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SEISMIC ANALYSIS OF A LIQUID STORAGE TANK WITH A BAFFLE

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The effects of a rigid baffle on the seismic response of liquid in a rigid cylindrical tank are presented. A baffle is an additional structural element which supplies a kind of passive control on the effects of earthquake motion. Fluid motion is assumed to be irrotational, incompressible and inviscid. The method of superposition of modes has been implemented to compute the seismic response. The boundary element method is used to evaluate the natural modes of liquid in a cylindrical tank. Linearized free surface conditions have been taken into consideration.

1. INTRODUCTION

In recent years, the civil engineering community has been concerned with the development and implementation of innovative design concepts for seismic protection of structures, particularly for the control of earthquake effects on buildings [1, 2].

Seismic response reduction systems need not be located only in the base of the structure. Control systems have mainly two categories called active and passive systems. The system is called an active control system if external forces are applied with the base isolation system to the structure to control the earthquake effects. In passive control systems external forces are not required [1].

Attempts have been made to install them in different parts of the structure, either in the form of additional response reduction masses, or dampers, friction devices, etc. One of the passive control systems is based on the known behavior of a braced steel frame when using friction effects of friction dampers. During an earthquake the friction damper mechanism develops additional energy-dissipating sources which can protect the main members from structural damage.

In liquid containers, breaking of surface waves, while highly dependent on vibration amplitude, is the main mechanism of energy dissipation. Liquid dampers have been in use in space satellites and marine vessels. The value of additional damping can increase with low viscosity of the liquid, with a smooth bottom of the container, and with an adequate gap between the liquid and the roof of the container. Another approach to the response reduction systems is the

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coupling of individual structural systems, one alongside another with different stiffness, and intermediate energy absorbing systems.

Vondorn [3] reported the damping effect of the bottom boundary layer on liquid motion. Miles [4] also studied the ring damping of free surface oscillations in a cylindrical tank.

If stiffeners are required in the tank design for structural integrity, the baffles and support rings may serve the dual purpose of slosh damper for passive control of the tank and stiffener. Several rings can be supported around the tank periphery and positioned slightly below the liquid surface.

The phenomenon of earthquake damage on the nuclear power plants and petroleum tanks creates an important research area in the seismic analysis of liquid storage tanks [5, 6]. The behavior of the liquid in rigid tanks has been examined by some authors over a number of decades [7, 8]. Studies with flexible tank assumptions are later than those with rigid tank assumptions [9–11]. There are studies that compare different methods of seismic analysis for partially liquid filled or empty containers [12–14].

Some authors make use of a mass–spring model of the liquid [15–19], while others tend to solve the potential problems [20–22]. Perturbation expansions also have been used for calculation of the water waves [23]. A semi-analytical method uses Fourier series and FEM [24]. Numerical inversion of transformation methods [25], the panel method based on the boundary integral technique [26], the finite element method [27] and Galerkin's approach [14] have been used to solve the liquid sloshing problem in cylindrical tanks that are elastic or rigid with linear or non-linear free surface conditions. Compressibility of the liquid has been considered for the analysis of dams [28, 29].

The boundary element method can be used to evaluate the natural frequencies and the natural modes of the liquid. The technique of superposition of the modes has then been used for the seismic analyses [8, 20].

Passive systems can be configured with additional structural elements, such as mass–damper–spring systems or baffles in liquid storage tanks [30, 31].

In this study, to examine the effectiveness of baffle for liquid oscillations as passive control systems, the forces acting on the foundation of the baffle–tank system, caused by the hydrodynamic pressure of the fluid, is determined by using the boundary element method.

By choosing the suitable geometry for the baffle–tank system, the magnitudes of the forces mentioned above can be minimized for a kind of passive control system.

1.1. ASSUMPTIONS

The following are assumed for the liquid: (1) either the velocity or the displacement of a particle on the free surface is so small that the kinematic and the dynamic conditions can be linearized; (2) the fluid is incompressible and inviscid; (3) the fluid motion is irrotational.

The following are assumed for the baffle–tank system: (4) the baffle–tank system is a rigid structure and fixed on a rigid foundation; (5) the baffle–tank system moves only in the horizontal direction under the effect of the recorded earthquake acceleration.

2. FUNDAMENTAL EQUATIONS

The cylindrical co-ordinate system (r, θ, z) for the baffle–tank system is fixed as shown in Figure 1. A Cartesian co-ordinate system is fixed at the bottom of the tank to make easy the definition of shear force and the overturning moment acting on the foundation. The relation between these two co-ordinate systems is

$$x = r\cos\theta \quad \text{and} \quad y = r\sin\theta. \tag{1}$$

A way to analyze the behavior of the liquid is the use of velocity potential as in references [20–22].

A non-dimensional form will be chosen because the results then become more understandable. The radius of the tank R, the gravitational acceleration g and the density of the liquid ρ_f are used in the procedure for establishment of the non-dimensional forms [20]. Thus, one has

$$\Phi \leftarrow \Phi\sqrt{gR^3} \text{ (velocity potenial)}, \quad p \leftarrow p/\rho_f gR \text{ (hydrodynamic pressure)},$$

$$a \leftarrow a/g \text{ (recorded earthquake acceleration in } x\text{-direction)},$$
$$r \leftarrow r/R \text{ (radial component of cylindrical co-ordinate system)},$$
$$z \leftarrow z/R \text{ (vertical component of cylindrical co-ordinate system)},$$

$$t \leftarrow t\sqrt{g/R} \text{ (time)}, \quad \omega \leftarrow \omega\sqrt{R/g} \text{ (angular frequency)},$$
$$\eta \leftarrow \eta/R \text{ (vertical displacement of a particle on the free surface)},$$

$$F_x \leftarrow F_x/\rho_f gR^3 \text{ (shear force at the bottom of the tank)},$$

$$M_y \leftarrow M_y/\rho_f gR^4 \text{ (overturning moment around axis of } y\text{)}. \tag{2}$$

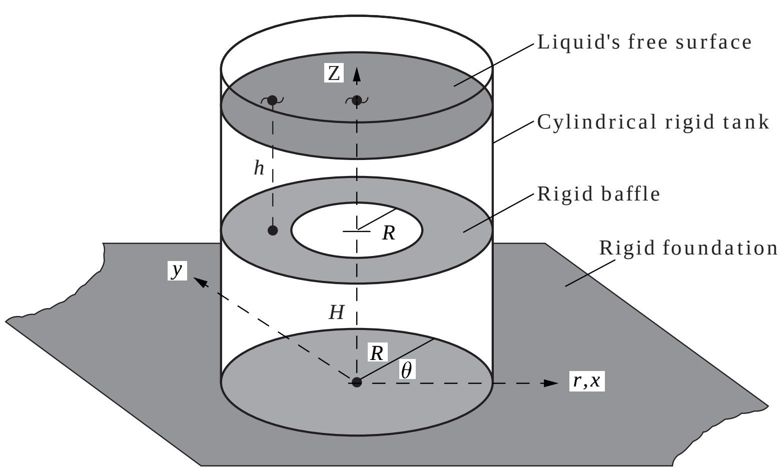

Figure 1. Rigid cylindrical tank with a baffle and co-ordinate systems.

Here the arrows indicate the non-dimensional terms. Shear force and overturning moment are respectively

$$F_x = \int_{S_r} pn_x \,\mathrm{d}S \quad \text{and} \quad M_y = \int_{S_r} (zn_x - xn_z)p \,\mathrm{d}S, \tag{3}$$

where n_x and n_z are the components of the outward normal of the surface in the x and z directions, respectively. A harmonic boundary value problem can be represented by using the velocity potential as follows:

$$\nabla^2 \Phi = 0 \text{ in the region of the liquid } R_f, \tag{4}$$

$$\Phi_{,n} = 0 \text{ on the rigid surface } S_r, \tag{5}$$

$$\Phi_{,z} = \dot{\eta} \text{ kinematic condition on the free surface } S_{fs}, \tag{6}$$

$$\eta = \dot{\Phi} + ax \text{ dynamic condition on the free surface } S_{fs}. \tag{7}$$

Here $a(t)$ is the recorded earthquake acceleration and a superposed dot implies time differentiation. A comma followed by a subscript indicates partial differentiation with respect to the corresponding spatial variable. Initial conditions are as follows: at $t = 0$

$$\Phi = 0 \text{ in } R_f, \quad \dot{\Phi} = 0 \text{ in } R_f. \tag{8, 9}$$

The hydrodynamic pressure of the liquid can be written as

$$p = -\dot{\Phi} - ax \quad \text{in} \quad R_f + S_r. \tag{10}$$

The meaning of the kinematic condition is that a particle on the free surface will always stay on the free surface and that of the dynamic condition is that pressure on the free surface is zero. A linear dynamic condition can be obtained by the use of Bernoulli's equation in the case of low velocities. Substituting equation (6) into equation yields (7) a linear free surface condition as

$$\Phi_{,z} = \ddot{\Phi} + \dot{a}x \quad \text{on} \quad S_{fs}. \tag{11}$$

2.1. SUPERPOSITION OF MODES

The velocity potential field of the liquid in the cylindrical tank can be written in the form

$$\Phi(r, \theta, z, t) = \sum_{k=0}^{\infty} \cos k\theta \sum_{n=1}^{\infty} \phi_n(r, z)\psi_{kn}(t), \tag{12}$$

where ϕ_n is the value of the velocity potential on the plane of $\theta = 0$ and ψ_{kn} is the weighting factor. k and n are the numbers for the modes in the circumferential and radial directions, respectively. Cases $k = 0$ and $k = 1$ correspond to axially symmetric and asymmetric mode shapes, respectively. In this paper, for the sake of simplicity and sufficiency, only the term $k = 1$ has been used, so omitting index k from equation (12) one has

$$\Phi(\theta, z, t) = \cos\theta \sum_{n=1}^{\infty} \phi_n(r, z)\psi_n(t). \tag{13}$$

For the modes of natural vibration, by taking $\psi_n(t) = \sin \omega_n t$ and $a(t) = 0$ then substituting equation (13) into equation (11), the following condition for the nth mode is obtained:

$$\phi_{n,z} = -\omega_n^2 \phi_n. \tag{14}$$

Here ω_n, is the natural frequency of the nth mode. The velocity potential field for the liquid under the effect of the recorded earthquake acceleration can be evaluated by the use of mode shapes and natural frequencies of natural vibration. Substituting equations (13) and (14) into equation (11) yields the following form for the function ψ_n:

$$\sum_{n=1}^{\infty} (\ddot{\psi} + \omega_n^2 \psi_n)\phi_n = -\dot{a}r \quad \text{on} \quad S_{fs}. \tag{15}$$

By the use of the orthogonality of the mode shapes of the velocity potential [20], the following form can be obtained from equation(15):

$$\ddot{\psi}_n(t) + \omega_n^2 \psi_n(t) = -I_n \dot{a}. \tag{16}$$

Here

$$I_n = \int_{\Gamma_{fs}} r^2 \phi_n \, \mathrm{d}s \Bigg/ \int_{\Gamma_{fs}} r\phi_n^2 \, \mathrm{d}s, \tag{17}$$

where Γ_{fs} is the intersection of S_{fs} and the $\theta = 0$ plane (see Figure 2). The solution of equation (16) satisfying the initial conditions (8) and (9) is Duhamel's integral

$$\psi_n(t) = -\frac{I_n}{\omega_n} \int_0^t \dot{a}(\tau) \sin[\omega_n(t - \tau)] \, \mathrm{d}\tau. \tag{18}$$

By partial integration of equation (18) with respect to time

$$\psi_n(t) = -I_n \int_0^t a(\tau) \cos[\omega_n(t - \tau)] \, \mathrm{d}\tau \tag{19}$$

is obtained, where $a(0) = 0$. A numerical integration of equation (19) is easier than that of equation (18). Duhamel's integral (19) has been numerically evaluated by using the trapezoidal integration rule.

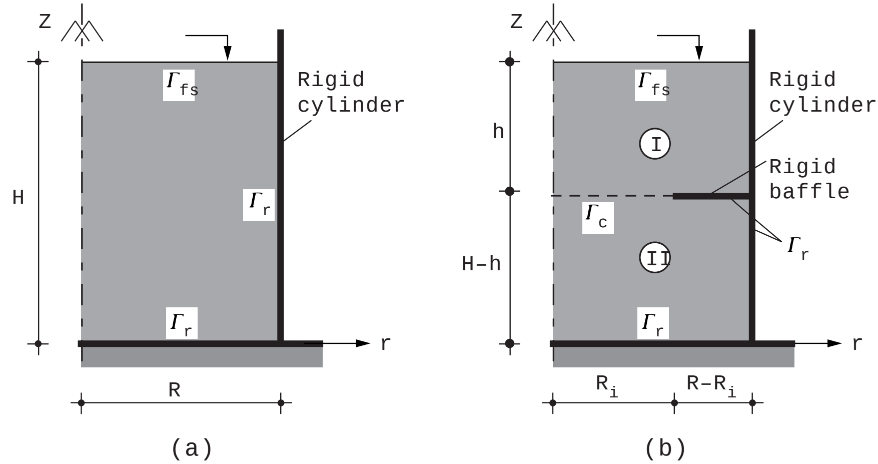

Figure 2. $\theta = 0$ plane. (a) Cylindrical tank; (b) cylindrical tank with a baffle.

3. BOUNDARY ELEMENT METHOD

The boundary integral equation form of equation (4) can be written for any mode shape of the velocity potential, upon omitting index n as [32]

$$-\alpha_P \phi(P) = \int_\Gamma \left\{ \phi \frac{\partial G^*}{\partial n} - G^* \frac{\partial \phi}{\partial n} \right\} r \, \mathrm{d}s. \tag{20}$$

Here G^* is the free space Green function for the axially-asymmetric problem ($\cos\theta$ type). α_P is defined by the position of the source point P as

$$\alpha_P = \left\{ \begin{array}{cc} 4\pi & P \in R_f \\ 2\pi & P \in S_f \\ 0 & P \notin R_f + S_f \end{array} \right\}. \tag{21}$$

The boundary element method with the constant elements is used for the solution of the initial value problem. By evaluating the integrals in equation (20) over constant boundary elements by using the shown source position in Figure 3, the following linear system of equations is obtained [33]:

$$-\alpha_P \phi(P) = H_{ik} \phi_k - G_{ik} \phi_{k,n}, \quad k = 1, 2, \dots N \quad \text{and} \quad i = 1, 2, \dots N. \tag{22}$$

Here the source point is near to the ith element and the boundary integral is evaluated over the kth element (see Figure 3). ϕ_k is the value of the velocity potential of the kth element. H_{ik} and G_{ik} are the boundary integrals given by

$$H_{ik} = \int_{\Gamma_k} G^*_{i,n}(P, s) r(s) \, \mathrm{d}s, \quad G_{ik} = \int_{\Gamma_k} G^*_i(P, s) r(s) \, \mathrm{d}s, \tag{23, 24}$$

where $G^*_i(P, s)$ is called the free space Green function which is the potential on the point s due to the unit source located on point P. For the axially-asymmetric problem ($\cos\theta$ type), one has

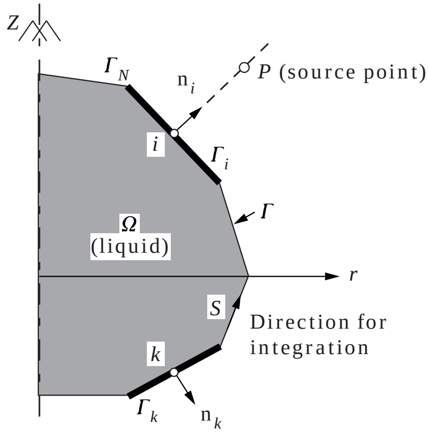

Figure 3. Constant boundary elements on the $\theta = 0$ plane and source point position.

$$G_i^*(P, s) = \frac{4}{r_{Ps}}\left\{\left(\frac{2}{\kappa^2} - 1\right)\mathrm{K}(\kappa) - \frac{2}{\kappa^2}\mathrm{E}(\kappa)\right\} \tag{25}$$

and the outward normal component of the velocity of liquid particles on the boundary for this potential field is [32]

$$G_{i,n}^*(P, s) = \frac{4}{r_{Ps}}\left\{\left[r_P\left(\frac{2}{\kappa^2} - 1\right) - r_s\right]n_r + (z_P - z_s)n_z\right\}x$$
$$\times\left\{\frac{1}{1-\kappa^2}\left(\frac{2}{\kappa^2} - 1\right)\mathrm{E}(\kappa) - \frac{2}{\kappa^2}\mathrm{K}(\kappa)\right\} - \frac{1}{2}G_i^*(P, s)n_r, \tag{26}$$

where $\kappa = 4r_P r_s/r_{Ps}^2$ and $r_{Ps}^2 = (r_P + r_s)^2 + (z_P - z_s)^2$. n_r and n_z are the components in the radial and vertical directions, respectively. $\mathrm{K}(\kappa)$ and $\mathrm{E}(\kappa)$ are the first and secod kind complete elliptic integrals, respectively [32].

A logarithmic singularity in $\mathrm{K}(\kappa)$ occurs when the source point P is located on the ith element, i.e., $\kappa \to 0$. In order to avoid a singularity, the source point may be located out of the liquid domain near to the boundary.

Let f, r and c indices denote the parts of the liquid's surface that are free, rigid and the interface of the liquid domains, respectively. By using these indices and equation (5), the system of equations (22) can be written as

$$\begin{bmatrix} \mathbf{H}_{ff} & \mathbf{H}_{fr} & \mathbf{H}_{fc} \\ \mathbf{H}_{rf} & \mathbf{H}_{rr} & \mathbf{H}_{rc} \\ \mathbf{H}_{cf} & \mathbf{H}_{cr} & \mathbf{H}_{cc} \end{bmatrix}\begin{Bmatrix} \boldsymbol{\phi}_f \\ \boldsymbol{\phi}_r \\ \boldsymbol{\phi}_c \end{Bmatrix} = \begin{bmatrix} \mathbf{G}_{ff} & \mathbf{G}_{fr} & \mathbf{G}_{fc} \\ \mathbf{G}_{rf} & \mathbf{G}_{rr} & \mathbf{G}_{rc} \\ \mathbf{G}_{cf} & \mathbf{G}_{cr} & \mathbf{G}_{cc} \end{bmatrix}\begin{Bmatrix} \mathbf{q}_f \\ \mathbf{q}_r = 0 \\ \mathbf{q}_c \end{Bmatrix}, \tag{27}$$

or

$$\mathbf{H}\boldsymbol{\phi} = \mathbf{G}\mathbf{q}, \tag{28}$$

where $\boldsymbol{\phi} = \{\phi_1, \ldots, \phi_N\}^{\mathrm{T}}$ and $\mathbf{q} = \{\phi_{1,n}, \ldots, \phi_{N,n}\}^{\mathrm{T}}$. The elements of matrices $\mathbf{H}$ and $\mathbf{G}$ are respectively given by equations (23) and (24) with the constant $\alpha_P = 0$.

3.1. SUB-DOMAINS AND THE CONTINUITY EQUATIONS FOR THE INTERFACES

If a baffle separates a liquid domain into two sub-domains (see Figure 2(b)), the system of equations (27) can be evaluated for each sub-domain as

$$\begin{bmatrix} \mathbf{H}_{ffI} & \mathbf{H}_{frI} & \mathbf{H}_{fcI} & & \\ \mathbf{H}_{rfI} & \mathbf{H}_{rrI} & \mathbf{H}_{rcI} & & \\ \mathbf{H}_{cfI} & \mathbf{H}_{crI} & \mathbf{H}_{ccI} & & \\ & & & \mathbf{H}_{ccII} & \mathbf{H}_{crII} \\ & & & \mathbf{H}_{rcII} & \mathbf{H}_{rrII} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\phi}_{fI} \\ \boldsymbol{\phi}_{rI} \\ \boldsymbol{\phi}_{cI} \\ \boldsymbol{\phi}_{cII} \\ \boldsymbol{\phi}_{rII} \end{Bmatrix} = \begin{bmatrix} \mathbf{G}_{ffI} & \mathbf{G}_{frI} & \mathbf{G}_{fcI} & & \\ \mathbf{G}_{rfI} & \mathbf{G}_{rrI} & \mathbf{G}_{rcI} & & \\ \mathbf{G}_{cfI} & \mathbf{G}_{crI} & \mathbf{G}_{ccI} & & \\ & & & \mathbf{G}_{ccII} & \mathbf{G}_{crII} \\ & & & \mathbf{G}_{rcII} & \mathbf{G}_{rrII} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_{fI} \\ \mathbf{q}_{rI} = 0 \\ \mathbf{q}_{cI} \\ \mathbf{q}_{cII} \\ \mathbf{q}_{rII} = 0 \end{Bmatrix}, \tag{29}$$

where subscripts I and II denote the domains. In order to get a coupled system of equations, continuity conditions for the velocities and velocity potentials must be satisfied.

3.2. CONTINUITY CONDITIONS

Hydrodynamic pressures on each side of the interface of two separated domains should be equal. When liquids in the separated domains are identical, i.e., $\rho_{fI} = \rho_{fII}$, the following continuity condition can be written:

$$\boldsymbol{\phi}_{cI} = \boldsymbol{\phi}_{cII}\,. \tag{30}$$

Here c_I and c_{II} denote respectively the surfaces of the separated domains on the interface (see Figure 2(b)). Continuity of the velocity is satisfied by

$$\mathbf{q}_{cI} = -\mathbf{q}_{cII}\,. \tag{31}$$

The coupled system of equations can be obtained by applying the continuity conditions on equation (29). After elimination of other unknowns, the following eigenvalue problem can be evaluated by using equation (14):

$$\mathbf{H}_{re}\boldsymbol{\phi}_f = -\omega_n^2 \mathbf{G}_{re}\boldsymbol{\phi}_f, \tag{32}$$

where components of $\boldsymbol{\phi}_f = \{\phi_{fI}, \ldots, \phi_{fN_f}\}^{\mathrm{T}}$ are the velocity potentials on the boundary elements of the free surface for the nth mode shape and the subscript re denotes reduced form. N_f is the number of boundary elements on the free surface. Velocity potentials on the boundary elements on the rigid surfaces, ϕ_{rI} and ϕ_{rII}, can be obtained by the back substitution of the evaluated velocity potentials.

4. NUMERICAL EXAMPLES

When the mode shapes and eigenfrequencies of equation (32) are calculated, the shear force and the overturning moment at the bottom of the tank, which are caused by the horizontal ground motion, can be determined. Duhamel's integral (19) is numerically evaluated by using the trapezoidal integration rule. The first 10 s of earthquake acceleration records with 0·01 s intervals has been used.

Only a few of the mode shapes corresponding to the smallest eigenfrequencies are required. The most effective modes, in response to the ground motion, correspond to the smallest eigenfrequencies, because of the fact that they always include most of the total energy of the system. In this study numerical examples were evaluated by using only the first two mode shapes. It has been checked numerically that these two modes provide sufficient accuracy.

All of the boundary elements are constant elements with the same length. On the free surface, for all examples, 10 constant boundary elements were used. On the other surfaces (wetted boundaries), the number of elements used depends on the ratios R_i/R and H/R.

4.1. NATURAL VIBRATION ANALYSIS

4.1.1. *Liquid in the cylindrical tank*

The natural frequencies of the liquid in the cylindrical tank are given in Figure 4 for different ratios H/R and for different radial wave numbers n. From Figure 4, it is seen that the natural frequency corresponding to the first mode reaches its limit value at about $H/R > 1$, while the value for the second mode reaches its limit value at about $H/R > 0{\cdot}3$. Likewise, it is clear that the limits corresponding to the highest modes will occur at smaller ratios H/R.

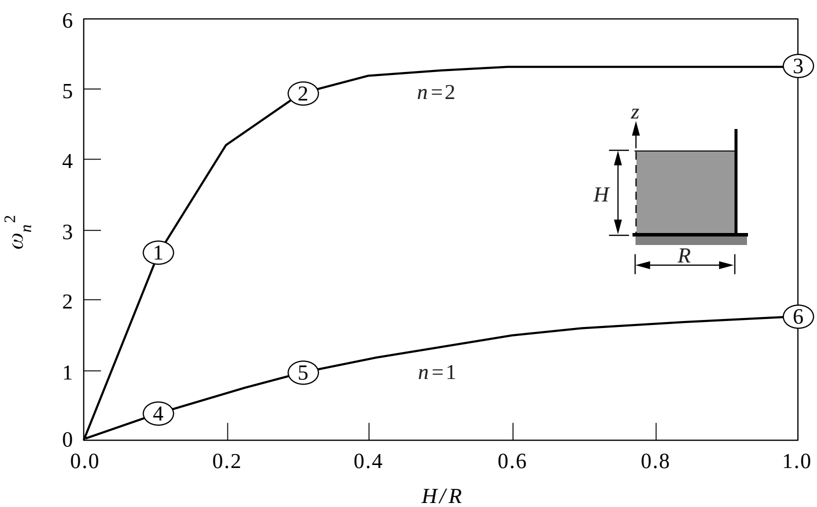

Figure 4. Variation of natural frequencies (cos θ type) versus H/R.

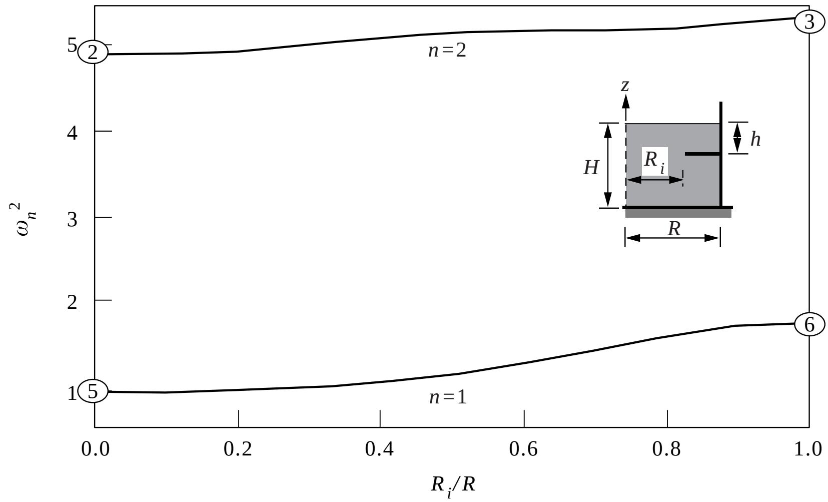

Figure 5. Variation of natural frequencies (cos θ type) versus R_i/R. $H/R = 1$; $h/H = 0{\cdot}3$.

When the internal radius of the baffle vanishes, the baffle separates the liquid domain into two domains. In this case, the liquid under the baffle behaves like a rigid solid and has no vibration, because it has no moving surfaces. Liquid in the upper domain has natural vibrations, because it has a free surface. Therefore, point 2 in Figure 5 for the cylindrical tank with a baffle ($h/H = 0{\cdot}3$) corresponds to point 2 in Figure 4 for the cylindrical tank without baffle ($H/R = 0{\cdot}3$). Similar situations are true for all of the points with the same numbers in the figures, because they denote identical situations in physical meaning.

4.1.2. *Liquid in the cylindrical tank with a baffle*

The natural frequencies are given in Figure 5, for $H/R = 1$ and the tank with a baffle. From Figures 5 and 6, upon taking the circles with 1 and 4 into account, it is seen that the lower the depth of the baffle, the larger the effect of the baffle on the frequency.

4.2. SEISMIC ANALYSIS

The record which is used in the numerical examples, with 0·01 s intervals, belongs to the *N-S* component of the 1992 Erzincan Earthquake, Turkey; see Figure 7. The acceleration values for the smaller intervals are obtained by using the linear interpolation method. The first 10 s of records has been used for all of the examples.

4.2.1. *Liquid in the cylindrical tank*

The maximum shear force and the overturning moment at the bottom of the tank without a baffle, for different values of H/R, are given in Figure 8. Some of the liquid, near to the base of the tall tank, has a rigid character like a solid. The rest has a behavior like a spring–mass system. A spring–mass system is the mechanical model of the sloshing part of the liquid [12, 15].

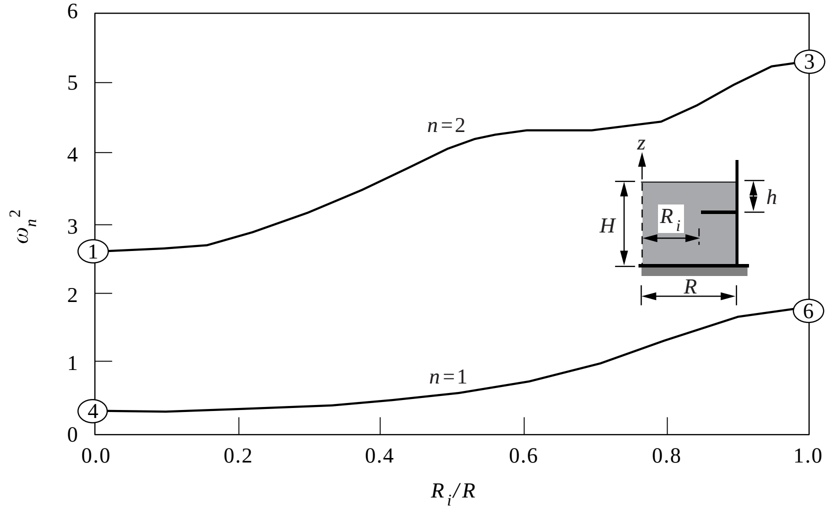

Figure 6. Variation of natural frequencies (cos θ type) versus R_i/R. $H/R = 1$; $h/H = 0{\cdot}1$.

4.2.2. *Liquid in the cylindrical tank with a baffle*

Any of the foundation forces can then be described by two components that are caused by the rigid part and the sloshing part. The liquid under the baffle behaves as a rigid part.

The rigid part causes larger shear force than the sloshing part. If the ratio h/H decreases, the shear force at the bottom of the tank will increase (see Figure 9) and, in practice, the overturning moment will decrease (see Figure 10). If the inner radius of the baffle vanishes, the liquid inside the volume surrounded by the rigid surfaces behaves, of course, like a solid.

Points 7 and 8 in Figures 8–10 show the values for a cylindrical tank without baffles. When the baffle is positioned as near as possible to the free surface of the liquid, it slightly affects the shear force and overturning moment at the bottom of the tank (see Figures 9 and 10).

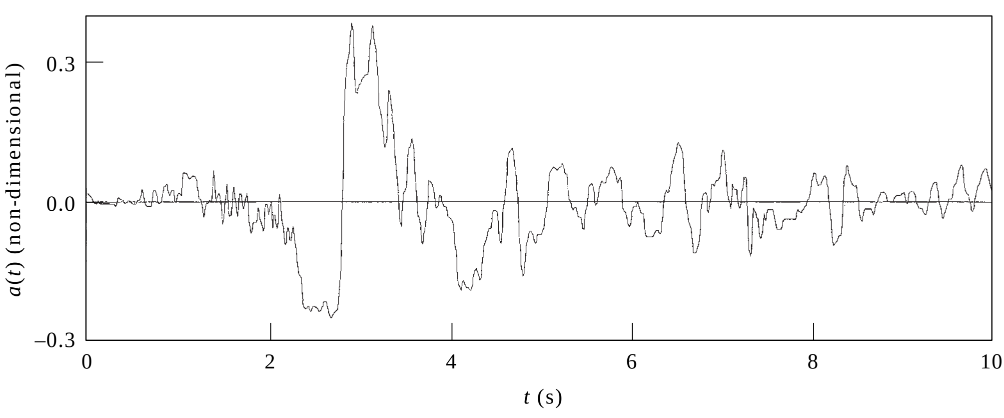

Figure 7. Acceleration diagram: *N-S* component of 1992 Erzincan Earthquake, Turkey.

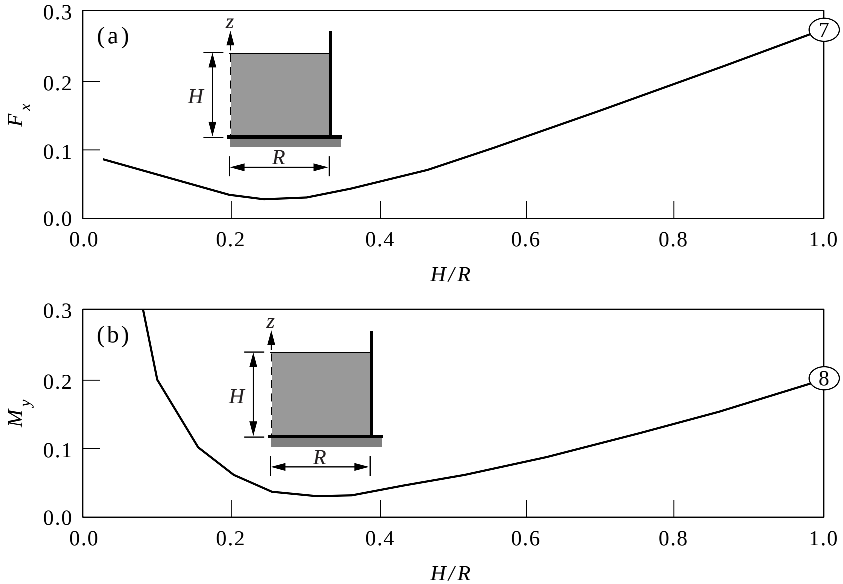

Figure 8. Foundation forces at the bottom of the cylindrical tank versus H/R. (a) Shear force; (b) overturning moment.

5. CONCLUSIONS

The effectiveness of a baffle for damping liquid oscillations has been examined in an attempt to develop more efficient baffle configurations for seismic analysis of the tank. The baffles usually consist of rigid annular rings or plates which are fitted around the internal periphery of the tank.

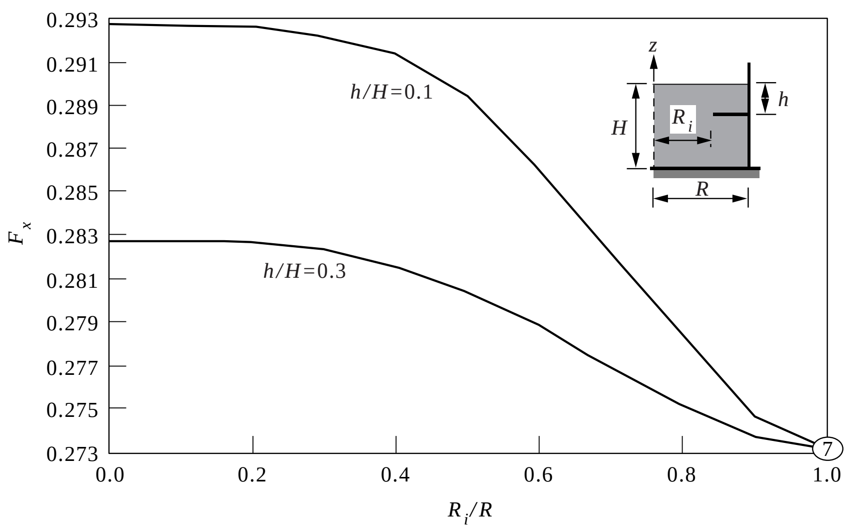

Figure 9. Maximum shear force at the bottom of the tank, occurring in the first 10 s of the earthquake, versus R_i/R. $H/R = 1$.

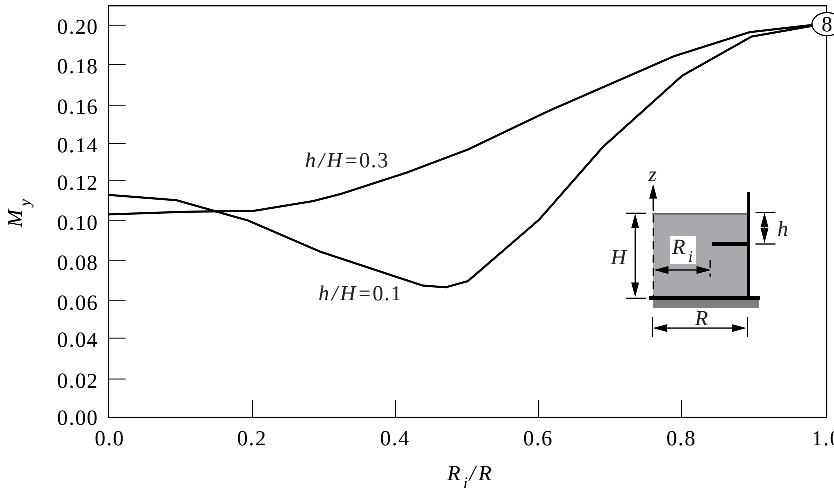

Figure 10. Maximum overturning moment at the bottom of the tank, occurring in the first 10 s of the earthquake, versus R_i/R. $H/R = 1$.

For an effective passive control system, configurations can be designed by freely suspending baffles between limits along the tank wall and by positioning them slightly below the liquid surface. If stiffeners are required in the tank design for structural integrity, the baffles and support rings may serve the dual purpose of slosh damper and stiffener.

A baffle can be successfully used as a passive control system. For an effective passive control system, the inner radius should be greater than a half of the outer radius and the baffle should be located as near as possible to the free surface of the liquid. A baffle just on the free surface causes a non-linear behavior because of the unknown free surface. In this paper it has been assumed that the baffle is always surrounded by the liquid.

Although the baffle causes an increase in the value of the shear force (Table 1), it should be used to get a smaller overturning moment. The decrease in the ratio

TABLE 1

The effects of the baffle on the foundation forces: (a) *ratio of shear forces*; (b) *ratio of overturning moments*

R_i/Rd	h/H 0·1	h/H 0·3
	(a) F_x with/F_x without	
0·5	1·06	1·03
0·8	1·02	1·01
	(b) M_y with/M_y without	
0·5	0·35	0·70
0·8	0·85	0·93

of overturning moments is strictly larger than the increase in the ratio of shear forces (see Table 1). This makes the usage of the baffle effective. As an example, for the location of the baffle such as $h/H = 0{\cdot}1$ and inner radius $R_i/Rd = 0{\cdot}8$, shear force is increased 102% by the baffle. However the overturning moment is decreased 85% by the baffle.

The overturning moment can cause an uplift problem in the liquid storage tanks under the earthquake motion. Therefore, a baffle can be used to prevent this problem.

Other types of baffles, i.e., baffles capable of deflecting, deforming, and/or moving with respect to the tank wall will be the subject of the next study. In addition, the damping provided by rigid baffles of comparable size will be examined to determine the relative effectiveness between rigid and flexible systems. Furthermore, the subject of preventing uplift problems in liquid storage tanks under earthquake motion by using a baffle will also be a study in the future.

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