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Dynamics of infinitely long 3-D rectangular tanks with submerged objects stored in periodic pattern

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ABSTRACT

Dynamic responses of the tank-fluid-submerged objects system subjected to ground excitation are investigated by a coupled boundary element-finite element method. A rectangular tank which stores submerged objects in regular periodic pattern is modeled by one period section of the infinitely long system. The effects of the submerged objects on the dynamics of structure and on the pressure and sloshing response of fluid are investigated and presented. The stability of the submerged objects in the isolated tank is analyzed.

1. INTRODUCTION

Reinforced concrete liquid containers of rectangular plane are usually preferred for the wet storage of nuclear spent fuel assemblies. Despite being massive structures, the effect of their flexibility is known to be significant on the dynamic fluid-structure interaction behavior. To investigate the fluid-structure interaction behavior, coupled boundary element-finite element methods have been proposed[1,2]. However, the effects of submerged objects on the dynamic responses of the fluid and structure are not adequately described. This paper investigates the effect of submerged objects inside the container on the fluid and structural behaviors by the present analysis method.

The tank-fluid-submerged objects system which consists of flexible side walls, rigid bottom slab and submerged objects is assumed to extend infinitely into the out of plane direction. The submerged objects standing fixed on the rigid bottom slab are assumed to be placed periodically into the out of plane direction, so that the tank-fluid-submerged objects system is modeled by one period section of the infinitely long system. The irrotational motion of the inviscid and incompressible ideal fluid is modeled by the three-dimensional boundary element method and the motion of structure and submerged objects by the finite element method. Coupling is performed by imposing compatibility and equilibrium conditions along the interface between fluid and structure and submerged objects. The interaction effects are reflected into the coupled equations of motion as added fluid mass matrix and sloshing stiffness matrix. Free surface sloshing motion and hydrodynamic pressure developed in rectangular containers due to ground motions are computed in time domain and compared to each other.

Dynamic responses of the tank-fluid-submerged objects system subjected to horizontal ground excitation are investigated. The effects of several factors such as the flexibility of the submerged objects, number of the submerged objects and other geometric factors on the dynamic responses of tanks are investigated. Also, the influence on the sloshing response of the above factors is presented. The behavior of tank and the stability of the submerged objects in the isolated tank is calculated.

2. BOUNDARY ELEMENT MODELING OF FLUID MOTION

The irrotational motion of inviscid, incompressible ideal fluid in a container can be described in terms of velocity potential which satisfies Laplace equation and Green-Lagrange Identity. Then the potential, $\phi(\tilde{x},t)$, at any point $\tilde{\xi}$ on the boundary as a solution of Laplace equation can be given in the following integral equation[1],

$$c(\tilde{\xi})\phi(\tilde{\xi},t) = \int_S \phi(\tilde{x},t)\frac{\partial G}{\partial \tilde{n}}(\tilde{x};\tilde{\xi})ds - \int_S \frac{\partial \phi}{\partial \tilde{n}}(\tilde{x},t)G(\tilde{x};\tilde{\xi})ds \tag{1}$$

where $c(\tilde{\xi})$ is a constant depending only on the geometry of the boundary, $G(\tilde{x};\tilde{\xi})$ Green's function of Laplace equation and $\tilde{x}$ the position vector of source point.

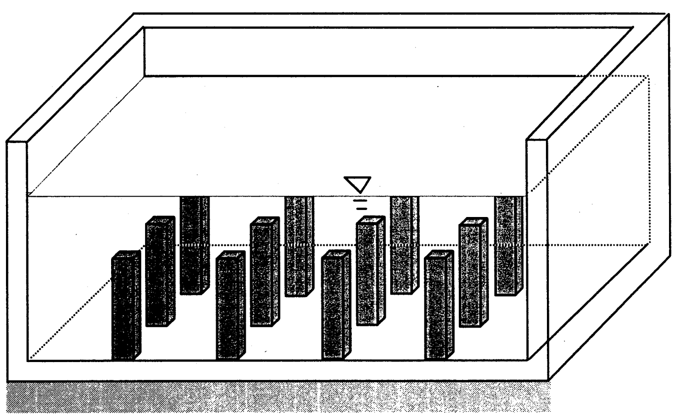

Figure 1. Tank-fluid-submerged objects system

Applying standard discretization procedure of boundary element method to Eq(1) the following algebraic equations can be obtained

$$[B]\left\{\frac{\partial\phi}{\partial n}\right\}-[H]\{\phi\}=\{0\} \tag{2}$$

where $[B]$ and $[H]$ are coefficient matrices and $\left\{\frac{\partial\phi}{\partial n}\right\}$ and $\{\phi\}$ denote nodal normal velocity vector and nodal potential vector respectively.

Under the horizontal ground excitations, the linearized dynamic boundary conditions for the model given in Figure 1 may be expressed as[1]

$$\frac{\partial\phi}{\partial t}(\tilde{x},t)+g\eta(x_1,x_2,t)=0 \quad \text{on free surface} \tag{3}$$

$$\frac{\partial\phi}{\partial x_3}(\tilde{x},t)=\frac{\partial\eta}{\partial t}(x_1,x_2,t) \qquad \text{on free surface} \tag{4}$$

$$P(\tilde{x},t)=-\rho\frac{\partial\phi}{\partial t}(\tilde{x},t) \qquad \text{on the interface} \tag{5}$$

$$\frac{\partial\phi}{\partial n}(\tilde{x},t)=n\bullet v_p \qquad \text{on the interface} \tag{6}$$

where $\eta(x_1,x_2,t)$ denotes vertical displacement of free surface from the stationary level, $P(\tilde{x},t)$ hydrodynamic pressure in excess of hydrostatic pressure, g gravitational acceleration, $\tilde{n}=\tilde{n}(\tilde{x})$ exterior normal vector on the boundary, ρ fluid density, and v_p the velocity vector.

Differentiating equation (2) with respect to time and applying boundary conditions, equations for the fluid region can be obtained as follows[1].

$$\mathrm{M}_{\eta p}\{\dot{\mathrm{v}}_p\} + \mathrm{M}_{\eta\eta}\{\ddot{\eta}\} + \mathrm{K}_{\eta\eta}\{\eta\} + \mathrm{M}_{\eta\eta}\{1\}\ddot{u}_{g3} = \{0\} \tag{7}$$

$$\mathrm{P}=\mathrm{P}_1\{\ddot{\mathrm{u}}_c\}+\mathrm{P}_2\{\ddot{\eta}\}+\mathrm{P}_3\{\eta\}+\mathrm{P}_1\{\ddot{\mathrm{u}}_g\}+\mathrm{P}_2\{1\}\ddot{u}_{g3} \tag{8}$$

where $\{\ddot{u}_g\}$ indicates horizontal ground acceleration vector.

3. COUPLING PROCEDURE

The equation governing the motion of containing structure and submerged objects can be derived by finite element method to be

$$\mathrm{M}^s\{\ddot{\mathrm{u}}(t)\} + \mathrm{K}^s\{\mathrm{u}(t)\} = -\mathrm{M}^s\left[\mathrm{r}^s\right]\{\ddot{\mathrm{u}}_g(t)\} + \mathrm{f}(t) \tag{9}$$

where M^s and K^s denote mass and stiffness matrices, respectively, $\{\mathrm{u}(t)\}$ relative nodal displacement vector, $\{\ddot{\mathrm{u}}_g(t)\}$ ground acceleration vector, $\mathrm{f}(t)$ external nodal force vector and $[\mathrm{r}^s]$ earthquake influence coefficient matrix.

Along the interface between the walls, submerged objects and fluid, compatibility and equilibrium conditions should be satisfied. Fluid particle acceleration normal to the interface boundary is set equal to the acceleration of the structure and submerged objects boundary in the same direction under the assumption of small displacement. In order to impose equilibrium condition at the coupled nodes, the fluid pressure is converted into equivalent nodal forces. The governing equation of the coupled system including the free surface sloshing motion. can be derived by imposing equilibrium and compatibility condition in the following form [1]

$$\begin{bmatrix} \mathrm{M}^s_{oo} & \mathrm{M}^s_{op} & 0 \\ \mathrm{M}^s_{po} & \mathrm{M}^s_{pp}+\mathrm{M}_{pp} & \mathrm{M}_{p\eta} \\ 0 & \mathrm{M}_{\eta p} & \mathrm{M}_{\eta\eta} \end{bmatrix} \begin{Bmatrix} \ddot{\mathrm{u}}_o \\ \ddot{\mathrm{u}}_p \\ \ddot{\eta} \end{Bmatrix} + \begin{bmatrix} \mathrm{K}^s_{oo} & \mathrm{K}^s_{op} & 0 \\ \mathrm{K}^s_{po} & \mathrm{K}^s_{pp} & \mathrm{K}_{p\eta} \\ 0 & 0 & \mathrm{K}_{\eta\eta} \end{bmatrix} \begin{Bmatrix} \mathrm{u}_o \\ \mathrm{u}_p \\ \eta \end{Bmatrix}$$
$$= -\begin{bmatrix} \mathrm{M}^s_{oo} & \mathrm{M}^s_{op} & 0 \\ \mathrm{M}^s_{po} & \mathrm{M}^s_{pp}+\mathrm{M}_{pp} & \mathrm{M}_{p\eta} \\ 0 & \mathrm{M}_{\eta p} & \mathrm{M}_{\eta\eta} \end{bmatrix} [\mathrm{r}]\{\ddot{\mathrm{u}}_g\} \tag{10}$$

where $\{\mathrm{u}_o\}$ and $\{\ddot{\mathrm{u}}_o\}$ are nodal displacement and acceleration vectors defined at the nodes of structure and submerged objects not in contact with the fluid region and $\{\mathrm{u}_c\}$ and $\{\ddot{\mathrm{u}}_c\}$ are those in contact with the fluid region.

4. NUMERICAL EXAMPLES

Dynamic responses of the tank-fluid-submerged objects system in Figure 2 are analyzed by the developed coupled boundary element-finite element method. The material properties of the tank are determined to be as follow density, $\rho = 1200 Kg/m^3$; Young's modulus, $E = 2.9 \times 10^9\ N/m^2$; and Poisson's ratio $\nu = 0.35$.

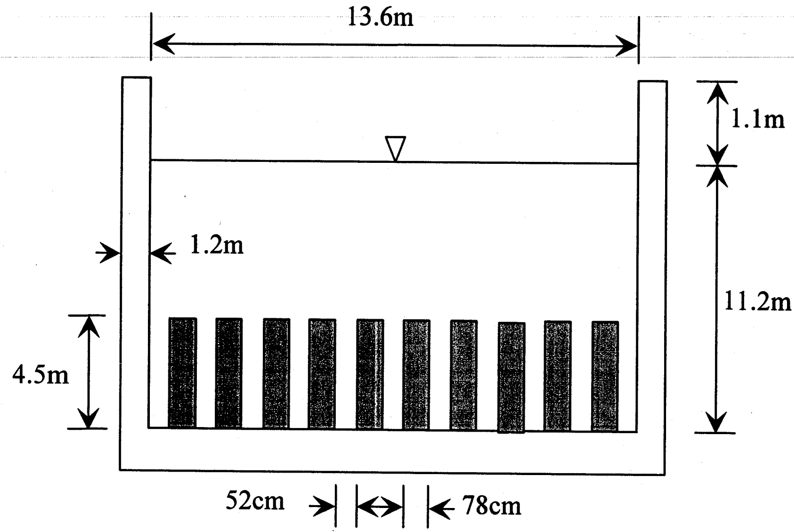

Figure 2. Dimensions of Tank-fluid-submerged objects model

The N-S component of the ground acceleration recorded at El Centro during the 1940 Imperial Valley Earthquake is used as input motion with peak ground acceleration adjusted to 0.2g. The effects of number of the submerged objects are investigated. The submerged objects are assumed to be rigid.

Figure 3 are time histories of the free surface sloshing motion at the intersection point of fluid and structure. It is found that the overall trends have minor difference in their detailed shapes. But any notable difference is not observed in general trend and magnitude. These facts suggest that sloshing response is not influenced by the presence of submerged objects. Displacement time histories at the crest are provided in Figure 4. The natural frequency of the tank with the submerged objects seems to be slightly lower than that of the tank without the submerged objects because of the submerged objects. However the magnitude and distribution pattern of the developed hydrodynamic pressure appear to be significantly influenced by the presence of the submerged objects. The profiles of pressure distribution along the height of the wall at the moment when the base shear reaches its peak value are made in Figure 5. It shows that amplification of the pressure in the tank with the submerged objects is much more pronounced than the tank without the submerged objects. In order to study stability of the submerged objects, pressure distribution around the left-most object is calculated at the moment when the base shear reaches its peak value and is plotted in Figure 6. From the pressure distribution, the overturning moment of the object can be calculated. From the pressure distribution, the overturning moment developed exceed the restoring moment by a factor 1.5.

The effects of the flexibility of the submerged objects are investigated. The material properties of the submerged objects are determined to be as follow Young's modulus, $E = 19.6 \times 10^{9} N / m^{2}$.

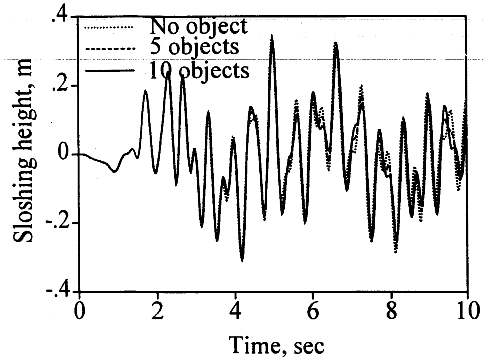

Figure 3. Histories of free surface sloshing motion at the intersection point in the tank with varying number of stored objects

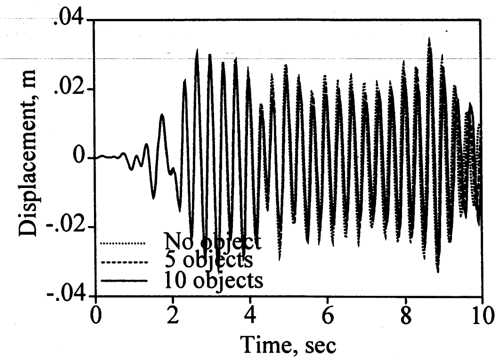

Figure 4. Histories of displacement at the crest in the tank with varying number of stored objects

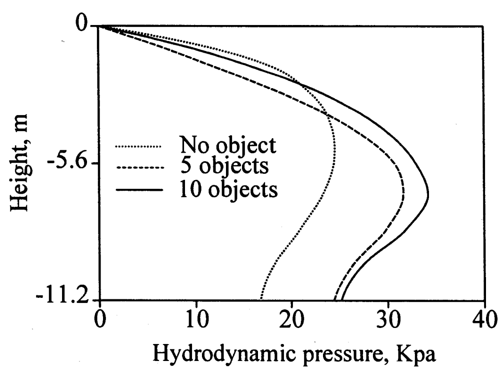

Figure 5. Hydrodynamic pressure distribution along the wall in the tank with varying number of stored objects

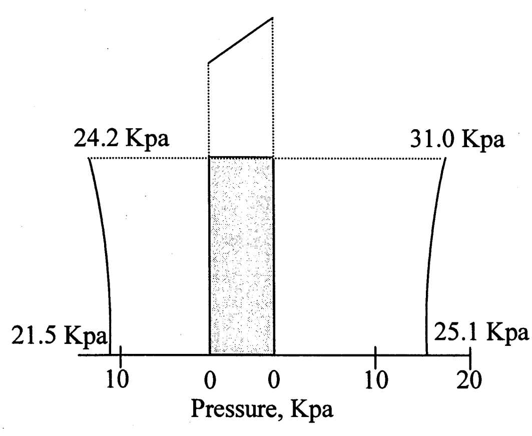

Figure 6. Hydrodynamic pressure distribution along the left-most object

The time histories of the free surface sloshing motion are compared in Figure 7. Comparison of pressure distribution along the height of the wall is made in Figure 8. Though the pressure distribution is affected significantly due to the flexibility of the submerged objects, the free surface sloshing motion seems to be not sensitive to the flexibility of the submerged objects.

By installing isolators, the dynamic response of the structure can be reduced significantly. The isolated tank with 0.5Hz effective frequency and 10% damping is considered. Figure 9 shows time histories of the free surface sloshing motion at the intersection point of fluid and structure. In the isolated tank, the component of the free surface sloshing motion associated with wall vibration is not visible. The profiles of pressure distribution along the height of the wall at the moment when the base shear reaches its peak value are given in Figure 10. The reduction of hydrodynamic pressure acting on the wall is achieved by the isolator. The base isolation system is confirmed to be very effective in reducing hydrodynamic pressure acting on the submerged objects as can be seen in Figure 11. In the isolated tank, the submerged object seems to remain stable. The restoring moment of an object is about five times larger than the overturning moment.

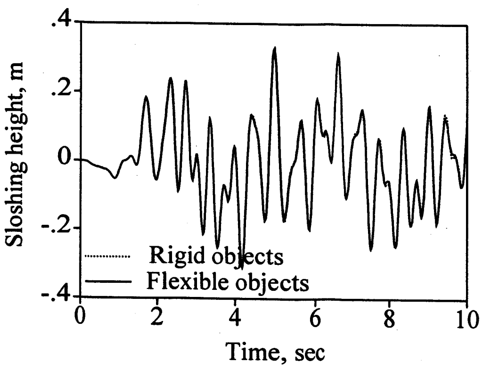

Figure 7. Histories of free surface sloshing motion at the intersection point with rigid/flexible objects

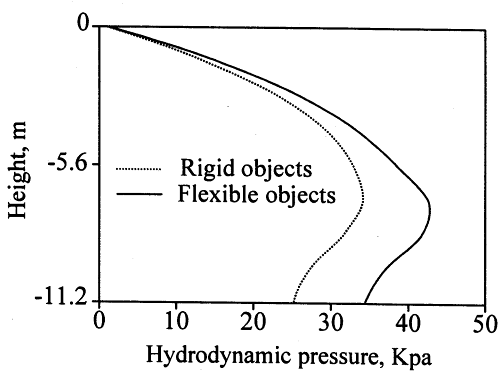

Figure 8. Hydrodynamic pressure distribution along the wall with rigid/flexible objects

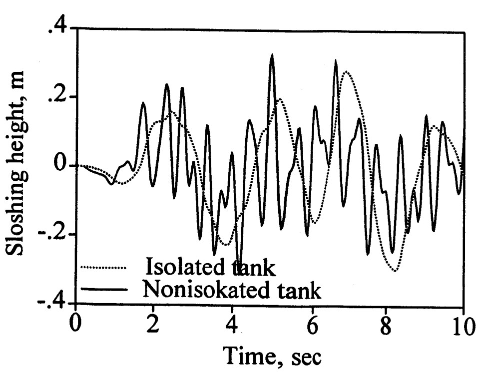

Figure 9. Histories of free surface sloshing motion at the intersection point in the isolated/nonisolated tanks

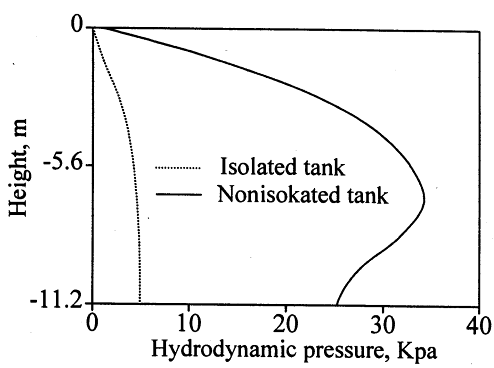

Figure 10. Hydrodynamic pressure distribution along the wall in the isolated/ /nonisolated tanks

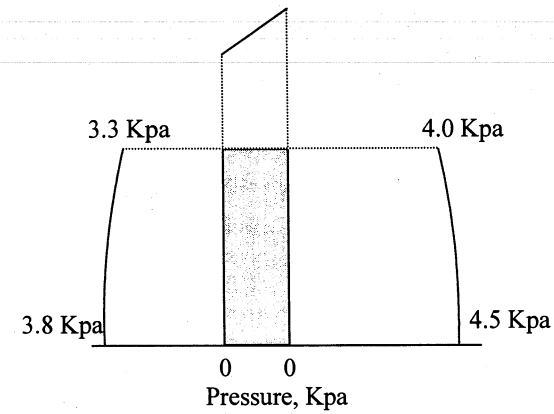

Figure 11. Hydrodynamic pressure distribution along the left-most object in the isolated tanks

5. CONCLUSIONS

A coupled boundary element-finite element method for the analysis of the tank-fluid-submerged objects system is developed and applied to investigated the effects on the dynamic response of fluid, structure and submerged objects.

The magnitude and distribution pattern of the developed hydrodynamic pressure are influenced by the presence and flexibility of the submerged objects. The pressure distribution developed in the tank with the submerged objects is found to be more amplified than that in the tank without the submerged objects. However, the structural behavior and the free surface sloshing motion are lesser influenced than the hydrodynamic pressure by the presence of submerged objects.

In the base isolated tank, remarkable reduction is obtained in the hydrodynamic pressure acting on the wall and stability of the submerged objects can be reached. However, the sloshing motion in the base isolated tank could be increased.

REFERENCES

1. Park, J.-H., Koh, H.M., Kim, J., "Fluid-structure interaction analysis by coupled boundary element-finite element method in time domain," *Proc. of 7th international conference on boundary element technology, BETECH/92*, Computational Mechanics Publications, Southampton, pp. 89-92, 1990.
2. Koh, H. M., Kim, J. and Park, J. -H., " Dynamic analysis of liquid storage rectangular container by a coupled boundary element-finite element method," *Proc. of 4th East Asia-Pacific Conference on Structural Engineering and Construction*, Seoul, Korea, pp. 1815-1820,1993.
3. Currie, I. G., *Fundamental Mechanics of Fluids*, McGraw-Hill Inc, 1994.
4. Cook, Robert D., David S. Malkus and Michael E. Plesha, *Concepts and Application of Finite Element Method*, John Wiley & Sons Inc., 1989.
5. Rammerstorfer, Franz G., Scharf, Kunt and Fisher, Franz D., "Storage tanks under earthquake loading," *Applied Mechanics Reviews,* ASME, Vol. 43, pp. 261-282, 1990.
6. Housner, George W., "Dynamics Pressure On Accelerated Fluid Container," *Bulletin of the Seismological Society of America*, vol. 47, pp.15-35, 1957.