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Numerical Investigations of Dam-break Flow Impacting on Elastic Barrier Based on CFD-FEM Method

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ABSTRACT

In severe sea conditions, ships often encounter the phenomena of green water and slamming. These phenomena can often be verified and studied numerically through some simplified problems with similar fundamental flow behaviors, such as dam-break problem. The flow characteristics of dam-break is similar to that on hull deck. The unsteady flows with strong nonlinear characteristic can easily make structural damage. Therefore, structural elasticity effect shall be taken into account in such problems.

In the present work, a fluid-structure coupling solution strategy based on CFD-FEM method is proposed to study the interaction of a three dimensional dam-break flow and a vertical rectangular column. Fluid field is solved by RANS method, and structural response is solved by Newmark method. Based on the dynamic mesh updating strategy in OpenFOAM, the two-way fluid structure interaction (FSI) simulation is realized. Both rigid barrier and elastic one are studied and the results are compared with experimental and numerical results. Results show that the proposed method and developed program are capable of providing reasonable and accurate numerical results for the FSI problem. The effect of barrier stiffness on structural responses and fluid pressure is also discussed.

KEY WORDS: Fluid-structure interaction, dam-break flow, elastic barrier, CFD-FEM method

INTRODUCTION

In marine and coastal engineering, the problems of wave slamming on structures are very common engineering phenomena. In severe sea conditions, ships often encounter the phenomena of green water and slamming. In coastal engineering, it's crucial to verify structural safety of coastal lighthouses under wave impact. These phenomena can often be verified and studied theoretically and numerically through some simplified problems with similar fundamental flow characteristic, such as dam-break problem. Faltinsen and Greco have concluded that there are two main types of water-on-deck scenarios in marine engineering. One type is dam-break type (type DB), and the other one type is plunging wave type (type PW). And they have studied and concluded that the former type, DB-type, is more common to happen (Faltinsen, 2005, Greco et al., 2007). Many researchers have studied model experiments and numerical simulations about the interactions between dam-break flow and simplified structure. Besides, the elasticity of structure has been more and more considered into the interaction research to study its influence.

In studies of interactions between dam-break flow and structures, vertical wall and square columns are usually set downstream. Experimental studies have been carried out on both dam-break flow conditions, and the measured results have been widely used as standard model comparison data for numerical algorithm validation and solver development (Liao et al., 2015, Bogaers et al., 2016, Martínez-Ferrer et al., 2018, Rakhsha et al., 2019, Sun et al., 2021, Yilmaz et al., 2021, Brown et al., 2022, McLoone and Quinlan, 2022, Hu et al., 2023). Slamming of three-dimensional dam-break flow acting on column is a typical case to study the interaction between nonlinear flow and structures. It includes free surface evolution and breaking, climbing and beating on structures, as well as vibration and deformation of structures in the phenomenon. It is crucial to accurately predict impact load and describe the fluid-structure interaction for evaluating structural safety.

Gesteira, Arnason and Raad examined the problem of dam-break flow impacting on structures of circular columns and square columns. In the experiment, water level, flow velocities, structure forces have been measured, which has provided rich data for validations and verifications of numerical simulations (Gesteira and Dalrymple, 2004, Arnason, 2005, Raad and Bidoae, 2005). Gesteira tested the accuracy and efficiency of developed program SPHysics with the help of experiment data (Gesteira et al., 2012). Based on smoothed particle hydrodynamic (SPH) method, Cummins studied the effect of different initial and boundary conditions and numerical parameters on the column load (Cummins et al., 2012). Barreiro validated a SPH code, DualSPHysics, with analytical and experimental data to show the reliability, accuracy and efficiency of program (Barreiro et al., 2013). Meng studied silted-up dam-break flow by coupling kinetic particle theory and computational fluid dynamics (CFD). Front propagation, free surface deformation, sediment movement, dynamic pressure loads and sediment deposition are studied (Meng et al., 2013). In the above studies, the square column is considered as rigid structure. Some researchers have also studied the effect of structural elasticity towards column pressure loads and deformation characters.

Lee validated the developed code by dam-break case and studied the effects of parametric settings on SPH method (Lee and Hong, 2020). Liu proposed a DEM-SPH model to analyze the interaction between irregularly shaped granular materials and fluids, and validate the model by dam-break case with a square column downstream (Liu et al., 2022).

In this paper, the problem of dam-break flow impacting on a square column is studied by CFD-FEM method. The solid solver is a self-developed FEM solver based on Euler-Bernoulli beam model. And in the present work, we coupled interFoam solver, one of OpenFOAM solvers to calculate problems with multiphase flow, and the developed FEM solver to simulate this 2D FSI dam-break problem. Two-way FSI simulation is realized, and both rigid and elastic columns are studied. The results are compared with previously published data to analyze the validity of developed program. The effect of column stiffness on structural vibration responses and fluid pressure load is also discussed.

THE MATHEMATICAL FORMULATIONS

Turbulence Model

In the simulation, the flow is assumed as incompressible, continuity equation and momentum equation of the flow field adopts Reynolds average equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[v\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] - \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

Reynolds stress term, $\tau_{ij} = \rho \overline{u_i' u_j'}$, represents turbulence effect. Reynolds stress tensor is assumed as a linear function of the mean velocity gradients:

$$\tau_{ij} = \rho \overline{u_i' u_j'} = -\mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3}\left(\rho k + \mu_t \frac{\partial \bar{u}_i}{\partial x_i} \right)\delta_{ij} \tag{3}$$

where k is turbulent kinetic energy term. It is necessary to introduce a suitable turbulence model to determine the turbulence viscosity coefficient μ_t , so that the equations can be closed. The shear stress transport (SST) $k-\omega$ model is adopted in this study. This kind of turbulence model has the advantages of wide application range, high precision.

Newmark Method

The structure is modelled as a cantilever beam. According to the theory of FEM, structural dynamics equation is:

$$M\ddot{x} + C\dot{x} + Kx = F(t) \tag{4}$$

$$C = \alpha_1 M + \alpha_2 K \tag{5}$$

where *M*, *C*, *K* and *F(t)* represent mass matrix, damping matrix, stiffness matrix and load vector respectively. In this paper, damping matrix adopts the form of Rayleigh damping matrix, α_1 and α_2 are Rayleigh damping coefficients. x , $\dot{x}$ and $\ddot{x}$ are generalized displacement, velocity and acceleration vectors respectively, containing linear and angular deformation.

Newmark method (Newmark, 1959) is used to solve the structural dynamic equations. It assumes that the velocity and displacement vectors at time step *i+1* take the forms of:

$$\dot{x}_{i+1} = \dot{x}_i + [(1-\gamma)\ddot{x}_i + \gamma \ddot{x}_{i+1}] \tag{6}$$

$$x_{i+1} = x_i + \dot{x}_i \Delta t + [(0.5-\beta)\ddot{x}_i + \beta \ddot{x}_{i+1}]\Delta t^2 \tag{7}$$

The deformation at time step *i+1* can be calculated by the displacement, velocity, acceleration vector at time step *i* and other known quantities:

$$K^* x_{i+1} = F_{i+1}^* \tag{8}$$

$$K^* = K + \frac{1}{\beta(\Delta t)^2} M + \left(\frac{\gamma}{\beta(\Delta t)} \right) C \tag{9}$$

$$F_{i+1}^* = F_{i+1} + CoeffM \times M + CoeffC \times C \tag{10}$$

$$CoeffM = \frac{1}{\beta(\Delta t)^2} x_i + \frac{1}{\beta(\Delta t)} \dot{x}_i + \left(\frac{1}{2\beta} - 1 \right) \ddot{x}_i \tag{11}$$

$$CoeffC = \frac{\gamma}{\beta(\Delta t)} x_i + \left(\frac{\gamma}{\beta} - 1 \right) \dot{x}_i + \frac{\Delta t}{2}\left(\frac{\gamma}{\beta} - 2 \right) \ddot{x}_i \tag{12}$$

The constant parameters β and γ are crucial for computational stability. In this study, we choose $\beta = 0.25$ and $\gamma = 0.5$ to make the simulation unconditional stable.

Fluid Structure Interaction Method

The fluid structure interaction method adopted in this paper is two-way coupling method. Firstly, topoSet tool in OpenFOAM is used to extract the cantilever beam surface mesh of different FEM elements. Force integration of fluid meshes is carried out to obtain the concentrated force acting on each FEM element. Then, the concentrated force is transformed as distributed load to calculate structural deformation. This procedure is shown in Figure 1.

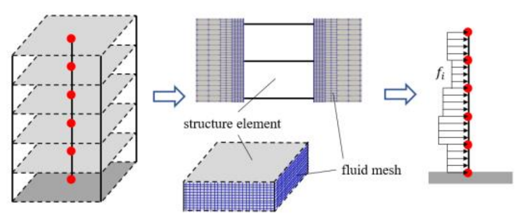


Fig. 1 Fluid structure coupling process

After obtaining deformations at each FEM node, the cubic spline function interpolation is adopted to calculate deformations of boundary fluid mesh points. Finally, the displacementLaplacian solver in OpenFOAM is used to calculate the whole update of fluid mesh. Figure 2 illuminates this procedure. To consider the angular deformation influence, the update of boundary mesh points in fluid field is calculated as:

$$x_{new} = x_{old} + \Delta x(1-\cos\theta_i) \tag{13}$$

$$y_{new} = y_{old} + \Delta y(1-\cos\theta_j) \tag{14}$$

$$z_{new} = z_{old} - \Delta x \sin\theta_i - \Delta y \sin\theta_j \tag{15}$$

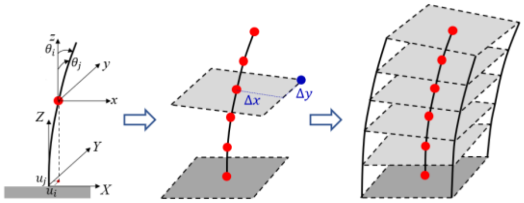


Fig. 2 Fluid structure coupling process

The flow chart of the above process is as shown in Figure 3.

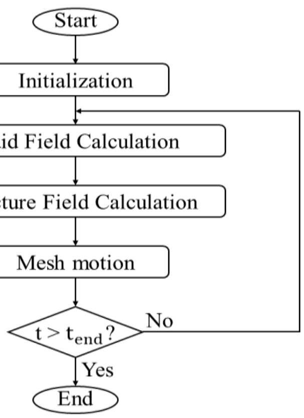


Fig. 3 Fluid structure coupling process

NUMERICAL SETUP

Geometric Models

The dam-break experiment was carried out by Gesteira at the University of Washington (Gesteira and Dalrymple, 2004). The rectangular tank is 1.6 m long, 0.61 m wide, and 0.75 m high. The volume of water (0.4 m long, 0.61 m wide, and 0.3 m high) is initially contained. The structure, which is 0.12 m × 0.12 m × 0.75 m, is placed 0.9 m from one end of the tank. As it's impossible to completely drain the tank downstream of the gate in the experiment, a thin layer of water (0.01 m deep) is present on the bottom of the tank, as shown in Figure 4. The Young's modulus of structure is $E_s = 3.1\times10^9$ N/m^2, density $\rho_s = 1190$ kg/m^2. Main parameter settings are shown in Table 1.

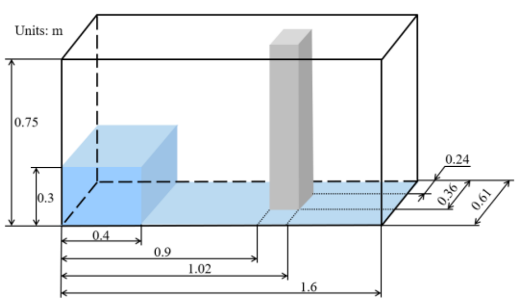


Fig. 4 Schematic diagram of the numerical dam-break tank

Table 1. The computational parameter settings

Parameters	Value
Water density	1000 kg/m^3
Kinematic viscosity	1×10^{-6} m^2/s
Gravity acceleration	9.81 m/s^2
Structure density	1190 kg/m^3
Time step	1×10^{-3} s
Simulation time	3 s

Computational Domain Setup

Computational domain settings are consistent with geometric models, except the height of computational domain. In order to calculate structural deflection, the computational domain is set 0.9 m high to make sure enough fluid meshes to have structural deformation. The numerical domain is discretized into unstructured grid. Additional refinement is prepared for accurate calculation of pressure integration, as shown in Figure 5. The total mesh number is 6.7×10^5.

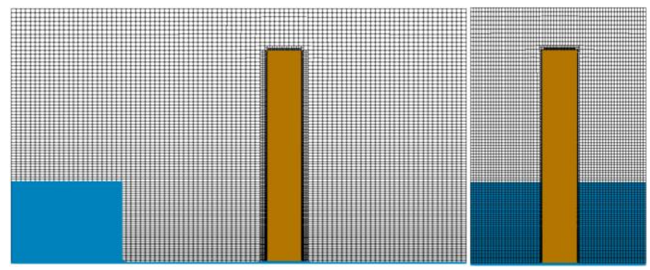


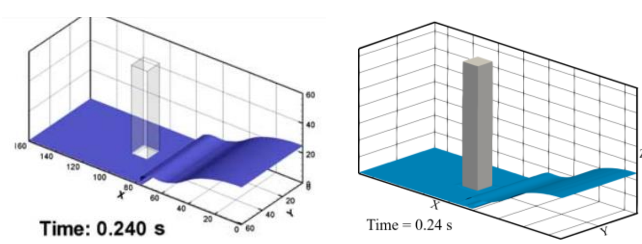
Fig. 5 Mesh section of computational domain

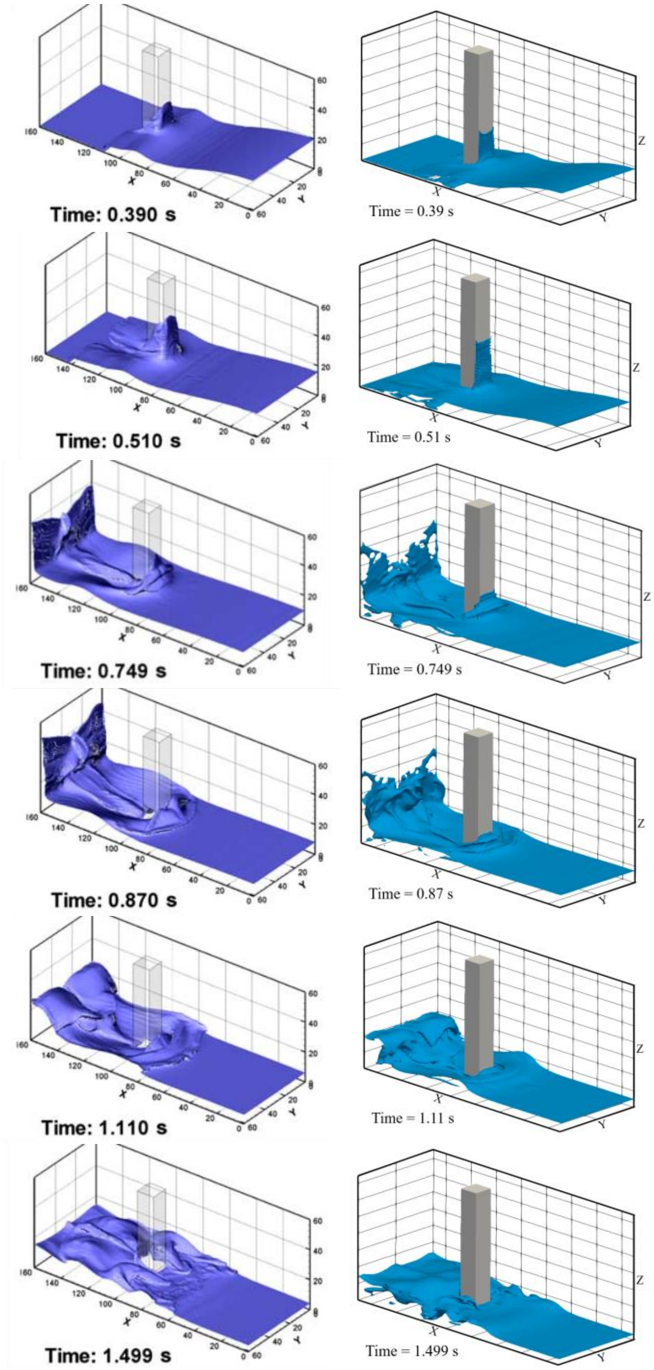
RESULTS AND DISCUSSIONS

Comparison Between Simulation and Experiment

In addition to the dam-break experiment, Gesteira also carried out numerical simulations to study the accuracy and efficiency of new proposed method to solve incompressible free surface fluid flow problems (Gesteira and Dalrymple, 2004). In this paper, some simulation snapshots are selected and compared with the results of Gesteira's studies.

Figure 6 shows that both researches can accurately describe the evolution and development of dam-break flow. The frame at t = 0.24 s, due to the presence of a thin layer of water downstream, it shows a clear rising leading edge of the dam-break flow, which is different from dry bottom dam-break characteristics. At t = 0.39 s, dam-break flow impacts on the structure, climbs along the column and the flow wraps around the column. The flow is separated by column, moves toward the vertical tank wall and impacts on it. Then, the dam-break flow turns its direction and impacts the square column again. This procedure is similar with that in the experiments and Gesteira's simulations.

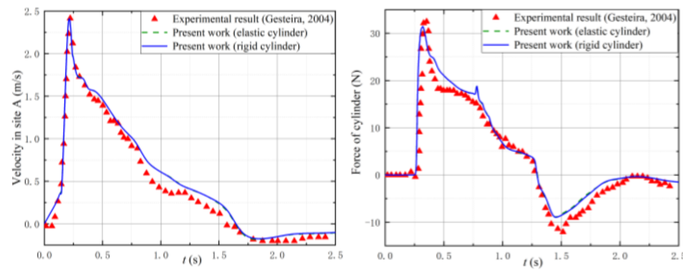




(a) Gesteira's work (b) present work

Fig. 6 Comparion of simulation snapshots of dam break on square column

In the experiment, time histories of both the net force on the structure and the dam-break flow velocity are measured. The velocity measurement is performed at 0.146 m upstream of the structure center and 0.026 m off the tank bottom. Figure 7 shows the comparison of the horizontal velocity and the impact force on the column between simulation and experimental results. The beginning of time history is translated to compare flow velocity and impact force changes between the peak and the slamming process. Data of flow velocity and impact force of elastic cylinder's case is smoothed for comparison. The results achieve satisfactory agreement. The amplitude of slamming force increases suddenly around t = 0.38s, and declines rapidly after an instantaneous pressure peak, which reflects the typical slamming characteristics. Besides, in this study, we considered the effect of structure elasticity. However, as the Young's modulus of structure in experiment is pretty high, the maximum deformation of structure is smaller than 1.2×10^{-6} m. Therefore, the structure can be seen as rigid column without leading to obvious calculation error, as shown in Figure 7. But when analyzing structural response, it becomes clear that whether elasticity is taken into account does make some effect, as shown in Figure 8.



(a) flow velocity in site A (b) impact force on the column

Fig. 7 Time histories of collected data in dam-break flow impacting on square column and comparisons with published experimental results

Effect of Structural Elasticity

Figure 8 shows the time history of column's top vibration with elasticity and without structural elasticity given in the experiment. Rigid column is realized by setting an extreme large value to the Young's modulus in the solver. It can be seen that the elastic column expresses violent high-frequency vibration under the action of slamming load. The shape of time histories of column's top displacement is roughly the same as that of impact load of the structure. The difference is that time history of column deformation displacement shows two high peaks. And the second peak at t = 0.75s is higher than the first one. The explanation for this phenomenon is that the second peak contains the influence of column's inertia.

When the first pressure load peak impacts on the structure, a large displacement and acceleration will be generated to have a deformation, which leads to the first displacement peak. Then, under the action of elastic force, the structure tends to return back to the initial position, but the continuously high level of impact load on the root of the column keeps the root bending. When the influence of root is transmits to the top free end, the partly released elastic force cannot resist the action of the inertia force. Thus, a larger peak will be formed after the former one. This process implies a greater accumulation of elastic potential energy. So when this energy is released, the top end of the column will return back to the initial position much faster than that after the first peak.

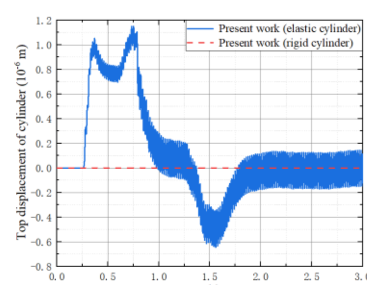


Fig. 8 Time history of top displacement of the elastic column, compared

with the rigid one

Three other elastic columns have been calculated of the interaction with dam-break flow. The Young's modulus of the columns are 3.1×10^8 N/m^2, 3.1×10^7 N/m^2 and 3.1×10^6 N/m^2 respectively. Both force of column and top displacement have been measured. Figure 9 shows the time histories of column force with four different Young's modulus. Obviously, the forces impact on the column with different elasticity are similar on the whole, which may be because the rigidity of the structure is still a large quantity compared to the slamming load. However, at two detail positions (circled in red), the force time history of column with different elasticity are obviously different. More elastic columns experience slightly larger peak of force and a smoother process over time. The former phenomenon may be related to the inertia of the column, while the latter one maybe because of the change of structural vibration from small high-frequency vibration to large low-frequency vibration with the increase of structural elasticity. As a result, the interactions between structure and dam-break flow become smoother. So, the impact force is reduced and the slamming load peak becomes less obvious.

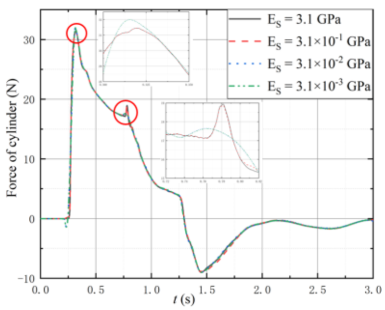
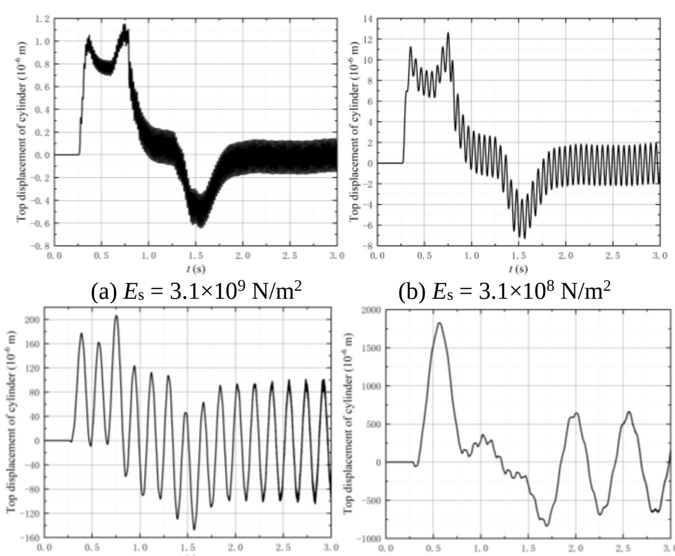


Fig. 9 Time history of cubic column force with different Young's modulus

Figure 10 shows the time histories of column top displacement with four different Young's modulus. It can be seen that although different structural elasticity has little effect on impact load, the vibration form of the structure becomes very different.



(a) $E_s = 3.1\times10^9$ N/m^2 (b) $E_s = 3.1\times10^8$ N/m^2

(c) $E_s = 3.1\times10^7$ N/m^2 (d) $E_s = 3.1\times10^6$ N/m^2

Fig. 10 Time history of top displacement of four elastic columns with different Young's modulus

With the increase of structural elasticity, the vibration frequency of column decreases significantly, and the vibration of structure transits from high-frequency vibration to low-frequency vibration. In addition, the amplitude of the structure gradually increases with the column elasticity decreasing as a similar proportion. For every magnitude decrease in elasticity, the amplitude of vibration increases by one magnitude. Lower vibration frequency shows a closer coupling between structure and dam-break flow. The structure becomes more and more compliant with the changes of the flow field, changing from elasticity to flexibility.

CONCLUSIONS

In this paper, a CFD-FEM solver is developed to simulate the problem of dam-break flow impacting on a square column. Numerical results are validated with experimental data to show the reliability and accuracy of the developed solver. The effect of structural elasticity towards impact load and column top displacement has been studied. The main conclusions of this paper are as follows:

From the aspect of impact load, as the rigidity of structures is usually high, deformation of structural is pretty small. In this situation, the structure can be simplified as rigid bodies with enough accuracy. It is reasonable to treat structures as rigid bodies when studying the external loads of structures.

From the aspect of structural response, material elasticity cannot be ignored. Structural elasticity is crucial for the dynamic response and construction safety. In this study, with the decrease of structural elasticity, vibration frequency of column decreases significantly while the vibration amplitude increases much, which may bring the risk of structural damage.

In the future, more benchmarks of FSI problems will be studied to further validate the accuracy and efficiency of the developed FSI solver.

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