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Analysis of dynamic response in consideration of coupling effect of pile and soil and water of large span cable-stayed bridge

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Abstract. Soil is treated using the equivalent form of the derived viscoelastic boundary. And use additional mass method to deal with the role of fluid. Time-history analysis and virtual excitation method are respectively used to calculate the response and internal forces of the long-span cable-stayed bridge. The analysis shows that hydrodynamic pressure changes the dynamic characteristics of the structure mainly in the form of additional mass, so as to change the seismic response of the structure and increase the structural displacement and internal force, generally by about 50%.

Key words. Viscous elastic artificial boundary, dynamic response of long-span cable-stayed bridge, time history analysis, various conditions.

1. Introduction

The finite element method is a fast-developed numerical method in recent years. In this paper, ANSYS is used to analyze the structural dynamics of the cable-stayed bridge with complex structure, and the seismic response in seismic design of Bridges is calculated. Most studies on the influence of water on piers are based on the assumption of rigid foundation, without considering the interaction between foundation, structure and water[1−3]. At present, the research has shown that the influence of this coupling effect on the dynamic characteristics of the structure cannot be ignored, but the influence on the large span cable-stayed bridge has not been determined. In this paper, the interaction of pile-soil-water structure is considered, and the water is treated as additive quality on the pile[4−5].

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2. Viscoelastic artificial boundary

In practical application, the scattering wave produced by local irregular region or structural foundation generally exists geometric diffusion. The cylindrical wave or spherical wave takes into account the geometric diffusion attenuation of the wave in the medium. The boundary will not cause the whole structure drift, also can improve the simulation precision [6]. It is more reasonable to use the cylindrical wave or spherical wave hypothesis for scattering wave. In the two-dimensional viscoelastic artificial boundary, the equivalent spring coefficients $K_B$and damping coefficientsC_B are respectively:

Tangential boundary:

$$K_{BT} = \alpha_T \frac{G}{R}, C_{BT} = \rho c_s \tag{1}$$

Norma1 boundary:

$$K_{BN} = \alpha_N \frac{G}{R}, C_{BN} = \rho c_p \tag{2}$$

In which, K_{BN} is the spring normal stiffness andK_{BT} is the tangential stiffness of the spring; $C_{BT}$is the normal damping of the spring, and$C_{BN}$is the tangential damping of the spring, $R$is the distance from the wave source to the artificial boundary; and $c_s$and$c_p$are the wave velocities of the transverse and longitudinal waves respectively; G is the ratio of shear stress to strain of the medium; $\rho$is the mass density of the medium; andα_T and α_N are the tangential and normal viscoelastic artificial boundary parameters respectively. In the literature, $0.35 \leq \alpha_T \leq 0.65$,$0.8 \leq \alpha_N \leq 1.2$.

3. Calculation method of pile water coupling

According to the Morison calculation method, it is assumed that the wave motion is not affected by the building itself. The dimension of the component is not more than 0.2 times of wavelength, and the surface is smooth. The members are rigid and vertically fixed to the sea floor. In engineering, the complete form of the Morison equation for a circular pier $D/L < 0.2$can be expressed as[8]:

$$P = P_D + P_I + P_M = \frac{1}{2} C_D \rho D (u - \dot{x}) \left| u - \dot{x} \right| + C_M \rho \frac{\pi D^2}{4} \dot{u} - C_M \rho \frac{\pi D^2}{4} \ddot{x} \tag{3}$$

In the formula, P_M,P_I and P_D represent the attached water mass and drag force (resistance) and inertial force on pile of per unit length respectively. and C_D and $C_M$are the drag coefficient (i.e. resistance coefficient) and the inertia force coefficient. And u and $\dot{u}$ are respectively the horizontal velocities and acceleration (at point Z above the bottom) of orbital motion of water point. And $\dot{x}$ and $\ddot{x}$ are respectively the horizontal velocities and acceleration at the section.$\rho$is water density. $D$is the diameter of pile. $L$is Wavelength[9].

The equivalent water mass$m_f$can be obtained by the kinetic energy balance between the total kinetic energy of the fluid particles in the outer cylinder and the kinetic energy of the additional water mass (unit length):

$$\frac{\rho}{2}\pi R^2 V^2 = \frac{1}{2} m_f v^2 \tag{4}$$

$$m_f = \rho \pi R^2 \tag{5}$$

4. Analysis method of structural dynamic

Modal analysis theory is developed on the basis of vibration theory, signal analysis, data processing, mathematical statistics and automatic control theory. It can provide theoretical basis for optimization design of vibration analysis, vibration fault diagnosis and prediction, structural dynamic characteristics, and so on. At present, modal analysis theory is quite mature. When the linear system is subjected to a single point stationary random excitation $x\,(t)$of the spectral rate$S_{xx}\,(\omega)$, and the self power spectrum of the response is $S_{yy}\,(\omega)$ [8˜9], and

$$S_{yy}\,(\omega) = |H|^2 S_{xx}(\omega \tag{6}$$

In the upper form, $H$is the frequency response function. If the unit harmonic function is used to stimulate$e^{i\omega t}$, the corresponding harmonic response is

$$y = He^{i\omega t} \tag{7}$$

According to the pseudo excitation method, the virtual excitation $\tilde{x}$can be obtained by multiplying$e^{i\omega t}$ the constant$\sqrt{S_{xx}(\omega)}$ and$\tilde{x} = \sqrt{S_{xx}(\omega)}e^{i\omega t}$. And there is:

$$\tilde{y} = \sqrt{S_{xx}} He^{i\omega t} \tag{8}$$

Consider that

$$\tilde{x}^* \tilde{y} = \sqrt{S_{xx}(\omega)}e^{-i\omega t} \cdot \sqrt{S_{xx}(\omega)} He^{i\omega t} = S_{xx}(\omega)H = S_{xy}(\omega) \tag{9}$$

$$\tilde{y}^* \tilde{y} = |\tilde{y}|^2 = |H|^2 S_{xx}(\omega) = S_{yy}(\omega) \tag{10}$$

If we think that a certain internal force$f$, stressσ and strain$\varepsilon$are important, we can easily obtain the virtual harmonic response $\tilde{f}$,$\tilde{\sigma}$ and $\tilde{\varepsilon}$ according to the formula (4-3), and then, we can directly obtain the self-spectral density function.

$$S_{ff} = \left|\tilde{f}\right|^2 S_{\sigma\sigma} = |\tilde{\sigma}|^2 S_{\varepsilon\varepsilon} = |\tilde{\varepsilon}|^2 \tag{11}$$

Or any cross-spectral density, for example:

$$S_{\sigma\varepsilon} = \tilde{\sigma} * \tilde{\varepsilon} S_{f\varepsilon} = \tilde{f} * \tilde{\varepsilon} \tag{12}$$

From (11), (12), it could be known that the virtual incentive method is simple, but the response and incentives need to be linear.

5. Numerical simulation of structural dynamic response

As the largest span cable-stayed bridge in the world, the span of the main bridge of the Sutong Yangtze River Bridge is 0.1 + 0.1 + 0.3 + 1.088 + 0.3 + 0.1 + 0.1km. The main bridge uses steel box girders, including a total of 17 species (A-O), 141 beams. The basic length of each beam is 16m. And the length of the cross-tail cable beam section is 12m. The maximum lifting weight of basic beam section is about 450000kg; the full width of steel box girder is 4lm. Pylon is inverted Y-shaped structure, divided into four parts, lower tower, middle tower legs, upper limbs and beams. Middle and lower tower limbs are reinforced concrete structures. The upper tower is a steel anchor box - concrete composite structure. And the tower is 300.4m high. Diagonal cable is Φ7 parallel wire system. The bridge has a total of 34 × 8 = 272 stay cable.

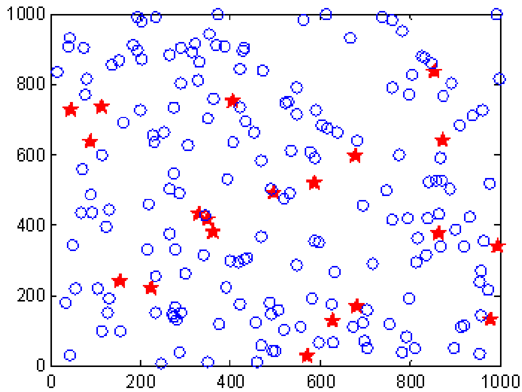

Fig. 1

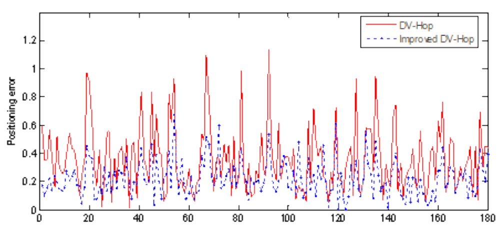

Fig. 2

As shown in Figure 1, the pile-soil-water-structure model has the largest displacement response in the Z direction at the midpoint of the main girder, followed by the pile-structure model. The smallest model is the bearing structure. The maximum of pile-soil-water-structure model is 40.7% larger than that of pile-structure model. The interaction between water and structure has a significant influence on the displacement response of the main girder of long-span cable-stayed bridge.

6. Conclusion

As Sutong Bridge is located in the deep water, it is very necessary to consider hydrodynamic pressure in seismic design. The internal forces of the vertical one-way excitation are smaller or nearly similar to those of the three-direction excitation. The pile-soil-water-structure is more sensitive to the excitation direction when calculating the displacement of the main girder, and the proportion of the influence is basically larger than that of the first three models. Different forms of motivation have a more significant effect on the displacement of the main girder. The lateral displacement of Sutong Bridge is obviously greater than the longitudinal displacement, showing that the transverse rigidity of the structure is weak, so lateral displacement should be controlled in the anti-seismic design. The input combination of seismic waves has obvious influence on the response of the four kinds of structural models, and the input and the combination of multiple working conditions are required in the seismic design.

Table 1 Analysis results of main tower displacement and seismic wave input

Constraint condition		Cap fixation	Pile structure	Pile soil structure	Pile - soil - water structure
	Input in x direction	18.2%	-384.2%	-385%	-326.3%
	Input in y direction	0.006%	0.006%	2.1%	0.002%
	Input in z direction	18.2%	-189.4%	-85%	-115.8%
	Input in x direction	42.9%	4.04%	2.04%	4.25%
	Input in y direction	-342.27%	-347.4%	-576.4%	-347.6%
	Input in z direction	-345.4%	-340.4%	-573.2%	340.4%

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