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ELASTIC MODEL SCALE AND MATERIAL FOR UNDERWATER STRUCTURE OF CROSS-SEA BRIDGE

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ABSTRACT: With the bridge construction gradually from inland to coast and offshore, underwater structure of cross-sea bridge can encounter more complex hydrodynamic action. When elastic model is used to simulate the hydrodynamic response of underwater structure, the model scale and model material is the first problem must be solved. Based on principle of similitude, elastic model should meet the geometric similarity, kinematic similarity and mechanical similarity. Formula derivation gives the scale conditions for elastic model are as follows, geometric scale (L_r) equals elastic modulus scale (E_r) and density scale (ρ_r) equals 1. Then, how to find a material with same density and the elastic modulus is 1/ L_r of prototype is the key to make a model.

Keywords: Elastic Model, scale, material, cross-sea bridge

INTRODUCTION

With the gradual development of bridge construction from the inland to the coast and offshore, extra large bridges are thus faced with harsher meteorological and hydrological conditions featuring by deep water, rapid flows and big waves. As the main mode of transportation across straits, extra large bridges have to withstand wave and current loads in the lower part and wind loads in the superstructure. In the coupling effect of wind, wave and current, bridge vibration or some displacement may occur in the construction and operation period, thus affecting the construction process or operational security.

In the face of numerous natural factors, load field observation on extra large bridges in wind-wave-circulation coupled environment and the load coupling characteristics are not clear. In addition, simulation technology and numerical analysis techniques remain in a blank state. The existing relevant design specification does not consider the coupling effect between multiple factors, so it is likely to overestimate the environmental design conditions or underestimate them. Therefore, in 2011, "*Study on the Theory and Method of Comprehensive Disaster Prevention and Mitigation of Oversize Bridge*", a major project of the Ministry of Transport, will conduct physical model test and numerical simulation in this respect. This study mainly analyses the selection of scale method and model materials in the elastic substructure model test of cross-sea bridges.

HYDROELASTIC MODEL SCALE

Hydroelastic model

The flow-induced vibration of hydraulic structures is caused by the structural vibration of hydrodynamic loads, where there exists a dynamic interaction between the structure and the fluid. According to its excitation mechanism, the flow-induced vibration can be divided into forced vibration, object-vibration-controlled excitation, self-excitation and parametric excitation. In fact, the flow-induced vibration of hydraulic structures is ubiquitous. In most cases, the vibration is within the permissible range. But in some cases, the vibration can be harmful and even cause an accident.

The flow-induced vibration is a kind of fluid-structure interaction, so it is closely related to hydraulic conditions and structural dynamic characteristics. To study its vibration state and the mitigation measures, it is necessary to use a physical model of fluid-structure interaction, namely, hydroelastic model experiments. The hydroelastic model is a development of the hydraulic model, which has similarities in both hydraulic conditions and structural dynamic characteristics.

The concept of hydroelasticity appeared in the field of hydraulics before 1958. The flow-induced vibration of gates was generally studied in indirect ways in the world before 1958. The hydraulics experiment and the structural dynamics experiment were carried out respectively. In 1964, Heller pointed out the concept of hydroelasticity is concerned with the interaction between inertia, hydrodynamic, and elastic forces. In 1965, Toebes defined the concept of fluid-elastic. When studying fluidelastic features of flow, he considered the

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interdependence between hydrodynamic force, inertial force generated by the structure, and elastic force. For hydroelastic modeling on the flow-induced vibration of hydraulic structures, the vibration phenomena caused by the interaction between hydrodynamic force, structural inertial force, and elastic force are studied, without consideration of the compressibility and elasticity of water.

The principles of similitude

To ensure that the main phenomena and performances of the prototype can be reflected from the model and that the quantitative predictions of the prototype can be made, the fluid motion and the structural vibration of the model and those of the prototype have to maintain a certain scale between corresponding physical quantities on corresponding points. To be specific, the model and the prototype must be similar in geometry, dynamics, and mechanics.

For dynamic similarity, several similitude criteria are to be satisfied. For two flow-induced vibration systems which are completely similar, the scales of Froude number, Cauchy number, Euler number and Reynolds number should all be 1. It should be noted that the Reynolds number and Froude number cannot be simultaneously satisfied, but as long as the Reynolds number is large enough, the similitude criteria can be automatically satisfied. They are not only the similitude criteria for two flow-induced vibration systems, but also the criteria for model design.

In addition, the friction of structure has various types, and different types of friction have different simulation methods. The frictions of structure are important because they can exert damping effect on vibration. Simulating coefficients of friction is not impossible but difficult as it requires high processing skills. An easier way is to not to simulate but to eliminate all frictions of the model, because by eliminating the frictions, the experimental results can be reliable for assessing the harmfulness of flow-induced vibration.

Selection of elastic model scales

The selection of elastic scale mainly involves inertia force, gravity, and elastic force. The scale factors can be derived as follows:

(1) Inertia force

$$F_{\text{inert}} = -ma \tag{1}$$

here, m is mass; a is acceleration. The scale of inertia force is given below:

$$F_{\text{inert},r} = \frac{-m_p a_p}{-m_m a_m} = \frac{\rho_p V_p a_p}{\rho_m V_m a_m} = \rho_r L_r^3 L_r T_r^{-2} = \rho_r L_r^4 T_r^{-2} = \rho_r L_r^2 v_r^2 \tag{2}$$

here, V is volume; ρ is density; the corner mark p represents the prototype and the corner mark m represents the model; ρ_r, T_r, v_r are the density scale, time ratio, and speed scale respectively.

(2) Gravity

$$F_{\text{grav}} = mg \tag{3}$$

here, g is gravity acceleration. The gravity scale is given below:

$$F_{\text{grav},r} = \frac{m_p g_p}{m_m g_m} = \frac{\rho_p V_p g_p}{\rho_m V_m g_m} = \rho_r L_r^3 g_r \tag{4}$$

here, g_r is the scale of gravity acceleration. In the gravitational field, g_r =1.

(2) Elastic force

$$F_{elast} = EA\frac{\Delta L}{L} \tag{5}$$

here, E is elasticity modulus; A is the cross sectional area under the elastic force; ΔL is the dependant variable of L; $\Delta L/L=\varepsilon$, ε is the strain value; and according to geometric similarity, $\varepsilon_p/\varepsilon_m=1$. The scale of elasticity force is given below:

$$F_{elast,r} = E_r A_r = E_r L_r^2 \tag{6}$$

According to the criterion of Froude number, the scale of inertia force is equal to that of gravity, namely,

$$\rho_r L_r^2 v_r^2 = \rho_r L_r^3 g_r \tag{7}$$

considering g_r=1, the simplified equation is as follows

$$v_r^2 = L_r \tag{8}$$

According to the criterion of Cauchy number, the scale of inertia force is equal to that of elastic force, namely,

$$\rho_r L_r^2 v_r^2 = E_r L_r^2 \tag{9}$$

by simplifying the equation, the following formula can be obtained:

$$\frac{\rho_r v_r^2}{E_r}=1 \tag{10}$$

substituting the equation (8) into the above, it is concluded that when $\rho_r=1$,

$$E_r = L_r \tag{11}$$

It can be concluded that the requirements of hydroelastic model to be met by the model material are $E_r=L_r$, $\rho_r=1$. Therefore, the key to establishing the model is to find a kind of material that has the same density with the prototype and the elasticity modulus is $1/L_r$ of the prototype.

HYDROELASTIC MODEL MATERIAL

No materials satisfying the above similitude criteria can be found currently in the market. According to relevant documents, the hydroelastic materials used in model experiments of water resources & hydropower engineering were specially developed. They were manufactured by relevant manufactures with given parameters.

The bridge substructure is mostly concrete, and the model material of the concrete structure should meet the above similitude criteria When Changjiang Scientific Research Institute was preparing "*Hydroelastic Model Test Research on Releasing Flood Vibration of Arch Dam for Goupitan Project*", they conducted a monographic study on the hydroelastic model materials of the dam body and the dam base for their physic-mechanical properties. Heavier rubber materials were employed to meet the elasticity criterion, while barite powder was used as filler to meet the density criterion. For example, a hydroelastic model with a scale of 150 : 1 was used in the test. The physic-mechanical parameters are listed in Table 1 below:

Table 1 physic-mechanical parameters of the hydroelastic model with 150:1 scale

Dynamic **elastic** modulus **(MPa)**		**Density** **(t/m^3)**		**D**amping ratio **(%)**		**Poisson ratio**	
prototype	model	prototype	model	prototype	model	prototype	model
2.7×10^4 $\sim3.15\times10^4$	198~220	2.4	2.43	2	5	0.167	0.2~0.25

It is noted that the elastic modulus of such material is largely affected by temperature. When the temperature is high, the elastic modulus will decrease significantly. As a result, when doing the experiment, the ambient temperature should be consistent with the temperature when elastic modulus was tested. Figure 1 is the waste model material and Figure 2 is the dam model after the test.

Fig. 1 The waste model material

Fig. 2 Dam model with hydroelastic material

CONCLUSION

This study explores how to select the elastic model scale of cross-sea bridge substructure. It points out that the key to establishing the elastic model is to find a type of material that has the same density with the prototype and that the elasticity modulus is $1/L_r$ of the prototype. On the basis of field visits, this study describes the features and methods of concrete elastic model material, and provides a reference for relevant elastic model tests.

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