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Numerical study on fluid-submerged block interaction in water pool

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ABSTRACT:
The arbitrary Lagrangian-Eulerian(ALE) finite element formulation allows a rational modelling for the analysis of large boundary motion problem with non-linear effects.

This paper describes a two-dimensional(2-D) nonlinear dynamic analysis of a typical submerged block structure set up on a pool floor under horizontal excitaion as an example.

During a resonant excitation, the block is subjected to vibratory motions, and complicated dynamic phenomena may take place. Since block is immersed in water, the hydrodynamic fluid force will be generated between the block and pool wall. On the other hand, nonlinear friction force will arise between the block and the pool floor.

In order to cope with the finite motion of a fluid-submerged block, the ALE formulation is adopted and satisfactory results are obtained. More practical problems are expected to be solved by the extension of the present computer code to the three-dimensional version, which is currently under way.

1 INTRODUCTION

Fluid-structure interaction is an important physical phenomenon in the seismic analysis of nuclear facilities such as the components with free liquid surface or the liquid-filled tanks.

The objective of this study is to introduce an application of the ALE formulation to evaluate a fluid-submerged block interaction effect in a water pool such as a fuel rack in a spent fuel pit for example.

In the present analysis, the fluid is modeled by the ALE finite element to cope with the large motions of the block and the free surface of water. Although the block is treated as rigid, the nonlinear sliding characteristics on the pool floor is considered. Then a frequency response corresponding to the first sloshing mode of a submerged block is studied.

2 ARBITRARY LAGRANGIAN EULERIAN FINITE ELEMENT FORMULATION

In the arbitrary Lagrangian-Eulerian formulation, the Navier-Stokes equation and the equation of continuity are described based on a moving coordinate system(e.g., Brooks, 1982).

As regards the finite element discretization, the Galerkin method is adopted for the equation of continuity, and the streamline upwind Galerkin method is employed for the equation of equilibrium and mesh motion.

The resultant equation of motion for fluid is given in matrix form as follows;

$$\bar{M}\dot{\varphi} + C\varphi = F \quad \text{---------------------------} \quad (1)$$

$$\bar{M} = \begin{bmatrix} M^P & & \\ & M & \\ & & \hat{M} \end{bmatrix}, \quad C = \begin{bmatrix} A^P & G^T & \\ -G & A + K_\mu & \\ & -\hat{M} & \hat{A} \end{bmatrix}, \quad \varphi = \begin{Bmatrix} P \\ v \\ x \end{Bmatrix}, \quad F = \begin{Bmatrix} 0 \\ f^{\text{ext}} \\ 0 \end{Bmatrix} \quad \text{--} \quad (2)$$

where,

$M^P, M, \hat{M}$: Mass matrices for pressure, velocity and mesh velocity
$A^P, A, \hat{A}$: Convection matrices for pressure, velocity and mesh velocity
f^{ext} : External force vector
K_μ : Viscosity matrix
G : Matrix for divergence
$\dot{P}, a$: Velocity of P and v in the ALE coordinate system

The equation of motion for a submerged block is given by the following equation;

$$M\ddot{x}_b + \mu M g - R_f = -M\ddot{y} \quad \text{----------------------} \quad (3)$$

where M, R_f and $\ddot{y}$ are the mass of block, the fluid force and the external vibratory acceleration such as seismic excitation. μ denotes the friction coefficient of the block to the pool floor and is assumed to have the dynamic friction coefficient value μ_D once the block starts moving. In other word, the static friction coefficient μ_S is not considered when the block velocity changes its sign.

As for the time integration scheme, the predictor-multicorrector algorithm(PMA) is adopted for the fluid and the Newmark method for the block.

3 NUMERICAL STUDY

3.1 Analysis model

The model for numerical study consists of a simplified block immersed in a water pool as shown in Fig.1 and the nonlinear sliding characteristics is assumed between the block and the pool floor. The dimensions of the pool and the block are 6 m(height) times 13 m(width), and 3 m(height) times 5 m (width), respectively. The mass of the block is 2×10^4 kg per unit thickness, and the dynamic friction coefficients μ_D on the pool floor is assumed as 0.1. The analysis model with the finite element mesh of fluid is shown in Fig.2. The fluid element used is quadrilateral and has four nodes for velocity and one node for pressure (constant pressure).

3.2 Motion of the block

As for the equilibrium of the submerged block, the fluid force, the inertia force of the block, and the nonlinear friction force of the block are balanced at any moment in the whole time duration.

Figure 3 shows the resultant force balance under 0.2 Hz excitation obtained by the coupled analysis of pool water and the block. The relative displacement, velocity and acceleration of the block to the pool floor are compared with the pool wall motion in Figs. 4a~4c.

The modelling of friction force of the block influences the stability and accuracy of analysis. In this paper, only the dynamic friction is considered during the motion of the block to enhance the numerical stability. On the other hand, if the velocity sign changes during a time increment, the zero velocity point is set as a new time step from the view point of accuracy.

3.3 Frequency response

In order to clarify the resonance characteristics of the system, the sinusoidal displacements with 0.3 m amplitude are applied to the pool wall for 15 seconds. In addition to the block with the friction, three extreme cases in the following arrangements are studied for comparison.

Case 1 - The block is set up on the pool floor with the friction.
Case 2 - The block is fixed on the pool floor.
Case 3 - The block is free on the pool floor.
Case 4 - Pool water without block.

Figure 5 shows the configurations of the maximum water level in the four cases under resonant excitation. The velocity vectors and the stream lines are also depicted in the figure. The frequency response of the maximum water level is investigated in the range from 0.18 to 0.25 Hz. As shown in Fig. 6, the sloshing frequencies of the first mode are found to be around 0.2 Hz in the both cases of the block with friction(Case 1) and the fixed block(Case 2), which shows lower frequency compared to the cases of free block(Case 3) and without block(Case 4). As for the maximum water level, the case of free block(Case 3) reaches about 8.6 m, that is 2.6 m heigher than the average level. In the case without block(Case 4), the maximum water level exceeds 8.4 m. On the other hand, the both cases of the block with friction(Case 1) and the fixed block(Case 2) show around 7.7 m to 8 m maximum water level. It is noted that the maximum water level is the lowest in the case of the block with friction(Case 1). It is found from the figure that the submerged block shows the definite effects on the suppression of sloshing and the decrease of the resonant frequency of the pool water, if friction is properly given.

4 CONCLUDING REMARKS

It is important for the design feasibility study of submerged structures in water to estimate the interaction between fluid and structures. In order to cope with the finite motion of a fluid-submerged block in water, the ALE formulation is adopted in this paper, and satisfactory results are obtained.

The extension of the present computer code to the three-dimensional version is currently under way, by which more practical problems such as the fluid-shell structure interaction are expected to be solved.

REFERENCES

Brooks, A. N., et al., 1982, Computer Methods in Applied Mechanics and Engineering, Vol. 32, pp199-259.

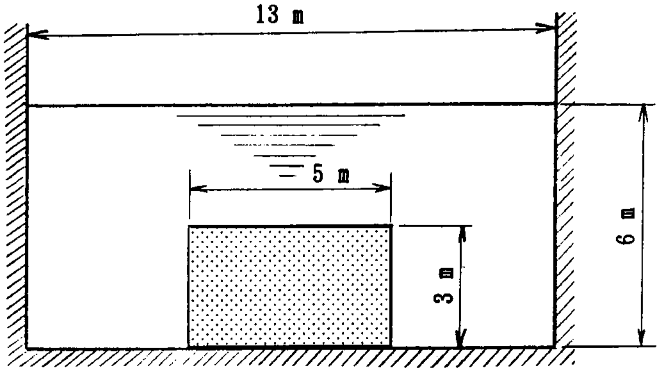


Fig. 1 Submerged block in a water pool

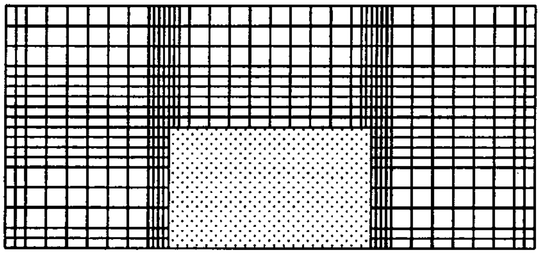


Fig. 2 Finite element model

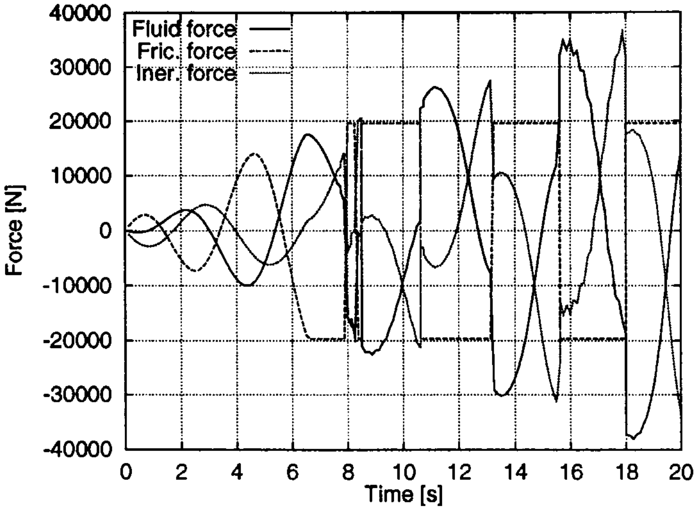


Fig. 3 The balance of the fluid force, the friction force, and the inertia acting on the block

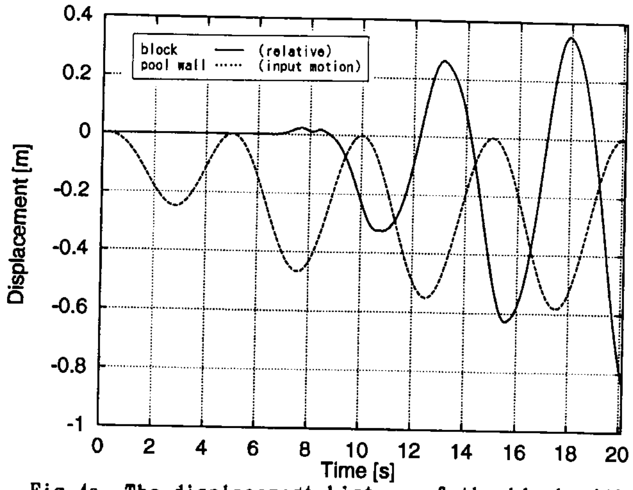


Fig. 4a The displacement history of the block with friction

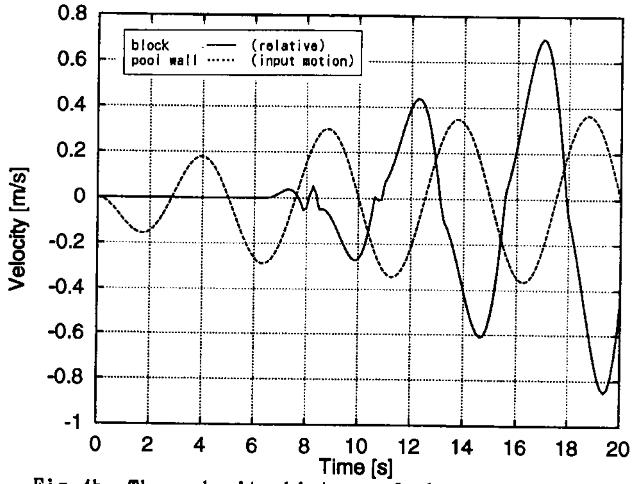


Fig. 4b The velocity history of the block with friction

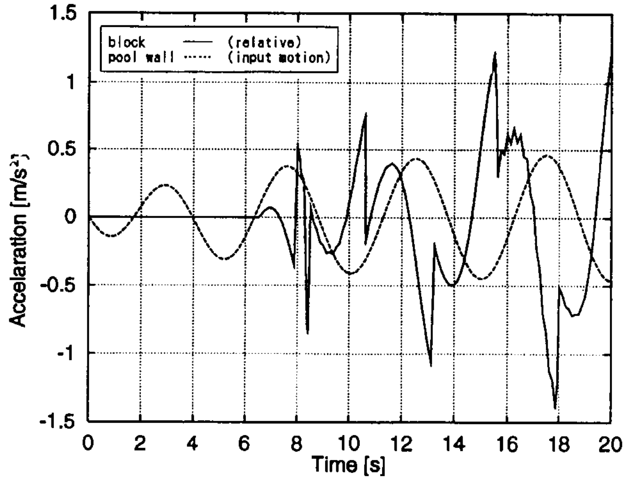
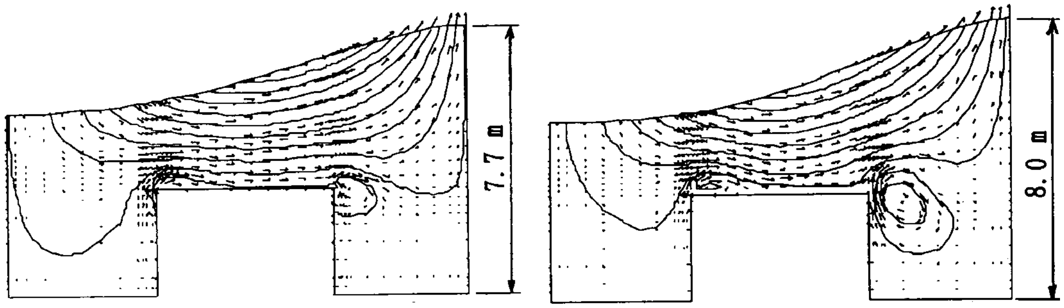
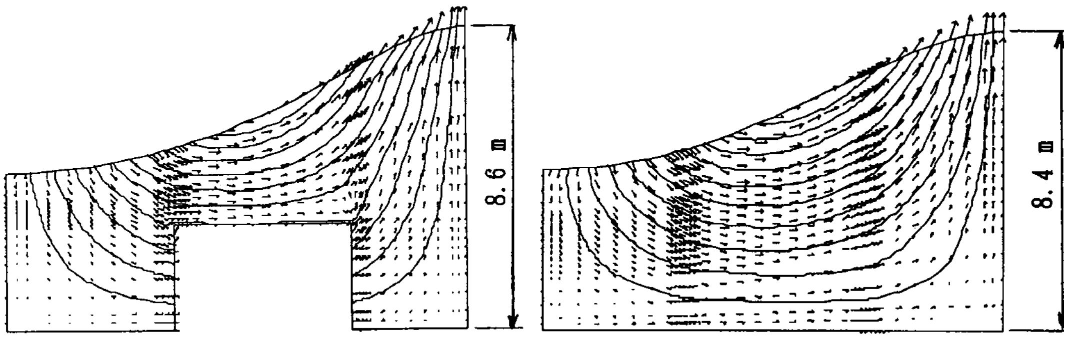


Fig. 4c The acceleration history of the block with friction



Case 1 - block with friction

Case 2 - block is fixed



Case 3 - block is free

Case 4 - without block

Fig. 5 The shape of water surface, velocity vectors, and the stream line

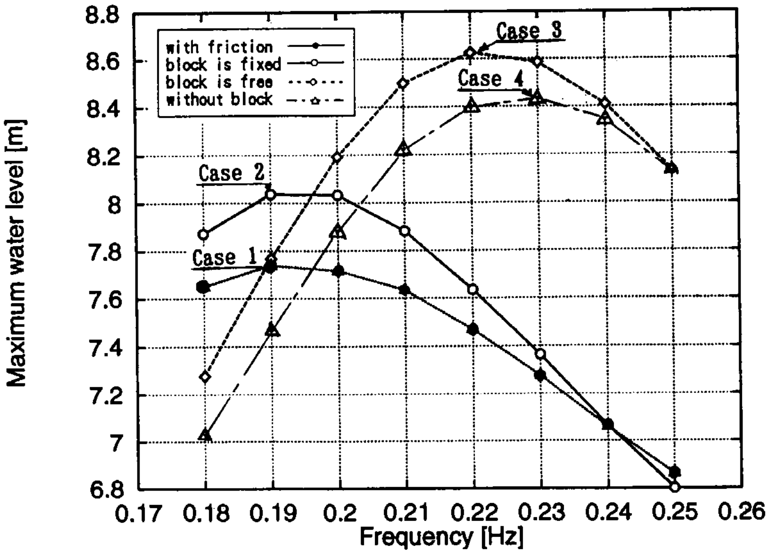


Fig. 6 Resonance curves for the sloshing