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PERFORMANCE OF BASE-ISOLATED SPENT FUEL STORAGE POOL STRUCTURES

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ABSTRACT

A modal analysis technique is presented for the seismic response analysis of base-isolated spent fuel storage structures taking into account of fluid-structure interaction effects and composite damping characteristics of the base-isolated structural system. Responses of a base-isolated pool structure subjected to 1940 El Centro earthquake load are analyzed by the developed method and compared with the responses of fixed base counter part. An objective function for the optimization of the base-isolated pool structure is proposed which is based on strain energies of the structure and base isolator.

1. INTRODUCTION

Spent fuel assemblies or canisters are usually stored in rectangular reinforced concrete pool structures, which may not be rigid dynamically, in the wet-type interim spent fuel storage facility(ISFSF). It is well recognized that hydrodynamic pressure in a flexible container can be greatly amplified due to the fluid-structure interaction effects between the fluid inside and the flexible walls[1]. But, if base isolators are installed between the base slab and foundation, the earthquake load transmitted to the superstructure can be reduced significantly, and vibration characteristics can be controlled too[2]. The reduced base acceleration of the superstructure will enhance the safety of stored canisters or spent fuel assemblies.

In this paper, a 2-D analysis method of the coupled system is described and its dynamic characteristics under horizontal ground acceleration are investigated.

Since the convective pressure due to the sloshing of the fluid can be practically decoupled and is one order of magnitude less than the impulsive pressure due to the fluid mass moving together with the structure[3], the impulsive mass alone is computed by finite element modeling of the potential flow of the incompressible ideal fluid and added to the structural mass lumped at the nodes. Because of the dominant contribution of the 1st mode, vibration of the fluid-structure system is described by the first mode alone.

Isolators are assumed to be laminated rubber bearing type which can be modeled by a linear spring and a viscous damper. The coupled equation of motion for the fluid-structure-isolator system does not accept classical modal decomposition because of composite damping of the system. In this study modal analysis is made possible by finding equivalent modal damping ratios.

Finally, an objective function for the optimization of the base-isolated pool structure is proposed which is based on strain energies of the structure and base isolator.

2. FINITE ELEMENT MODELING OF FLUID MOTION

Two dimensional motion of invicid and incompressible ideal fluid (Fig. 1) can be expressed in terms of velocity potential. The velocity potential $\phi(x,t)$ satisfies two-dimensional Laplace equation in the fluid region;

$$\nabla^2\phi = \left(\frac{\partial^2}{\partial x_1^2}+\frac{\partial^2}{\partial x_2^2}\right)\phi(x,t) = 0. \tag{1}$$

Applying Galerkin finite element method to Eq. (1), algebraic equations governing fluid motion are derived easily in the following form;

$$[B]\{\dot{v}\} = \{p\} \tag{2}$$

where $\{p\}$ and $\{\dot{v}\}$ denote nodal pressure vector and nodal acceleration vector in inertia reference frame defined at the nodes along the wall respectively.

By employing shape functions used to interpolate pressure distribution and acceleration along the boundary of each finite element and by applying virtual work principle, the relationship between nodal force vector, $\{F\}$, and nodal acceleration vector can be derived in the following form;

$$[M_f]\{\ddot{u}\} = -\{F\} - [M_f]\{1\}(\ddot{u}_b+\ddot{u}_g) \tag{3}$$

where $\{\ddot{u}\}$ is nodal acceleration vector relative to the base of the structure, $\ddot{u}_b$ is base acceleration relative to the ground and $\ddot{u}_g$ is ground acceleration.

3. EQUATION OF MOTION FOR THE COUPLED SYSTEM[4]

The motion of dry structure may be described by the next equation;

$$[M_d]\{\ddot{u}\} + [C_d]\{\dot{u}\} + [K_d]\{u\} = -[M_d]\{1\}(\ddot{u}_b+\ddot{u}_g) + \{F\} \tag{4}$$

where $[M_d]$, $[C_d]$, and $[K_d]$ are mass, damping and stiffness matrix of the dry structure model respectively. The governing equation for the coupled fluid-structure system may be easily obtained by combining Eq. (3) and (4);

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{1\}(\ddot{u}_b+\ddot{u}_g). \tag{5}$$

Assuming that damping matrix $[C]$ can be diagonalized, the following modal equations are obtained;

$$\{u\} = \eta_n\{\phi_n\}, \tag{6}$$

$$\ddot{\eta}_n + 2\xi_n\omega_n\dot{\eta}_n + \omega_n^2\eta_n = -\Gamma_n(\ddot{u}_b+\ddot{u}_g) \tag{7}$$

where ω_n, η_n, ξ_n, $\{\phi_n\}$ and Γ_n denote the natural frequency, modal amplitude, modal damping ratio , mode shape vector and modal participation factor of the n-th mode respectively. Since the motion of the superstructure will be dominated by the first vibration mode, it may be expressed as follows;

$$\{u\} = \eta_1\{\phi_1\}, \tag{8}$$

$$\Gamma_1\ddot{u}_b + \ddot{\eta}_1 + 2\xi_1\omega_1\dot{\eta}_1 + \omega_1^2\eta_1 = -\Gamma_1\ddot{u}_g \tag{9}$$

The substructure consisting of the base mass and isolator may be modeled mechanically by the following equations;

$$m_b(\ddot{u}_b+\ddot{u}_g) + c_b\dot{u}_b + k_bu_b - F_s = 0 \tag{10}$$

$$F_s = -\{1\}^T[M](\{\ddot{u}\} + \{1\}(\ddot{u}_b+\ddot{u}_g)) \tag{11}$$

where m_b, c_b, and k_b denote base mass, viscous damping and stiffness of the isolator. Introduction of Eq. (8) and (11) into Eq. (9) will render the following equation;

$$(m_s+m_b)\ddot{u}_b + c_b\dot{u}_b + k_b u_b + q_1\ddot{\eta}_1 = -m_t\ddot{u}_g \tag{12}$$

where $q_1 = \{1\}^T[M]\{\phi_1\}, m_s = \{1\}^T[M]\{1\}$, $m_t = m_s + m_b$. Eq. (9) and Eq. (12) constitute the governing equation for the coupled fluid-structure-isolator system, which can be expressed in the (2 x 2) matrix equation;

$$[M_c]\{\ddot{u}_c\} + [C_c]\{\dot{u}_c\} + [K_c]\{u_c\} = -\{q_c\}\ddot{u}_g. \tag{13}$$

Because damping characteristic of the superstructure is quite different from that of the isolator and the matrix, $[C_c]$, in the above equation may not be diagonalizable in general, Eq. (13) can not be solved by the traditional modal analysis method. In order to remedy this shortcoming and make the response spectrum analysis be possible, equivalent modal damping ratios are calculated explicitly as explained in next section.

4. EQUIVALENT MODAL DAMPING RATIOS

It starts from the assumption that modal damping ratios are given as ξ_{1c} and ξ_{2c}. From the assumed modal damping ratios, damping matrix for the system may be composed as

$$[\overline{C_c}] = [\phi_c]^{-T}\begin{bmatrix} 2\xi_{1c}\omega_{1c}M_{1c} & 0 \\ 0 & 2\xi_{2c}\omega_{2c}M_{2c} \end{bmatrix}[\phi_c]^{-1} \tag{14}$$

where $[\phi_c]^{-T}$ is the transpose of the inverse of the mode shape vector matrix, $[\phi_c]$, of Eq. (13) and $M_{nc} = \{\phi_{nc}\}^T[M_c]\{\phi_{nc}\}$. Equating $[\overline{C_c}]$ in Eq. (14) with $[C_c]$ in Eq. (13), equivalent modal damping ratios ξ_{1c} and ξ_{2c} can be calculated. Since there are three equations for two unknowns, they can be calculated by least square method or by equating only diagonal elements.

5. OBJECTIVE FUNCTION FOR THE OPTIMIZATION

Earthquake load may not be known deterministically. Therefore base isolation system need be designed to show good performance against varying earthquake loads expected at the particular site. Usually structural optimization is attempted by stochastic analysis method. But stochastic method requires the earthquake load be described in terms of power spectrum. However, since design response spectrum is employed for the design of most nuclear or non-nuclear facilities, it may be more practical to rely on the spectrum analysis for the optimal design of spent fuel storage structures. The objective function proposed is based on the strain energies of the structure and isolator.

The relative advantage of the isolation system is the increased safety compared with the fixed base structure. Therefore this aspect may be taken into account by the following expression;

$$R_s = \frac{E_{si}}{E_{sf}} \tag{15}$$

where E_{sf} is the maximum strain energy in the fixed base structure model and E_{si} is the strain energy in the isolated superstructure model calculated by response spectrum analysis.

For a given isolator the maximum shear deformation may have to be within the design specification. Therefore the increased safety of the isolator may be expressed by the ratio between the strain energies developed in the isolator;

$$R_b = \frac{E_{ba}}{E_{bo}} \tag{16}$$

where E_{bo} means the maximum strain energy based on the allowable shear deformation limit and E_{ba} is the actually developed strain energy in the isolator. Because one may give different weights to the two ratios, more general form of the objective function $R(k_b,c_b)$, may be written as

$$R(k_b,c_b) = \alpha R_b + \beta R_s \tag{17}$$

where α and β are weighting factors which depend on the importance consideration. Thus optimization of the isolator may be defined as finding k_b and c_b which produce the minimum value of Eq. (17) within prescribed constraints. The usual constraint is the limit in the base displacement. This kind of constraint can be easily imposed to Eq. (17).

6. PERFORMANCE ANALYSIS

Using the developed program, seismic responses of an isolated pool structure are analysized. The model is described in Fig. 1. The superstructure of the isolated system is identical with that for fixed base model. Mechanical properties of the isolator chosen are given in Table 1.

Table 1. Properties of isolator

Type	k_b	c_b	ω_b*	ξ_b**
Laminated Rubber Bearing	120.16t/m	11.47t·s/m	3.14r/s	0.15

* $\omega_b = \left[\dfrac{k_b}{m_d+m_f}\right]^{1/2}$, ** $2\xi_b\omega_b = c_b/(m_d+m_f)$

m_f = total fluid mass/4, m_d = total mass of the dry structure

Acceleration responses at the top of the dry structure subject to N-S component of 1940 El Centro earthquake records whose peak ground acceleration is scaled down to $0.2g$ are given in Fig. 2. It is easily observed that base isolation system is very effective in reducing acceleration responses. Responses of the pool structure containing fluid excited by the same earthquake input are analyzed. Calculated acceleration responses at the top of the structure are provided in Fig. 3. It is confirmed that isolation system is more effective in the reduction of the seismic responses for the pool structure than for the dry one.

Comparisons of the base displacements in the dry structure with those in the wet one are made in Fig. 4. The maximum base displacement of the wet structure is larger than the dry structure as expected. This may be primarily because of the added fluid mass and increased base shear due to the dynamic fluid-structure interaction effects.

As explained in the introduction section, one of the major concern is determining mechanical properties of the base isolator to show good performance under uncertain earthquake load. Using the objective function defined previously, optimization of the isolator is attempted for the pool structure model. Shown in Fig. 5 is objective function defined by Eq. (17) with $\alpha = \beta = 1$ and $\xi_b = 0.15$. The independent variable, ω_b, for the calculation is defined in Table 1. The earthquake load is prescribed by site-independent design response spectrum given in Reg. Guide 1.60[5] with $PGA = 0.2g$. It is observed for the given damping ratio, the optimal ω_b is found to be around $(2\pi)(1.03)$.

7. CONCLUDING REMARKS

A simple modal analysis method of a coupled fluid-structure-isolator system is presented. The final equation has only 2 degrees of freedom. Seismic analysis results for a pool structure indicate that base isolation system is very efficient in reducing the transmitted earthquake load. Also presented is an objective function based on the strain energy consideration. The good behavior of the derived function suggests that it may be utilized in the actual design process. But still further works need be done to include 3-dimensional effects to the dynamic response analysis of the pool structure.

Since free surface sloshing may be another important design concern especially for the spent fuel storage pool structures, the effect may have to be included both in the objective function, possibly in a form of kinetic energy, and in the fluid-structure interaction modeling.

8. REFERENCES

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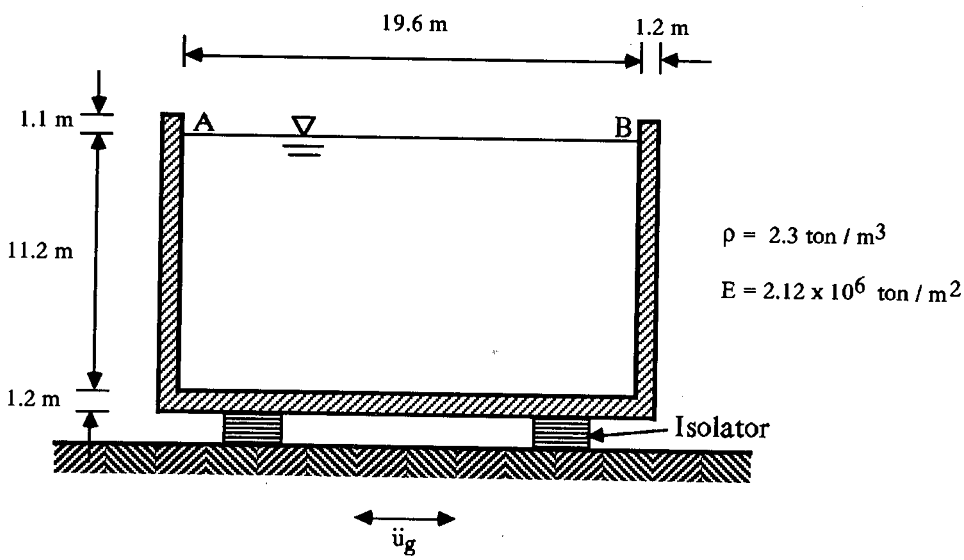

Fig. 1 Spent Fuel Storage Pool Model and Isolators

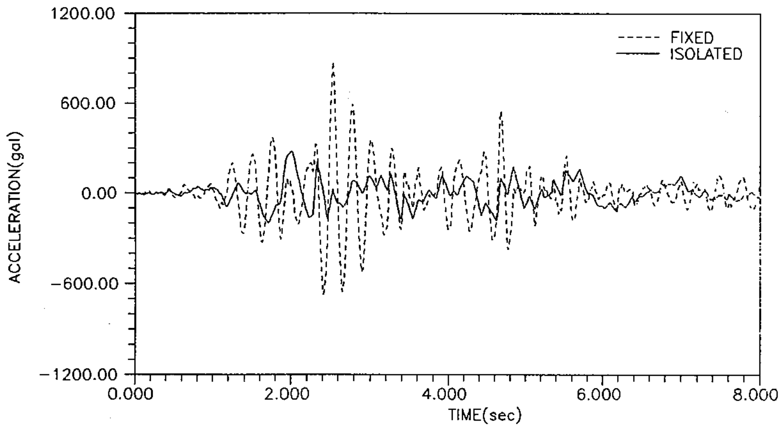

Fig. 2 Performance comparison of dry structure model (Top Acceleration)

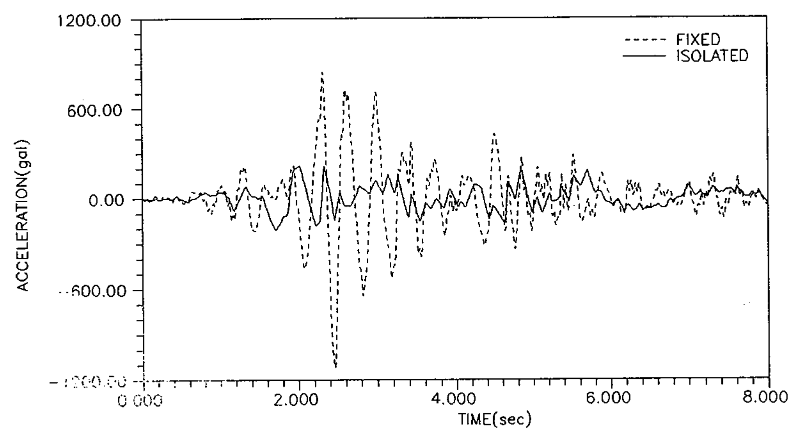

Fig. 3 Performance comparison of the pool structure (Top Acceleration)

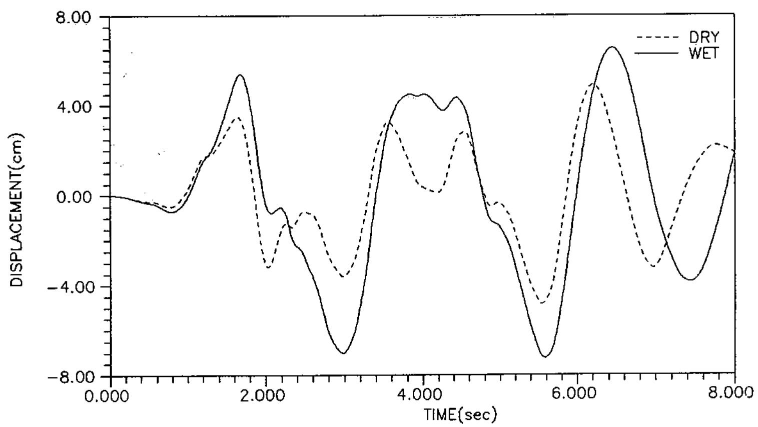

Fig. 4 Comparison of base displacements between dry and wet structure

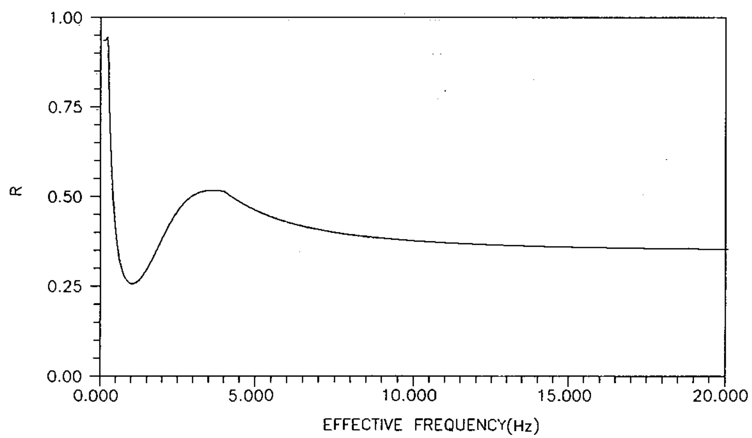

Fig. 5 Objective function under the earthquake load defined by Reg. Guide 1.60 site-independent design spectrum(PGA=0.2g)