Research of Non-linear 2.5D Fluid-structure Interaction Model of Gravity Dam

Yiran Li 1,2, Menghua Xu 2,* , Hao Sun 2

1Hunan Province Key Laboratory of Key Technologies for Water Power Resources Development, Changsha, China.
2School of Civil engineering and Transportation, South China University of Technology, Guangzhou, China

*Corresponding author e-mail: mhxu@scut.edu.cn

Abstract. Aseismic safety of dam involves people’s lives and properties, even has a great impact on national economic development. The key to this project is to have a fairly complete fluid-structure interaction (FSI) theory and a calculation method with a good accuracy. Therefore, focused on the FSI dynamic problem of gravity dam under seismic action, this paper presented the non-linear 2.5D dynamic theoretical model of concrete gravity dam established by segmenting fluid model and numerical solution method, compared the numerical simulation result under preliminary gravity action with 3D model. The study showed that the 2.5D dynamic calculation model could well reflect the seismic dynamic FSI behavior and effect of concrete gravity dam in the respects of displacement and stress and benefited the large-scale non-linear 3D aseismic calculation of gravity dam because of the effective reduction of 3D FSI numerical calculation time, which improved the calculation efficiency.

1. Introduction

Violent earthquakes often happen to China. When large engineering structures suffer an intense earthquake, it will cause not only direct engineering loss, but also secondary disasters what are hard to expect and threat to people’s lives and properties, even a great impact on national economic development. So higher requirement for critical engineering and lifeline engineering is necessary. The key to this project is to have a fairly complete FSI theory and a calculation method with a good accuracy. Since H.M.Westergaard published his famous paper Water pressure on dams during earthquakes, it has caught many researches’ attention for a long time, because of the significance of this project in engineering practice.

FEM applied to solving FSI problem is presented first in The finite element method, a noted book by iZeknieMcz[1]. After developing from low level to high level and simplicity to complexity, FEM is extensively and profoundly practical in engineering projects, as the most efficient analytic method. According to FSI research project, large finite element software is usually used to build theoretical models and do simulation calculation and analysis, where the adopted models are most 2D and 3D models. Ghaedi[2] builds 2D model to analyze the concrete dam under seismic action. And Puigdellivol[3] also builds a 2D model to study a topology optimization method for laminated busbars in power converters and he points out that Comparison with 3D FEM proves the 2-D approach to be
faster while remaining accurate and a perfect method. However, it is obvious that considering the complexity of large engineering projects like dam, there are too many factors what should be taken into account that 2D theoretical model cannot meet the accuracy requirement. In Crosta’ [4] study about collapse and rockslide–reservoir interaction, a fully 3D rockslide–water reservoir simulation has been considered to provide a more realistic simulation. But 3D simulation calculation of large engineering has a high requirement for computer and that will takes a long time, which greatly decreases the calculation efficiency. However, 2.5D simulation calculation can increase the accuracy and efficiency of calculation at the same time. This 2.5D theory has extensive application and research in many fields. But at present, the research of 2.5D theory in hydraulic engineering is mainly about large aqueduct [4], little attention is paid to gravity dam. However, finding a rational and effective FSI dynamic calculation methods is of great significance to the large-scale seismic dynamic analysis of gravity dam.

Therefore, the main objectives of this study are (1) to present a 2.5D fluid-structure interaction dynamic model of gravity dam, (2) to compare the calculation results in non-linear numerical test method with 3D model to verify the feasibility, rationality and accuracy of 2.5D simulation, and(3) to discuss how to build a 2.5D model with the best simulation.

2. Case study

2.1. Concept of 2.5D Numerical Models of Gravity Dam
The FSI 2.5D theory means that the model is consist of 3D solid structure and 2D fluid structure, where 2D fluid structure simulates the FSI effect between structure and fluid. Structure part is the system of 3D dam body-2D dam shells, fluid part is 2D fluid coupling with 2D dam shells, FSI effect is transferred by the interaction between 2D fluid and 2D dam body completely consolidated with 3D dam body. The model concept is shown in Figure 1.

![Figure 1](image)

**Figure 1** The concept of 2.5D model

2.2. Introduction of studied dam
Because the practical application of the 2.5D theory in gravity dam has not been studied at all and this paper is mainly focused on the feasibility, rationality and accuracy when 2.5D theory is used to solve problems of gravity dam, a geometrically simple gravity dam under a comparatively ideal circumstance was simulated and analyzed.

The concrete dam is 120m high with upstream slope vertical, downstream slope gradient 0.75, crest dam 1.5 times the length of dam height and 0.1 times the breadth of dam height. Dam body of gravity dam uses homogeneous concrete material whose elastic modulus of concrete $E$ equals $2.85 \times 10^8$ Pa, Poisson’s ratio $\nu$ equals 0.15, density $d$ equals 2600 Kg/m$^3$, tensile strength $f_t$ equals $1.96 \times 10^6$ Pa and compressive strength $f_c$ equals $22 \times 10^6$ Pa.
Fluid uses water adopting laminar flow model whose parameters are shown as follows: density equals 1000 Kg/m³, viscous coefficient equals 0.002(Pa·s), bulk elastic modulus equals 0.002(Pa·s), and the fluid is set as incompressible liquid with the height of 108 m and the length of 240 m.

2.3. The finite element model
This paper adopted the large finite element software ADINA to accomplish numerical solution. With regard to concrete gravity dam, the adopted numerical solution characteristics of FSI 2.5D theoretical model was as follows:

the 3D solid elements were applied to dam body structure which was set gravity and Rayleigh damping;
the 2D solid elements were applied to fluid whose amount and location of 2D shells corresponded with 2D dam shells, and the model was built with top surface as free surface, surface contacting dam as FSI surface, surface on the inverse side as uniform surface and bottom surface as wall surface;
the material of 2D dam shells is linear elastic material with no rigidity to avoid impacting the rigidity of dam body and at the same time contribute to transfer the action of fluid for dam body, 2D dam shells are completely consolidated with 3D dam body, plane-strain model is adopted, calculated length of each dam shell equals to the width of the 3D solid dam body.

This paper respectively established three 2.5D model with 6, 12, 24 shells. The calculation results of 2.5D models were all compared with 3D model. The 2.5D model with 6 shells is shown in Figure.2 (2.5D models with 12 and 24 shells only had more equally spaced shells; 3D model had the same parameter set as 2.5D models):

![Figure.2 The 2.5D model with 6 shells](image)

The test picked up the displacement data of points A, B, C, D, E on upstream sideline of dam crest and stress data of points F, G, H, I, J on upstream sideline of dam bottom and points K, L, M, N, O on downstream sideline of dam bottom to compare. The positions of these points are shown in Figure.3.
3. Results analysis and discussion

3.1. Displacement data comparison of points on upstream sideline of dam crest

As is shown in below charts, Figure 4 shows the displacement data comparison of point B and C in static response analysis, and Table 1 shows the comparison of maximum error values of stable data.

![Figure 4](image)

**Figure 4** The comparison of static displacement process lines of point B

| Point  | A     | B     | C     | D     | E     |
|--------|-------|-------|-------|-------|-------|
| 6 shells | 11.09% | 11.16% | 11.13% | 11.16% | 11.09% |
| 12 shells | 0.47%  | 0.46%  | 0.46%  | 0.46%  | 0.47%  |
| 24 piece  | 0.08%  | 0.08%  | 0.07%  | 0.08%  | 0.08%  |

Under the only action of gravity, calculation models did not reach a stable with calculation time less than 0.5s, and the data of the 0.5s do not have research value. So Table 1. Shows the comparison of maximum error values of displacement data without the first 0.5s, and all the below comparison only picks the stable calculated data like here.

As in depicted in Figure 4, displacement data of 2.5D models with 12 and 24 shells are similar to 3D model in trend and numerical value, but that of model with 6 shells have similar trend with obvious difference in numerical value. Table 1 shows that maximum error value is decreasing gradually with 2D shells in 2.5D model increasing, and the errors in the models with 12 and 24 shells are far less than the model with 6 shells.
It can be concluded that under gravity, the 2.5D model with more 2D shells will simulate better 3D model in displacement data on upstream sideline of dam crest.

3.2. Stress data comparison of points on downstream sideline of dam bottom
As is shown in below charts, Figure 5 shows the displacement data comparison of point M (a) and L (b) in static response analysis, and Table 2 shows the comparison of maximum error values of stable data.

![Figure 5](image)

**Figure 5** The comparison of static stress process lines of point M

| Point  | K  | L  | M  | N  | O  |
|-------|----|----|----|----|----|
| 6 shells | 6.27% | 37.51% | 6.27% | 37.51% | 6.27% |
| 12 shells | 0.02% | 0.02% | 0.02% | 0.02% | 0.02% |
| 24 shells | 0.02% | 0.02% | 0.02% | 0.02% | 0.02% |

As is depicted in Figure 5, the models with 12 and 24 shells simulate well with 3D model in stress data, but there is a great difference between the model with 6 shells and 3D model; Table 2 shows that errors of the models with 12 and 24 are far less than the model with 6 shell where errors of models with 12 and 24 shells are very close to each other; as for the model with 6 shells, data errors of points L and N are bigger than the others.

It can be concluded that under gravity, the 2.5D model with more 2D shells will simulate better 3D model in stress data on downstream sideline of dam bottom. And that Points L and N have bigger errors than the other points in the model with 6 shells is because points L and N are located on the 2D dam shells and then directly participate in the transfer of FSI effect.

3.3. Stress data comparison of points on upstream sideline of dam bottom
As is shown in below charts, Figure 6 shows the displacement data comparison of point H and G in static response analysis, and Table 3 shows the comparison of maximum error values of stable data.
Figure 6 The comparison of static stress process lines of point H.

| Point | F   | G   | H   | I   | J   |
|-------|-----|-----|-----|-----|-----|
| 6 shells | 30.86% | 16.24% | 30.86% | 16.24% | 30.86% |
| 12 shells | 21.74% | 21.74% | 21.74% | 21.74% | 21.74% |
| 24 shells | 7.79% | 7.79% | 7.79% | 7.79% | 7.79% |

It can be seen from Figure 6 (a) that under gravity, the 2.5D model with more 2D shells simulates better 3D model in stress data on upstream sideline of dam bottom and the data process lines have the same trend; Table 3 also shows that error values of the models with 6 to 24 shells are decreasing gradually. But as is depicted in Figure 6 (b) and Table 3, point G has a different performance from point H that process line of the model with 6 shells is above the others and maximum error value obviously decreases. The reason why this happened is the same to what causes the performance of Table 2, which is that point G is located on the 2D dam shell. However, this time it makes the error decrease.

It can be concluded that under gravity, the 2.5D model with more 2D shells will simulate better 3D model in stress data on upstream sideline of dam bottom. As for the reason why point G and I in the model with 6 shells have less errors, this paper suggests that when the stress condition of points on fluid of 2.5D model is similar to 3D model, the corresponding points on dam body directly respond to the force similar to that from 3D fluid model, then the stress data is closer to that by 3D model; for the points on downstream sideline of dam bottom, they are not in direct contact with fluid, which is why their errors are bigger.

4. Conclusion
This paper presented a 2.5D fluid-structure interaction dynamic model of gravity dam and compared the calculation results in non-linear numerical test method with 3D model to verify the feasibility, rationality and accuracy of 2.5D simulation. After the comparison and analysis, conclusions are shown as follows:

1. 2.5D FSI model of concrete dam simulates well 3D model in respects of displacement on upstream sideline of dam crest and stress on upstream and downstream sidelines of dam bottom;
2. 2.5D model with 24 shells has the best simulation effect in displacement and stress, which shows that under static condition, more 2D shells to transfer FSI will make numerical test results closer to that by 3D model.
3. As for the special points on 2D shells, the data error of displacement on the upstream sideline of dam crest are similar to the others, that of stress on the downstream sideline of dam bottom are bigger and on the upstream sideline of dam bottom, the data error of stress are smaller than the others, which is because of the local stress concentration.

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