HYBRID SIMULATION OF COASTAL LOADING ON STRUCTURES

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Hybrid simulation combines the physical testing and computer modeling to analyze the dynamic responses of structures to external impacts (Hakuno et al., 1969). This relatively novel technique has been widely used in earthquake engineering. In the present study, it is extended to analyze the responses of structures to coastal loadings. This paper concerns mainly on the hydrodynamic loading induced by storm surge and tsunami events.

In the present study, the interaction between fluid and structure is achieved by employing two models which are physically apart from each other: fluid and structure. The structural model consists of a scaled physical model and a numerical solver, whereas the fluid model is pure numerical. During a simulation, the structural model accounts for the dynamical effects and the fluid model considers the effect of moving structure on the flow field.

The two models have to exchange the necessary data to carry out the next step. Data exchange between fluid and structure is achieved by employing the client-server model. Figure 1 illustrates the data communication between two models. In addition to data, the server and client exchange commands to start, pause, and stop the corresponding models. The two parties communicate via the local area network (LAN) using the TCP/IP protocol. The fluid side sends out force and expects deformation and the structure side vice versa. The information sent and received is arranged in a predefined standard format, so that both sides can easily decode the message. Besides force and displacement, if required, the developed standard can be extended to include more information.

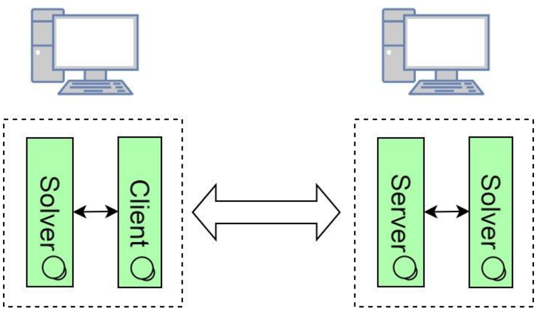

Figure 1 - Data exchange between fluid and structure models

The three-dimensional (3D) Navier-Stokes (NS) equations can be used for describing general fluid motions but the process of finding numerical solutions to the NS equations is computationally expensive. Therefore, in the present study, the flow field is modeled with the two-dimensional (2D) shallow water equations. These equations are numerically solved using an explicit finite volume method. An approximate Riemann solver with a first-order spatial accuracy is used to calculate the inter-cell fluxes. A second-order accuracy is obtained by using a flux reconstruction technique along with a slope limiter function. Manning's equation is used to calculate the bed friction. The total force acting on the structure is computed using the height of water level in the front of the structure.

The fluid model is validated by comparing the time history of force in an experimental test case found in the literature (St-Germain et al., 2012). The test case consists of a dam-break experiment, in which the hydrodynamic force on a rigid square block is measured. The block is partially immersed in the incoming water flow with no overtopping. The results in Figure 2 show that the force calculated by the 2D flow simulation agrees well with the experimental data.

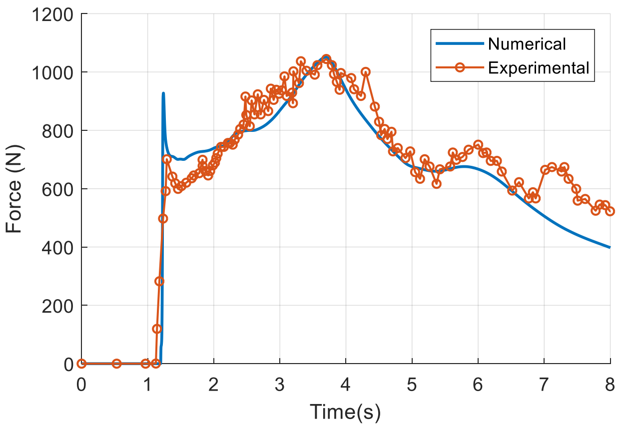

Figure 2- Validation of the flow model.

The hybrid simulation is carried out on a hypothetical scenario shown in Figure 3, where the structure is impacted by a solitary wave from the seaside. The fluid domain is discretized with uniform rectangular cells. The wave is generated at the inlet (seaside), the outlet boundary is non-reflective, and the two cross-shore boundaries are free-slip.

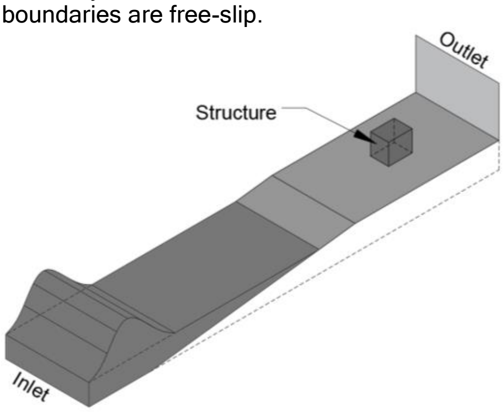

Figure 3 - Fluid domain (not to scale).

The influence of the oscillating, partially immersed structure in the fluid is modeled with a cut-cell method (Yang et al., 1997a, 1997b). The cut-cell method uses a fixed mesh on which a solid body moves. This technique can be applied to an existing Cartesian flow code with minimum modifications to incorporate moving boundary capability. To have stable numerical solutions, the cut-cell method requires a cell with small volume (less than a threshold limit) to be merged with an adjacent fluid cell.

A zero-flux boundary condition is applied to the cell face in contact with the oscillating structure and the rate of change of control volume is taken into account. Additionally, the zero-gradient boundary condition is applied to the water surface elevation in contact with a face of the oscillating structure.

In the present study, the deformation of the 3D structure needs to be converted to a 1D translatory motion in the fluid simulation. This equivalent deformation is calculated based on the displaced fluid volume by the oscillating structure from its preloaded position. Furthermore, the structure is assumed to be deforming similar to a cantilever beam loaded at a preselected point.

Due to the limited availability of the structural testing facility, the structural simulation prefers a relatively large time step to reduce the duration of the experiment, but for numerical stability, the fluid simulation requires a smaller time step which may change during the simulation. Therefore, two different time steps are used in the fluid and structure simulations. After every data exchange, the party with a smaller time step (fluid) needs to be synchronized with the other party. Moreover, the fluid simulation needs to distribute the change in the equivalent deformation among a number of time steps to obtain smooth structural motions.

Figure 4 shows the time history of the calculated total force acting on the structure, which is assumed rigid or flexible. The figure illustrates the expected force lag of the flexible structure compared to the rigid one. Additionally, the force on the flexible structure oscillates with the natural frequency of the structure. The variation in force is correlated to the instantaneous velocity of the vibrating structure after the wave impacts. Furthermore, the magnitude of the drop/increase in the hydrodynamic force depends on the structure stiffness, damping coefficient, etc.

Even though the present fluid model is capable of capturing the variation of force due to the oscillating structure, it has a major limitation of being incapable of resolving the force/pressure distribution along the water depth. For an application with such requirement, a 3D flow model with a suitable turbulence closure needs to be used. Furthermore, techniques such as immersed boundary, arbitrary Lagrangian-Eulerian method, and cut-cell method can be used to incorporate the general 3D oscillatory motions of the structure.

In conclusion, with this study, we have demonstrated that the hybrid simulation can be applied to analyze the dynamical responses of structures to coastal loadings. It has been observed that the interaction between the incoming wave and oscillating structure alters the imposed hydrodynamic force and hence the response of the structure.

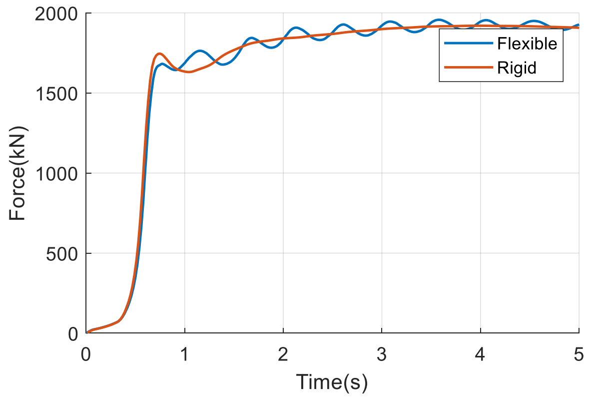

Figure 4 - Time history of the calculated total force acting on flexible and rigid structures.

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