cables are given in Table 2. The left and right anchor supports are kept as roller supports. The bridge deck is assumed to be a continuous beam, rigidly connected to the towers such that the deck moment will not be transferred to the tower through the deck–tower connection. The towers are considered to be fixed at the base.

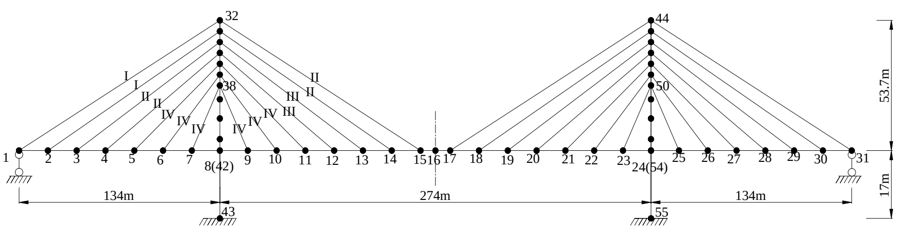


Fig. 1 Node numbering of the finite element model

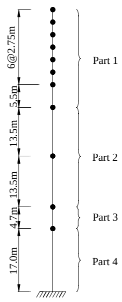


Fig. 2 Finite element model of towers

Table 1 Properties of the deck and the towers of the cable stayed bridge

Part of the structure	Cross-sectional area(m^2)	Moment of inertia about z-z axis (m^4)	Moment of inertia about y-y axis (m^4)	Moment of inertia about x-x axis (m^4)	Young's modulus (MPa)	Mass density (kg/m^3)
Deck	0.827	0.341	19.760	0.027	205000	7850
Tower part 1	14.120	28.050	531.580	15.390	30787	2400
Tower part 2	14.120	28.050	670.970	15.390	30787	2400
Tower part 3	17.540	30.620	1239.400	19.760	30787	2400
Tower part 4	35.390	32.750	1422.420	27.640	30787	2400

Table 2 Properties for the stayed cables of the cable stayed bridge

Cable number (Fig.1)	Cross-sectional area(m^2)	Young's modulus (MPa)	Cable weight(N/m)
Ⅰ	0.0180	205000	1765.80
Ⅱ	0.0135	205000	1324.35
Ⅲ	0.0107	205000	1049.67
Ⅳ	0.0070	205000	686.70

After discretization, there are 55 nodes and 80 elements, including 28 cable elements(simulated using spatial truss element) and 52 spatial beam elements. For each node, there are 6 degrees of freedom (including three translational and three rotational degrees). Therefore, for the whole bridge, there are 330 degrees in total. Lumped mass matrix is adopted, and the mass of the rotational degrees are zero. The damping ratio of the bridge is 3%.

4. NUMERICAL RESULTS

In the Ph.D thesis of the author, vertical, longitudinal and transverse multi-support seismic response analyses to the large-span cable-stayed bridge are conducted, respectively. Conclusions are drawn as follows: (1) As for vertical multi-support excitation, the tower will vibrate longitudinally, and the deck will vibrate vertically and longitudinally. The vibration of the other directions can be ignored; (2) As for longitudinal multi-support excitation, the tower will vibrate longitudinally, and the deck will vibrate longitudinally and vertically. The vibration of the other directions can be ignored; (3) As for transverse multi-support excitation, the tower and the deck will vibrate transversely, and the vibration of the other directions can be ignored.

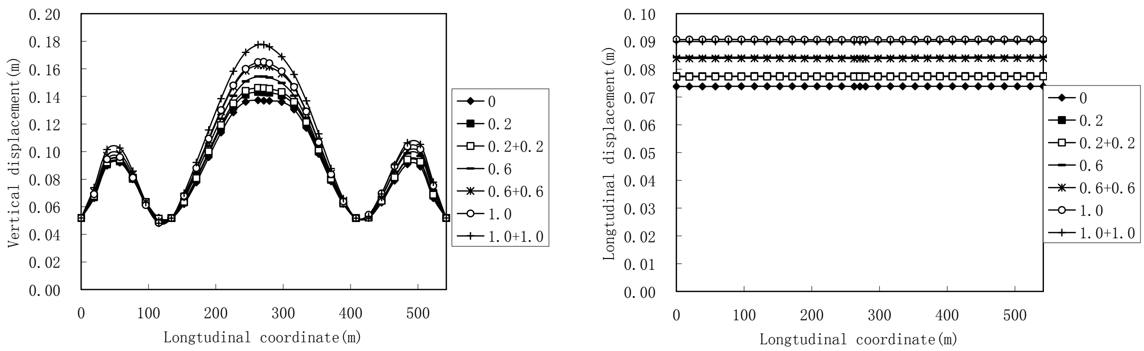
Therefore, we can know that vertical and longitudinal seismic excitations are coupled, and transverse seismic excitation is independent. In this paper, when multi-component multi-support seismic response spectrum analysis is performed, only longitudinal and vertical excitations are considered in the same time. The influence of the coherency between different components of the same and different supports to seismic response of cable-stayed bridge is investigated.

In the study, the coherency functions of the same component of different supports (vertical or longitudinal component) are all assumed to be Luco-Wong model($\alpha/v_s = 2.5\times10^{-4}$). Apparent wave velocity is 250m/s. In order to study the influence of the coherency between different components of the same support, multi-component multi-support response spectrum method is utilized, and four grades, 0, 0.2, 0.6, 1.0 are adopted. Moreover, on the basis of considering the coherency between different components of the same support, the coherency between different components of different supports is taken into account. Also, coherency is assumed to be independent with frequency, and four grades, 0, 0.2, 0.6, 1.0 are adopted. The method considering wave-passage effect is the same with the same component between different supports.

Deck vertical displacement under different degrees of coherency are shown in Fig.3(a). In the figure, 0.2+0.2 refers to considering both the coherency between different components of the same support (coherency factor is 0.2) and the coherency between different components of different supports (coherency factor is 0.2). The meaning of the other symbol can be obtained similarly.

From Fig.3, vertical displacement tends to increase along with the increase of the coherency coefficient. The calculation results of span center displacements are shown in Table 3. When only considering the coherency of different components of the same supports, the value under coherency coefficients 0.2, 0.6, 1.0 increases up to

4.4％, 12.8％ and 20.5％ compared with the value under coherency coefficient 0. When considering both the coherency of different components of the same supports and different components of the different supports, the value under 0.2+0.2, 0.6+0.6 and 1.0+1.0 increases up 6.6％, 18.7％ and 29.6％. Therefore, if the coherency between different components of the different supports is omitted, the safety of the bridge can not be guaranteed.



(a) Vertical displacement (b) Longitudinal displacement

Fig. 3 Deck displacements of two-dimensional earthquake with different coherency

Deck longitudinal displacement curves under different degrees of coherency are shown in Fig.3(b). The calculation results of span center displacements are given in Table 3. From above, compared with considering only the coherency of different components of the same support, the value considering both the coherency of different components of the same and different supports has little difference as to longitudinal displacement. Therefore, the coherency between different components of the different supports can be omitted for deck longitudinal displacement.

Tower longitudinal displacement curves under different degrees of coherency are shown in Fig.4. The calculation results of tower top displacements are given in Table 3. From above, compared with considering only the coherency of different components of the same supports, the value considering both the coherency of different components of the same and different supports has little difference as to tower longitudinal displacement. Therefore, the coherency between different components of the different supports also can be omitted for tower longitudinal displacement.

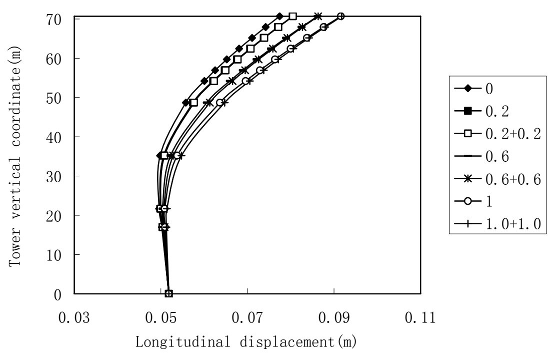


Fig. 4 Tower longitudinal displacements of two-dimensional earthquake with different coherency

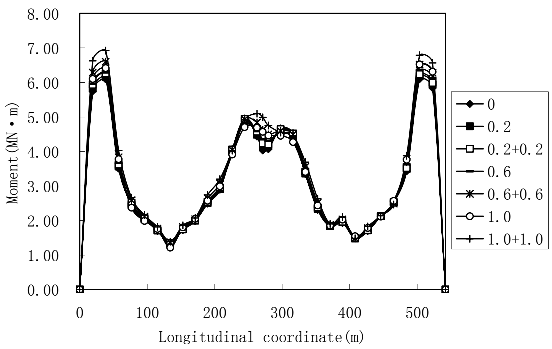
Combined with the displacement results of the deck and tower, conclusions can be drawn: the influence of the coherency between different components of the different supports is large for deck vertical displacement, and for the deck and tower longitudinal displacement, it can be omitted.

Table 3 Displacement response under different degrees of coherency (unit: m)

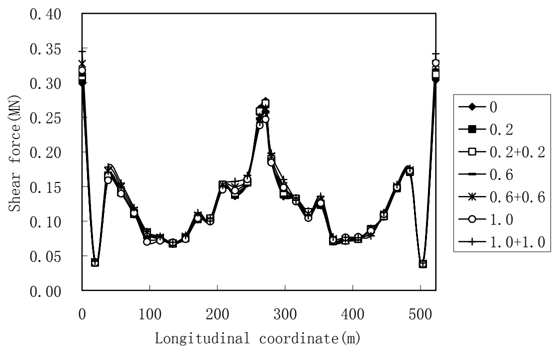
Response items	0	0.2	0.2+0.2	0.6	0.6+0.6	1	1.0+1.0
Vertical displacement of span center	0.137	0.143 (4.4%)	0.146 (6.6%)	0.154 (12.8%)	0.163 (18.7%)	0.165 (20.5%)	0.178 (29.6%)
Longitudinal displacement of span center	0.074	0.077 (4.9%)	0.077 (4.7%)	0.084 (14.1%)	0.084 (13.6%)	0.091 (22.7%)	0.090 (21.8%)
Longitudinal displacement of tower top	0.077	0.080 (3.9%)	0.081 (4.0%)	0.086 (11.3%)	0.086 (11.5%)	0.092 (18.3%)	0.092 (18.5%)

Note：The number in the bracket is the adding percentage of different coherency value compared with coherency 0.

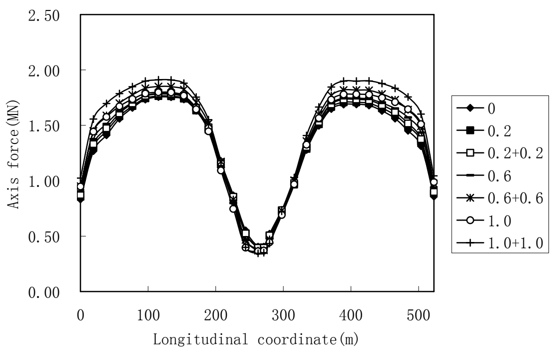
Deck and tower internal forces under different degrees of coherency are given in Fig. 5(a)-(f). The calculation results of deck span center and tower bottom are given in Table 4.



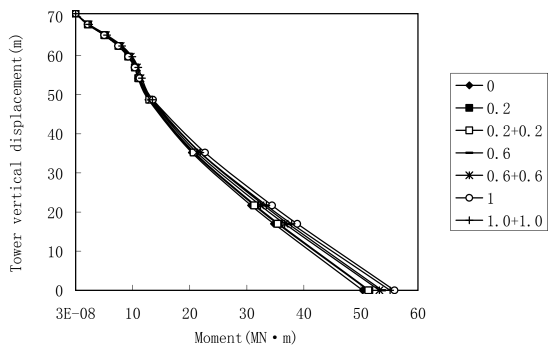
(a) Deck moments



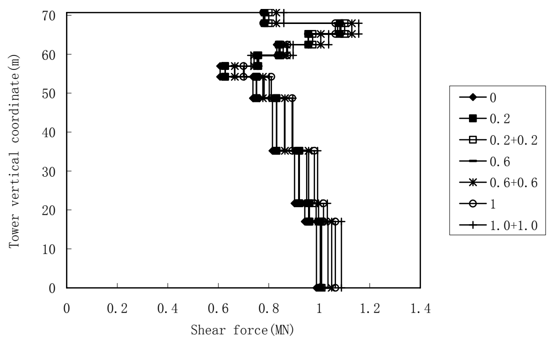
(b) Deck shear forces

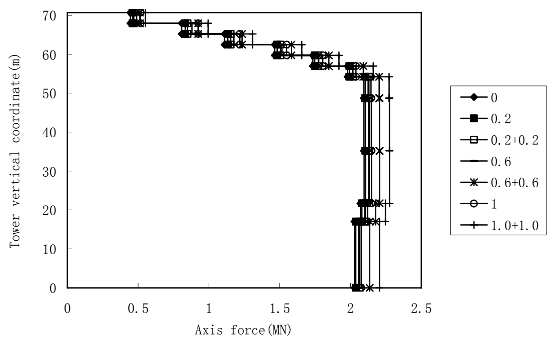


(c) Deck axis forces



(d) Tower moments along transverse axis





(e) Tower longitudinal shear forces (f) Tower axis forces

Fig. 5 Deck and left tower internal forces under different degrees of coherency

Table 4 Internal forces under different degrees of coherency

Response items	0	0.2	0.2+0.2	0.6	0.6+0.6	1.0	1.0+1.0
Deck moments (MN·m)	4.03	4.14 (1.03)	4.24 (1.05)	4.36 (1.08)	4.63 (1.15)	4.57 (1.13)	4.99 (1.24)
Deck shear forces(MN)	0.26	0.26 (0.98)	0.26 (0.99)	0.25 (0.95)	0.25 (0.96)	0.24 (0.91)	0.24 (0.92)
Deck axis forces(MN)	0.41	0.40 (0.98)	0.39 (0.97)	0.38 (0.94)	0.37 (0.91)	0.36 (0.90)	0.35 (0.85)
Tower moments (MN·m)	50.31	51.47 (1.02)	51.31 (1.02)	53.72 (1.07)	53.25 (1.06)	55.87 (1.11)	55.12 (1.10)
Tower shear forces(MN)	0.99	1.00 (1.02)	1.01 (1.02)	1.03 (1.05)	1.05 (1.06)	1.06 (1.08)	1.09 (1.10)
Tower axis forces(MN)	2.03	2.04 (1.00)	2.06 (1.02)	2.06 (1.01)	2.14 (1.05)	2.08 (1.02)	2.20 (1.09)

Note：The number in the bracket is the adding percentage of different coherency value compared with coherency 0.

From Fig. 5 and Table 4, conclusions can be drawn as follows:

1) As for deck moments, compared with considering only the coherency between different components of the same support, the value considering both the coherency of different components of the same and different supports increases a certain degree. As can be seen from Table 4, the deck span center moment of case 1.0+1.0 increases up to 24% compared with coherency 0. While the value of case 1.0 increases only 13% compared with coherency 0. For deck shear forces and axis forces of the middle span center, considering both the coherency of different components of the same supports and different components of different supports has no instinct influence.

2) As for the tower, the influence of the coherency between different components of the different supports is little in which tower moment decreases a little, and shear forces and axis forces increase a little.

5. CONCLUSIONS

Through the analysis above, conclusions can be drawn as follows:

(1) For large-span cable-stayed bridge, longitudinal earthquake excitation and vertical earthquake excitation are coupled, and the transverse earthquake excitation is independent. When considering longitudinal and vertical seismic excitation together, the coherency between different components of the same and different supports should be taken into account. The coherency interval is [0, 0.6] as recommended by the author. Therefore, the amplification factor for the displacement is about 15%, and for the internal force is about 10%.

(2) For simplicity, multi-component multi-support analysis can be reduced to single-component multi-support analysis. Owing to the coupling between longitudinal and vertical earthquake excitation, SRSS method can be used. Moreover, in order to consider the coherency between different components of the same and different supports, amplification factors are introduced to the seismic response of the structures. As for transverse excitation, the calculation is conducted independently. The formulas are as follows:

$$R_1 = \gamma\sqrt{R_z^2 + R_s^2}\ ; \qquad R_2 = R_h \tag{5.1}$$

in which, R_z refers to the structural response under longitudinal seismic excitation; R_s refers to the structural response under vertical seismic excitation; R_h refers to the structural response under transverse seismic excitation; R_1 and R_2 refer to the response value under longitudinal and vertical excitation together and transverse excitation only. The value of γ can be obtained as the bridge, for displacement , γ=15%, for internal forces, γ=10%。

REFERENCES

Kiureghian A.D.,Neuenhofer A. (1992). Response spectrum method of multi-support seismic excitations. *Earthquake Engineering and Structural Dynamics*, **21:** 713-740.

Chen，Y.P., Zhou H.Y. (1996). Wave-passage effect of cable-stayed bridge. *Journal of civil engineering* **29:6,** 61-68. (in Chinese).

Xiang H.F. (1983). Earthquake response analysis of cable-stayed bridge under wave-passage effect. *Journal of tongji university* **11:2,** 1−9. (in Chinese).

Fan L.C., Wang J.J., Chen W. (2001). Response characteristics of long-span cable-stayed bridges under non-uniform seismic action. *Journal of computational mechanics.* **18: 3,** 358−363. (in Chinese).

Allam S.M., Datta T.K. (2000). Analysis of cable-stayed bridges under multi-component random ground motion by response spectrum method. *Engineering structures*,**22:**1367-1377.

Soyluk K. Dumanoglu A.A. (2004). Spatial variability effects of ground motions on cable-stayed bridges. *Soil dynamics and earthquake engineering*, **24:** 241-250.

Luco J.E., Wong H.L. (1986). Response of a rigid foundation to a spatially random ground motion. *Earthquake Engineering and Structural Dynamics*, **14:** 891-908.

Wilson J.C., Gravelle W. (1991). Modeling of a cable-stayed bridge for dynamic analysis. *Earthquake engineering and structural dynamics*, **20:** 707-721.

Soneji B.B., Jangid R.S. (2007). Passive hybrid systems for earthquake protection of cable-stayed bridge. *Engineering structures*, **29:** 57-70.

Quan W. (2008). Studies on seismic analysis of large-span bridges subjected to multi-component and multi-support earthquake excitations: (Ph.D. thesis). Dalian: Dalian University of Technology, 2008.(in Chinese).