Seismic Performance of Non-overflow Gravity Dam Considering Dam-rock Coupling Effect

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Abstract—**Theoretical profile stress and displacement of a certain non-overflow gravity dam in a key water-control project was studied in this paper. Plane finite element method and dam-rock coupling effect were both considered. It is concluded that the tensile stress concentration was appeared at the heel and toe of dam, especially the dam heel with significant compression. Therefore, the former position is of great importance in the design. However, the stress is still less than the strength of dam concrete and foundation rock, which is means the seismic design of the non-overflow gravity is reasonable. Moreover, it is indicated that the dam-rock coupling effect will significantly affect the simulation results.**

Keywords-dam-rock coupling effect; plane finite element method; non-overflow gravity dam; seismic performance

I. INTRODUCTION

The non-overflow gravity dam means the dam without overflow. In most of the key gravity dam engineering, the overflow dam are always in the middle riverbed or main stream, and the non-overflow dams are in the both side, connecting to the bank and isolated by abutment pier and guide wall. The engineering background of this paper is the non-overflow gravity dam in Yunnan province, Nujiang drainage basin. The foundation is weak-weathered calcite dolomite and dolomite limestone. The width and height of dam is 5.0m and 34.5m separately with the top elevation EL.824.50m. The grade of upstream side is 90°, and the downstream side is 1:0.75. For the small cross section, C20 concrete (W8, F100, 3-grading）is adopted. The site of dam is located in the region of 7 degree seismic fortification intensity, where is the interface between 7 and 8 degree. The peak value of earthquake acceleration is 0.15g, predominant period is 0.3s. To guarantee the seismic safety, the non-overflow dam was numerical simulated by ANSYS based on plane finite element method. The deformation and stress distribution in different earthquake cases were studied, meanwhile, the weak parts were revealed according to the simulation results.

II. CALCULATION ASSUMPTION AND CASE SETTING

It is specified in the Chinese code [1] that: during the seismic calculation of non-overflow dam, only normal pool level is considered on the upstream water level, and the earthquake also only combine with the normal pool level situation. Only the earthquake along the river is considered. The seismic loads to be considered are earthquake inertia force, hydrodynamic pressure under lateral earthquake. Other acting forces such as the uplift pressure, silt pressure, dynamic earth pressure and hydrodynamic pressure under vertical earthquake are ignored. The representative value of hydrodynamic pressure under lateral earthquake can be converted to the corresponding added mass in the dam surface.

Two loading combination patterns were considered as follows: ① basic combination of normal pool level; ② accidental combination of earthquake and check flood. The basic combination is including dead weight of dam's concrete, static water pressure in both upstream and downstream and uplift pressure. In the accidental combination, earthquake action is composed of lateral earthquake and 2/3 vertical earthquake, along with the overall consideration of static and dynamic response.

III. PLAN FINITE ELEMENT SIMULATION ON THE NON-OVERFLOW DAM

A. Parameters and FEM model

FEM software ANSYS was adopted in this paper to simulate the non-overflow dam and its foundation. Firstly, the theoretical profile according to the self-weight, hydrostatic pressure and seepage pressure is modelled by ANSYS, which can satisfy the requirements of strength, stability, construction and economy. To accurately consider the dam-rock coupling effect and reflect the elastic dynamic effect of foundation, the foundation rock was modelled, and its dimension on upstream, downstream and depth are all set the value of twice height of the dam. Plane42 element in ANSYS was selected both in the dam concrete and foundation rock. The reversed added mass of hydrodynamic pressure was modelled by MASS21 element in ANSYS [2]. The material parameters are shown in the Table 1.

TABLE I. MATERIAL PARAMETERS IN THE ANSYS SIMULATION

Material	Elasticity modulus (Mpa)	Poisson's ratio	Density (Kg/m^3)	Dynamic compressive/tensile strength （Mpa）
concrete	2.55E+10	0.2	2450	8.93/1.67
rock	2.5E+09	0.28	2600	1.31/-

For the non-overflow dam is constructed by concrete, the following terms are regulated by current specification

in China [1]: in earthquake case, the dynamic modulus of elasticity and bearing capacity of concrete can be 30% increase compare to static case; the dynamic modulus of deformation and bearing capacity of rock can also be 30% increase compare to static parameters; Shearing strength for both earthquake and static cases are the same.

4-node plane strain element was chosen to simulate the dam and rock. A 2D FEM model was established, which is consist of a concrete gravity dam and a foundation 2 times higher than the dam. The boundary condition of the bottom and surroundings is defined as linkage constraints. The total quantity of FEM model is 6786 with 7012 joints. Concern to the coordinate system, along the river to the downstream is X axis positive, straight up is Y axis positive. In the ANSYS stress results, positive value is tensile stress, and negative value is pressure stress. The 2D ANSYS model is shown in Fig 1.
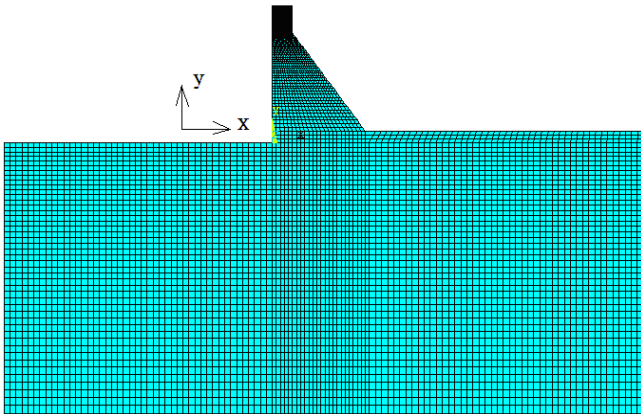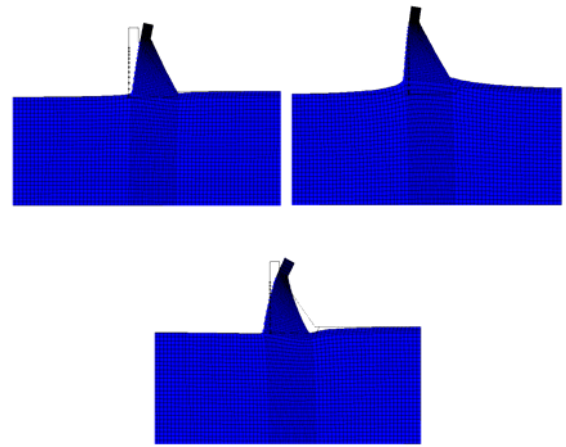

Figure 1. Plane finite element model of the non-overflow dam

B. Mode analysis results

According to the mode analysis results, low order frequency dominated the earthquake response of the non-overflow gravity dam. The effective mass ratio of first 3 orders reached up to 98.9%, whereas, the first 6 orders of modes were extracted in the spectral analysis. The results indicated that the mode shape conformed to the general rules, as shown in Fig.2. No adverse mode shape appeared. The natural frequency of reservoir full is less than the reservoir empty. The first 8 orders of nature frequencies were combined by SRSS method, which were listed in table 2.

TABLE II. FIRST 6 ORDERS NATURAL FREQUENCY OF THE NON-OVERFLOW DAM UNIT: HZ

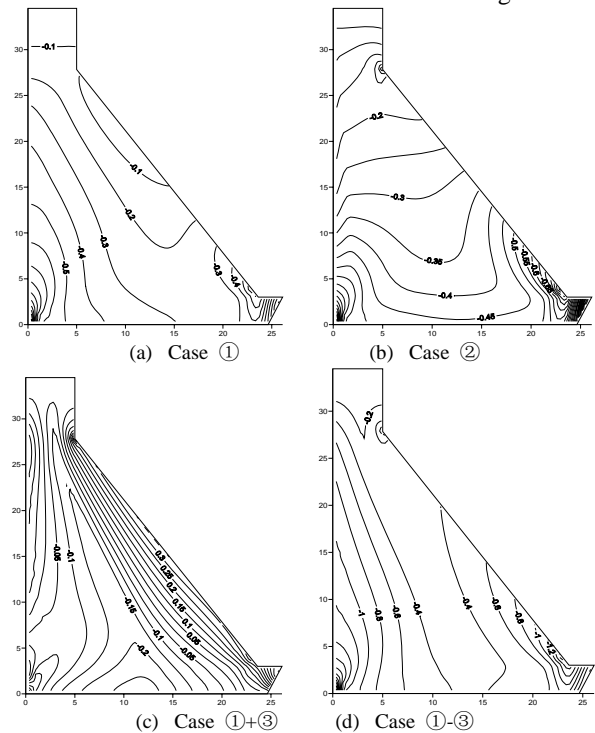| Mode	1	2	3	4	5	6
Full	4.1010	7.8714	11.069	24.011	43.928	45.759
Empty	4.6966	8.0209	12.579	25.862	48.825	54.582

| (a) First order | (b) Second order | (c) Third order |

Figure 2. First 3 orders of vibration modes

C. Stress results by ANSYS

Firstly, the stress distribution of normal pool level case (case ①) and check flood case (case ②) were studied. Then the static case of normal pool level was combined with the other two dynamic cases, such as frequently occurrence earthquake case (case ③) and rarely occurrence earthquake (case ④). The obtained contour lines of theoretical profile on stress distribution under above mentioned cases were demonstrated in Fig.3.
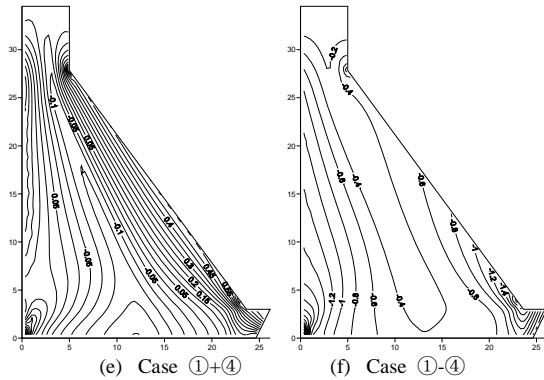

| (a) Case ① | (b) Case ② |
| (c) Case ①+③ | (d) Case ①-③ |

(e) Case ①+④   (f) Case ①-④

Figure 3.Von Mises of theoretical profile of the non-overflow gravity dam

By analyzing the Fig.3, the maximum stress and its position were listed in Table 3. It can be concluded that stress concentration appeared in the heel of upstream and toe of downstream, where need to be carefully pay attention to. Moreover, no maximum stress listed is exceeding the strength of concrete and rock listed in Table 1.

TABLE III. MAXIMUM AND POSITION OF VON MISES STRESS

UNIT: MPA

Case	Stress in the upstream		Stress in the downstream	
	maximum	position	maximum	position
①	-0.489	dam heel	-0.398	dam toe
②	-0.631	dam heel	-0.528	dam toe
①+③	0.334	dam heel	0.470	dam toe
①-③	-1.099	dam heel	-0.955	dam toe
①+④	0.493	dam heel	0.626	dam toe
①-④	-1.301	dam heel	-1.148	dam toe

D. Displacement results by ANSYS

Displacement of the non-overflow dam was listed in Table 4. The maximal displacement along the river appeared at the upstream dam heel, and the maximal vertical displacement is at upstream dam top. This conclusion seems strange. It will be explained in next section.

TABLE IV. SUMMERY OF MAXIMAL DISPLACEMENT   UNIT: MM

CASE	Along the river		Vertical	
	maximum	position	maximum	position
①	1.32	Heel upstream	-3.04	Top upstream
②	2.14	Top downstream	-2.35	Toe upstream
①±③	9.37	Top downstream	-6.06	Top upstream
①±④	12.19	Heel upstream	-7.07	Toe upstream

IV. INFLUENCE ON ANSYS RESULTS BY DAM-ROCK COUPLING EFFECT

It is indicated that the value of rock elasticity modulus may affect the displacement significantly. Take the results of case① as example. When the rock elasticity modulus valued as infinity, which means that the boundary condition was treated as completely rigid constraint without considering the dam-rock coupling effects, the maximal displacement along the river appeared at the top of dam with the value of 0.49mm and the vertical displacement of dam top was 0.14mm , and no displacement at the dam heel, shown as Fig.4(a). However, when the dam-rock coupling effects was considered, and the rock elasticity modulus valued as 2.9Gpa, the maximal displacement along the river appeared at dam heel with the value of 1.32mm, and the maximal displacement along the river at the dam top was 0.52mm. The vertical displacement at the dam heel was -2.93mm, and the value at dam top was -0.34mm, as shown in Fig.4(b). According to the above results, it is concluded that the rock elasticity modulus significantly affect the dam top displacement in the direction of along the river and vertical, but no noticeable influence on the displacement of dam heel along river direction. Therefore, all the obtained displacements in ANSYS were global. Because the heel displacement along the river is more than the dam top, makes it seem to incline to the back of dam.
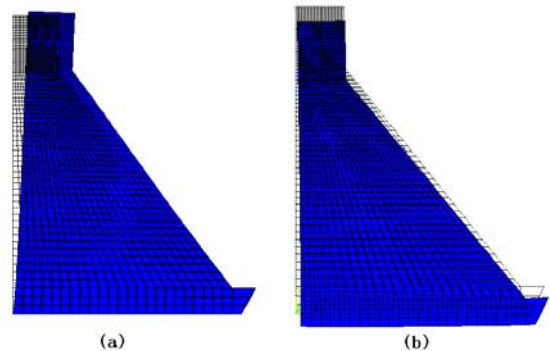

(a)   (b)

Figure 4. Dam displacement under different rock elasticity modulus

V.CONCLUSIONS

According to the numerical simulation results, adverse stress state may appear in the non-overflow dam during earthquake. Noticeable stress concentration may occur in dam heel, dam toe and toe corners, especially tensile stress. After the combination of static and dynamic response, the displacement was not enough to cause the dam leakage. By considering all kinds of cases and dam-rock coupled effect, the maximal Von Mises stress was still in safe range.

VI. ACKNOWLEDGEMENTS

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