FEM ANALYSIS OF THE ORIFICE ANTI-SEIMIC REINFORCEMENT FOR HIGH ARCH DAM

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ABSTRACT :

The high arch dam has a large orifice size, a compliance shape, and a very complex stress distribution around its orifice under dynamic loading. Therefore, there are many difficulties in the orifice reinforcement design of high arch dams. In this paper, the 3-D elastic Finite Element Method (FEM) is introduced to study the dynamic behavior of the orifice, which is picked out from the entire dam structure, refined and applied with dynamic displacement boundary conditions and dynamic loading of the earthquake. According to the proposed method, more accurate stress results around the orifice than those in the whole structure analysis are obtained. Based on the stress analysis, the quantity of the steel bars around the orifice can be calculated from tensile stress graphs.

KEYWORDS: high arch dam, dynamic substructure, substructure refinement, orifice reinforcement

1. INTRODUCTION

With high quality and low prices, arch dams are widely used in the world. A group of super-high arch dams higher than 300 meters are being and will be constructed in the Southwest and Northwest of China, and therefore it is urgent to find solutions to problems including orifice anti-seismic reinforcement for high arch dams. On the basis of a lot of model tests on stress distribution characteristics around the dam orifice, quite a few researchers have given some advices on the place for reinforcement and the quantity of steel bars needed. Linear and Nonlinear FEM have been employed by many other scholars to study orifice structure reinforcement. With the method of reinforcing the orifice through tensile-stress diagrams, a linear FEM recommended in *Hydraulic Concrete Structure Design Criterion*, researchers are now able to calculate the amount of steel bars with three-dimensional models, compared with the simplified plane models at first. To analyze the situation in which concrete has creaked and the real mechanics characteristics of the orifice, the other method, Nonlinear FEM, was introduced. However, the problems about concrete constitutive relation, bond-slip relationship between steel bars and concrete and crack width have not yet been solved satisfyingly through Nonlinear FEM.

Most of the researches above were done in the static working condition. There are not many studies on orifice anti-seismic reinforcement for high arch dam at present yet. The prime reason is that, under dynamic load, the accurate stress distribution around orifice is hard to study. The calculation error of the FEM consists of discretization error and numerical rounding error. The latter can be minimized through modern computers with many valid numbers, which is also called high-precision computation, while discretization error can only be minimized by reducing the element size, which means calculation accuracy is improved by using high-density mesh [Chen Aijiu, Zhang Qing and Liu Zhongqiu, 2006]. .But high-density mesh and high-precision computation will greatly increase computational efforts, so we proposed dynamic substructure to solve this problem.

The traditional substructure methods are wildly used in many domains such as aerospace, automobile manufacture, building construction, etc. Those methods can be divided into three categories:

mode-displacement method, interface transformation synthesis method and transfer substructure method [Fang Mingxia, Wu Lei and Feng Qi, 2006]. The basic idea of them is to calculate dynamic characteristics and establish dynamic equations for each substructure at first, and then to form dynamic equations for the whole structure by integrating the substructure dynamic analysis results. Through those methods, the dynamic analysis of the whole structure is transformed into calculation of dynamic characteristics and low order matrices of substructures, thus lowering the demand of computer capacity.

But those kinds of dynamic substructure methods have to form the whole structure dynamic equations besides analysis dynamic response of each substructure [Wang Mengpu and Shen Pusheng, 1994)]. We bring forward a new kind of dynamic substructure analysis method, in which large elements are used in dynamic response analysis of the whole structure at first, and then the substructures of interest are selected to compute its dynamic responses by refining it and imposing it with constraint conditions. The basic idea of this new method is different from those dynamic substructure methods mentioned above.

2. BASIC THEORY

The orifice of high arch dam belongs to complicated hydraulic non-member system structures. The current *Hydraulic Reinforced Concrete Structures Codes* (DL/T5057-1996) points out if the section internal force of the concrete structure can not be calculated by member-bar structural mechanics methods, the quantity of steel bars can be determined through the area of diagram of principal-tensile stress, which is calculated with elasticity analysis method. Therefore, there are two key procedures in the analysis of the orifice anti-seismic reinforcement for high arch dam with FEM. The first is to obtain accurate dynamic stress results. The second is to compute areas of stress diagrams and then the quantity of steel bars based on the dynamic stress results.

2.1. Obtaining accurate dynamic stress around orifice with FEM

In the calculation of the stress of arch dam, the stress stations for the whole dam under different static and dynamic load combination should be computed at first, which is called the whole structure calculation. We adopted time-history method in this calculation. For joints in arch dams would open under dynamic load and release local stress, the destructive action of strong earthquake could be reduced in certain degree. So we adopted contact-nonlinear method to simulate the joints and to get more accurate stress of the whole structure in this paper [Zhao Lanhao, 2004].

Because the simulated range of the whole dam structure is very large, elements allocated to simulate orifice are not many and are in large size, the accuracy of stress could not meet the requirement of reinforcement. According to the FEM principles, as the element size decreases, the calculation accuracy of stress and the area of stress–diagram will be improved. But the computer memory size limits the element number. We proposed the local-refined dynamic-substructure analysis method to solve the contradiction between the stress accuracy and the element number.

2.1.1 The principles of dynamic-substructure method

After the whole structure has been calculated, the orifice substructure is refined. Then the dynamic stress for substructure can be calculated out, by applying it with static and dynamic loads and imposing it with special constraint conditions. Those special constraint conditions are the nodes-displacements in the interface between substructure and the whole structure. As the time-history method was adopted in the whole structure calculation, the nodes-displacements in the interface changed with time, and thus the displacement constrains of the substructure changed with time.

2.1.1.1 Local refinement of the substructure

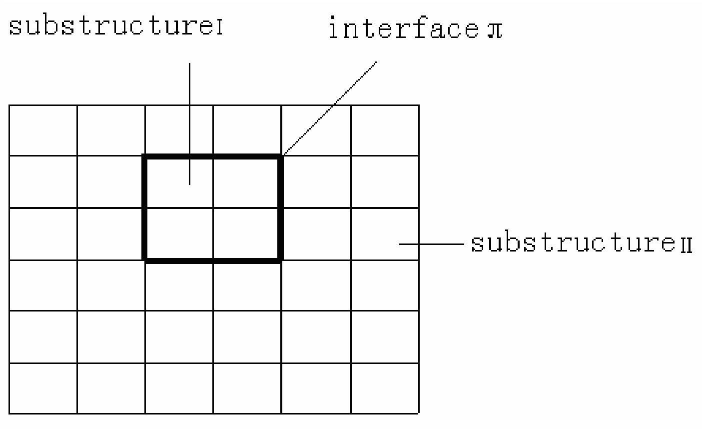


Figure 2.1 The structure calculation schematic diagram

In the whole structure calculation, according to the normal FEM, the substructure Ⅰ and Ⅱ (shown in figure 2.1) are computed together as a whole, resulting in the nodes displacement time history in the interface π. Suppose the nodes number in the section π is m. For each moment in the calculation period, the nodes displacement components in xyz coordinate system are as following:

$$\delta_i(t)=\{\delta \mathrm{X}_i(t) \quad \delta \mathrm{Y}_i(t) \quad \delta \mathrm{Z}_i(t)\} \tag{2.1}$$

It is assumed that the displacements for any point in element can be obtained through element shape function interpolation with the known node-displacement components.

$$\delta \mathrm{X}(t)=\sum_{i=1}^{m} N_i \delta \mathrm{X}_i(t) \tag{2.2}$$

$$\delta \mathrm{Y}(t)=\sum_{i=1}^{m} \mathrm{N}_i \delta \mathrm{Y}_i(t) \tag{2.3}$$

$$\delta \mathrm{Z}(t)=\sum_{i=1}^{m} \mathrm{N}_i \delta \mathrm{Z}_i(t) \tag{2.4}$$

After the whole structure has been calculated, the substructure Ⅰ is picked out and refined, the displacements of new nodes in section π can be obtained form the element-shape-function interpolation with original node displacement-components [Li Tongchun and Zhang Hanghui, 2004].

2.1.1.2 Calculation of substructure under dynamic load

Dynamic finite element equation is:

$$[\mathrm{K}]\{\delta\}+[\mathrm{C}]\{\dot{\delta}\}+[\mathrm{M}]\{\ddot{\delta}\}=\{\mathrm{R}\} \tag{2.5}$$

Where K is structural stiffness matrix, C is structural damping matrix, M is structural mass matrix, δ is unknown node displacement vector, R is load vector.

The equation (2.5) equals to:

$$\begin{bmatrix} k_{ii} & k_{ic} \\ k_{ci} & k_{cc} \end{bmatrix}_{\mathrm{I,II}} \begin{Bmatrix} \delta_i \\ \delta_c \end{Bmatrix}_{\mathrm{I,II}} + \begin{bmatrix} c_{ii} & c_{ic} \\ c_{ci} & c_{cc} \end{bmatrix}_{\mathrm{I,II}} \begin{Bmatrix} \dot{\delta}_i \\ \dot{\delta}_c \end{Bmatrix}_{\mathrm{I,II}} + \begin{bmatrix} m_{ii} & m_{ic} \\ m_{ci} & m_{cc} \end{bmatrix}_{\mathrm{I,II}} \begin{Bmatrix} \ddot{\delta}_i \\ \ddot{\delta}_c \end{Bmatrix}_{\mathrm{I,II}} = \begin{bmatrix} R_i \\ R_c + r_c \end{bmatrix}_{\mathrm{I,II}} \tag{2.6}$$

Where: c indicates the nodes in the section π, while i stands for the nodes out of the section; R_i indicates the load-vector of nodes in the section π, while R_c stands for that out of the section; $(r_c)_{\mathrm{I}}$ and $(r_c)_{\mathrm{II}}$ indicate the constraint internal force between the substructures Ⅰ and Ⅱ.

The nodes displacement time history $\{\delta_c\}_t$ can be obtained after the whole structure is computed and the substructure is refined. As for the substructure Ⅰ ,equation (2.6) at the moment of t can be simplified as:

$$[k_{ii}]\{\delta_i\}_t + [c_{ii}]\{\dot{\delta}_i\}_t + [m_{ii}]\{\ddot{\delta}_i\}_t = \{R_i(t)\} \tag{2.7}$$

With the normal FEM, the internal displacement and stress of the refined-substructure can be obtained.

The element number around the orifice region increases when the dynamic substructure method is adopted, therefore the steel bar quantity can be computed based on those results, which are more accurate than those in the whole structure calculation.

2.2. Calculation of area of tress–diagram and steel bar quantity based on dynamic stress result of FEM

According to experiences and engineering analogy, positions and directions of the steel bars in the orifice of high arch dams can be known in advance. In current *Hydraulic Reinforced Concrete Structures Codes (DL/T5057-1996)*, the steel-bar quantity of arch-dam orifice can be calculated through the areas of principal-tensile-stress diagrams. In the paper *Application of Elastic Stress Reinforcement,* Chen Rujin pointed out that the direction of the principal tensile stress is always different from that of the steel bars, and thus the quantity of steel bars may not be calculated accurately through the areas of principal-tensile-stress diagrams. Therefore, he proposed the normal-stress diagram method [Chen Rujin, 2004].

Combining the code [Hydraulic Reinforced Concrete Structures Codes (DL/T5057-1996),1997] and the normal-stress diagram method, we calculated the tensile stress in the direction of steel-bar, computed out area A of tensile-stress diagram on the basis of the tensile stress depth of tensile bar control area, and calculated out the section area A_s of tensile bars according to the code. The formula is as following:

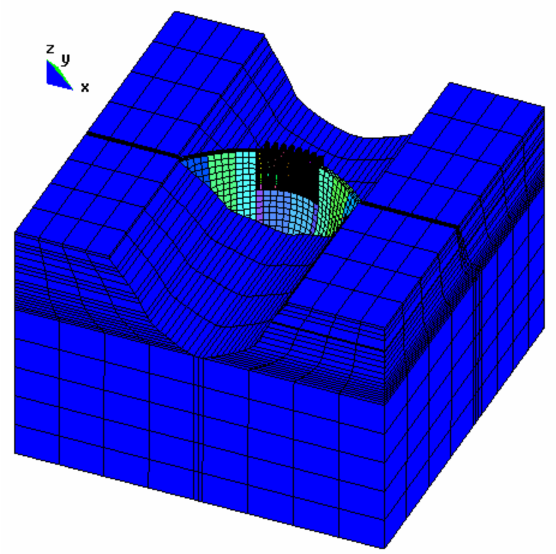
$$A_s = \frac{1}{f_y}\left(\gamma_d T - 0.6T_c\right) \tag{2.8}$$

Where T is the total elastic tensile force calculated from stress result computed by FEM, $T = Ab$,and A is the area of elastic-tensile-stress diagram, b is the width of structure section; T_c is the total force concrete bears, $T_c = A_{ct} b$, A_{ct} is area of the region where tensile-stress is small than f_t in the elastic- tensile-stress diagram, and f_t is the design value of direct tensile strength of concrete; f_y is the steel-bar tensile stress design value; γ_d is the structure coefficient of reinforced concrete structure,1.2.

3. NUMERCIAL EXAMPLE

3.1. Dynamic stress around orifice of high arch dam

This paper took the Xiluodu double curvature arch dam in feasibility research for example. With five joints, seven surface orifices and eight deep orifices, the dam is 278m in height and 332m in its base elevation. This paper took the 1#surface orifice as the substructure to be refined. The load in the dynamic calculation was composed of dead weight of the structure, water pressure (surface elevation of dead water level is 540m), and seismic load (duration time of the seismic wave is 10s, time step is 0.02s). The simulated earthquake wave was obtained based on hydraulic standard response spectrum. The material mechanical properties of the dam and the base adopted in the calculation are as following: the dam elastic modulus is 2.6×104MPa, the Poisson's ratio is 0.167, the bulk density is 25kN/m^3, the linear expansion coefficient is 1.0×10-5/℃, the Poisson's ratio of the base is 0.167.



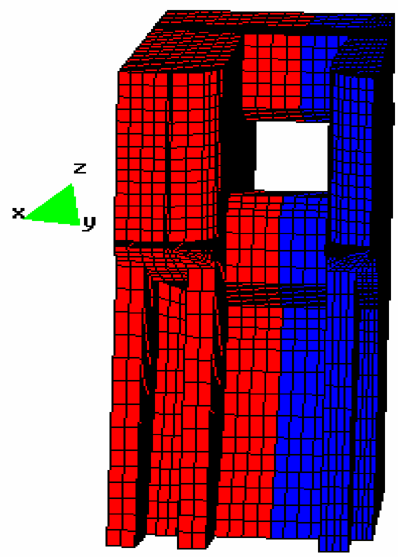


Figure 3.1 The whole structure FEM model   Figure 3.2 The substructure FEM model

Figure 3.1 shows the whole structure model with 19310 nodes and 13918 elements. While Figure 3.2 shows the substructure model with 21568 nodes and 17872 elements.

If the element size of the whole structure model was divided as small as that of the substructure model, the node number would surpass 100,000. Therefore, it is impossible to compute out all the freedoms through the LU decomposition method, which takes too much memory and time.

The dynamic stress results were obtained after the whole structure and the substructure calculations. Because we adopted time-history method, there were totally 500 steps of stress result.

3.2. Steel-bars quantity calculation from tensile-stress diagrams

The steel-bars distribution around the orifice of high arch dam is usually very complicated. According to the usual engineering practices, the orifice structure can be divided into different parts, such as piers in the entrance region, corbels of the entrance section, hole, piers in the outlet section, corbels of the outlet section, girder and so on. The steel-bar distribution forms of each part vary greatly, but they are all composed of radial steel bars, annular reinforcing steel bars and vertical steel bars. Taking the 1# surface orifice for example, this paper introduce the procedures of calculating the quantity of steel bars. The concrete tensile strength adopted in the numerical model is 1.4MPa, and the reinforcement tension strength is 310MPa.

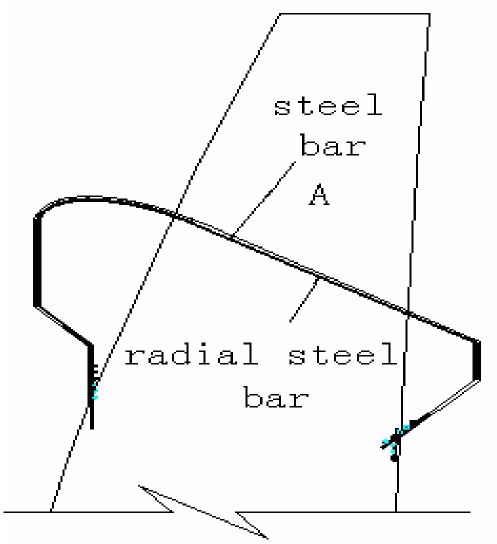


Figure 3.3 The radial steel bar distribution of 1# surface orifice

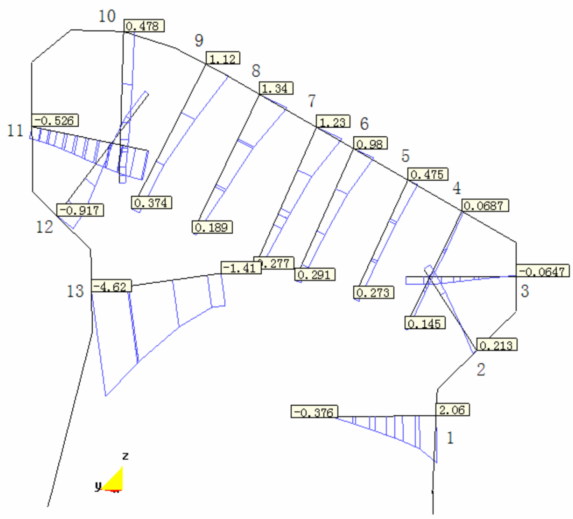


Figure 3.4 The tensile-stress diagram used to calculate the quantity of steel bar A

Table 3.1 Quantity calculation for steel bar A of 1# surface orifice

Position	Time step of dynamic load	Total pulling force	Cncrete bearing tension Tc(10^6N)	Area of rebar As(mm^2)	Maximum tensile stress (MPa)	Maximum compressive stress (MPa)	Maximum value of As (Position)
1	258	7.727	0	29911.438	2.058	-0.376	
2	269	0.261	0.078	858.369	0.181	-0.078	
3	258	1.818	0	7035.65	0.35	-0.065	
4	105	1.694	0	6556.132	0.215	0.088	
5	257	3.76	0	14554.423	0.506	0.263	
6	258	6.518	0	25231.582	0.98	0.291	
7	258	8.12	0	31431.533	1.234	0.277	34705.086 (8)
8	258	8.965	0	34705.086	1.337	0.189	
9	258	8.528	0	33011.488	1.119	0.374	
10	258	5.289	0	20474.242	0.478	0.283	
11	500	0	0	0	-0.359	-0.935	
12	258	0.811	0.243	2667.373	0.208	-0.917	
13	500	0	0	0	-1.104	-2.433	

The radial steel bars distribution of 1# surface orifice is shown in figure 3.3, those steel bars were named of steel bar A. In order to improve the accuracy of the quantity calculation of steel bar A, we chose 13 different positions along it, with considering their tensile stress depth, and the areas of tensile-stress diagrams were computed out for each of them. The tensile-stress diagrams for one step used in calculating the quantity of steel bar A is shown in figure 3.4. 500 steps of stress results were obtained from the dynamic time-history method, so there were 500 tensile-stress diagrams at one position. The largest one was picked out for the quantity calculation of the steel bar A. The results are shown in table 3.1.

Table1 indicates that in the width of one meter, the calculated quantities at the positions 1,5,6,7,8,9,10 are larger than those at other positions. That means more steel bars are needed at upper and middle sides of orifice overflow surface, and the lower side of corbel in the outlet section. The largest quantity is 34705.086mm^2, which means 36mm diameter steel bars will be distributed at 20cm intervals in 5 layers. The calculated quantity is too large.

In fact, the quantity was calculated through the areas of tensile-stress diagrams, which was got from elastic mechanics method. In this method, when the stress is beyond the concrete tensile strength, concrete is assumed to lose the ability to bear tensile stress, and the steel bars would undertake all the tensile force. It can be known that this assumption is conservative, and makes the calculated quantity more than needed [Chen Jin, Huang Wei and Ding Qian, 2000].Meanwhile, the dynamic stress was calculated by massless foundation method, which is a simplify method with its own defects, can also enlarge the dynamic stress. In our calculation we just considered the demand of tensile bearing capacity of steel bars but did not pay attention to section shear capacity, because the depth of the section is too large to get shear failure. In a word，the quantity calculated method is too conservative and needs further improvement.

4. CONCLUSIONS

In this paper, the dynamic substructure method is used in the research on orifice anti-seismic reinforcement for high arch dam, thus improving the accuracy of stress results. Given the steel bars distribution, the quantity of steel bars can be calculated out through diagrams of tensile-stress in the given direction. This method makes the relationship between the structure and steel bar clearer.

The result of steel bars quantity in this paper is calculated at ultimate capacity state through tensile-stress diagram. As the nonlinear working state of the structure has not been fully considered, the method just provides guarantee in strength. In order to get the final result of practical application, crack width and fracture shape at serviceability limit state must be computed, and steel bars quantity and distribution need to be optimized.

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