STUDY ON NUMERICAL SIMULATION APPROACHES FOR SLOSHING IN RECTANGULAR WATER POOLS UNDER SEISMIC EXCITATION

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1. INTRODUCTION

Sloshing in water pools generated by seismic motion has caused severe damages in number of past earthquake events. The inability of analytical models to account viscous effects of the liquid and violent nature of sloshing in high amplitudes has highlighted the importance of the application of non-linear numerical models for the accurate predictions of the phenomena. Ibrahim (2005) provides a comprehensive overview of the mechanics of liquid sloshing and up to date research studies. In the current study, two major approaches which can be followed to simulate the behavior of fluid body in a pool under seismic excitation are compared. Firstly, the effect of seismic motion on the fluid is formulated in terms of time-varying volumetric body force [Liu and Lin (2008)] while boundary container remains static in space. Second is to employ a moving mesh technique to simulate the motion of container according to the external excitation. Even though numerical methods are applicable for pools of arbitrary shape which are subjected to translational and rotational motion, in the current study we are focusing on rectangular pools undergoes translational motion.

2. NUMERICAL MODEL

Three-dimensional computational study was conducted using OpenFOAM open source numerical toolbox. General k-ε model was incorporated in a Finite Volume solver as turbulence model considering incompressible fluid, and the basic governing equations, continuity and momentum conservation equations for the simulation can be found as,

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

$$\rho \frac{\partial \overline{u}_i}{\partial t} + \rho \frac{\partial \left(\overline{u}_i \overline{u}_j + \overline{u'_i u'_j} \right)}{\partial x_j} - \mu \frac{\partial}{\partial x_j} \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) = -\frac{\partial p}{\partial x_i} + \rho g + f \tag{2}$$

where, i,j =1,2,3; u is velocity; ρ is mass density; p is pressure; μ is dynamic viscosity, and f is body force. Volume of fluid method is employed to capture the free water surface and the advection equation contains the volume fraction function α ($0 \le \alpha \le 1$) can be expressed as,

$$\frac{\partial \alpha}{\partial t} + \frac{\partial \left(\overline{u}_i \alpha \right)}{\partial x_i} = 0 \tag{3}$$

In case of the moving mesh, dynamic mesh capabilities of the OpenFOAM [Jasak and Tukovic (2010)] is adopted and whole domain is moving with a pre-assigned velocity u=U_i where, U_i is the time-varying velocity of the seismic motion.

3. COMPUTATIONAL MODEL SET-UP

A rectangular water pool of 25m length (along the excitation direction), 5m in width and 3m in height is considered for the simulation. The arrangement and dimensions of the computational set-up is shown in the Fig. 1. The simulation was conducted for a still water depth of 2m and mesh size of 0.05x0.05x0.05m was assigned in the near-wall and around the free surface area for effective capturing of free water surface. In the study two acceleration waveforms for the earthquake excitation were considered depending on the collected data from past earthquake events, which were obtained from National Research Institute for Earth science and Disaster resilience (NIED) of Japan, K-NET and KiK-net systems. Those acceleration waveforms were directly applied in estimating the time-varying body force in the computation.
In the case of moving-mesh, the induced motion of grid points was provided as the time-varying displacement which was obtained from the available acceleration waveforms using the inverse Fast Fourier Transformation. The calculated displacement histories together with corresponding acceleration histories are shown in Fig. 2.

4. RESULTS AND DISCUSSION

4.1 Comparison of two approaches

Temporal variation of near-wall free water surface observed from each simulation are shown in Fig. 3. It can be noted that both simulation methods have predicted the water surface variation with significant similarity. Slight differences between the estimations can be occurred due to the near-wall mesh size in the moving-mesh approach. However, simulation using a non-inertial reference frame is economical in the sense

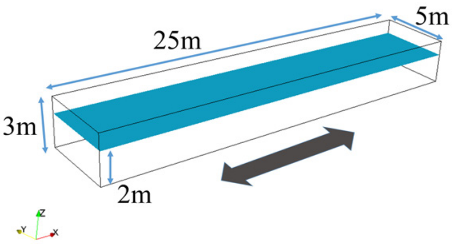

Fig. 1 Layout of the sloshing pool

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of computational cost and can be a significant advantage in assessing the effect of seismic motion which generally spread over a lengthy period. On the other hand, simulation using a moving mesh is closer to the actual phenomenon and has the capability to provide accurate and robust outcome in exchange for higher computational cost.

4.2 Comparison with analytical solution

Numerical analysis is also compared with the solution of the linear analytical method developed by Faltinsen (1978) for a two-dimensional rectangular tank, considering a periodic excitation of the tank in the form of Eq. (4).

$$x = A\sin(\omega t) \tag{4}$$

where, A is the amplitude of the oscillatory motion and ω is the angular frequency. In the study ω was selected closer to the lowest natural frequency of the pool, ω_0. Wu et al. (1998) showed that the temporal variation of free surface elevation estimated from the Faltinsen's solution can express as a summation of two components. The first component corresponds to the excitation frequency (ω) and the second component corresponds to the natural frequencies in which the lowest frequency (ω_0) is dominant. Therefore, near-wall free surface elevation (ζ) can be estimated as,

$$\zeta = \frac{l}{2g}A\sin(\omega t) + \left\{\frac{4Al}{\pi^2 g\left(\omega_0^2-\omega^2\right)}\right\}\left(\omega^4\sin(\omega t)-\omega_0^3\omega\sin(\omega t)\right) \tag{5}$$

where, l is the pool length. The comparison near-wall free surface level estimated from Eq. (5) with the estimations from each numerical method is shown in Fig. 4. It can be observed from the figure that numerical solutions from both methods are close agreement with linear analytical wave form in lower amplitudes of sloshing wave. Meantime, in higher amplitudes, some discrepancy is starting to appear between analytical and numerical solutions under the influence of non-linearity effects. Overall, the analytical results confirm the validity of the results from the numerical analysis.

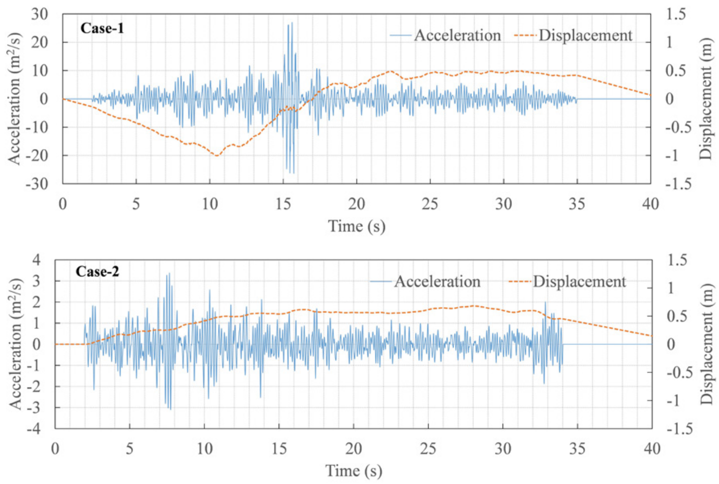

Fig. 2 Acceleration wave forms and the estimated displacement profiles for Case-1 (Top) and Case-2 (Bottom)

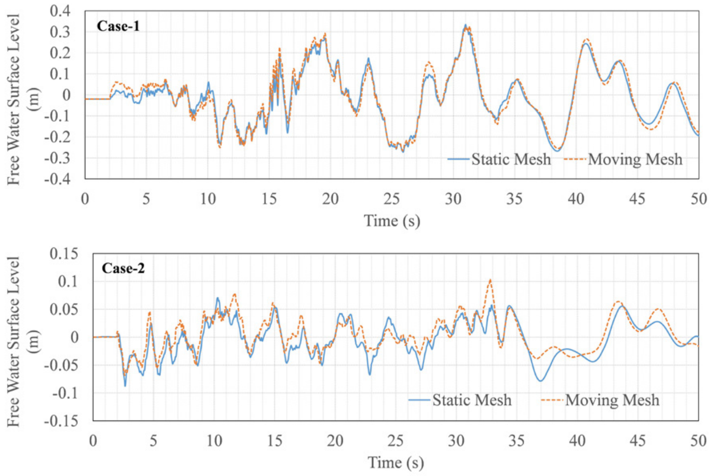

Fig. 3 Comparison of near-wall free surface level observed in numerical simulations; Case-1 (Top) and Case-2 (bottom)

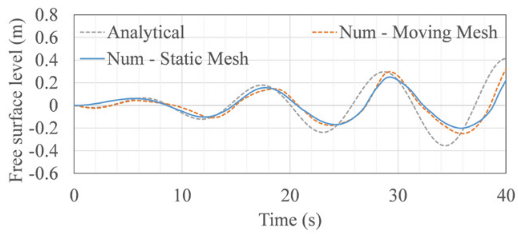

Fig. 4 Temporal variation of near-wall free water surface levels from analytical solution and numerical methods

5. CONCLUSIONS

Applicability of two numerical approaches in the simulation of sloshing in a water pool under seismic effect is discussed and compared. Both moving and static mesh approaches showed near-similar results in near-wall free surface variation under sloshing. Further, the numerical results showed a good agreement with the linear-analytical solution by Faltinsen (1978), which confirmed their validity.

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