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Seismic analysis of base isolated spent fuel storage structures

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ABSTRACT : An extensive series of experiments was conducted to evaluate the mechanical characteristics of laminated rubber bearings. The pseudo-dynamic test method was employed in this study to predict the seismic response of a base isolated spent fuel storage system. The numerical analyses on the base isolated spent fuel storage structures were conducted using the various numerical models obtained from test results. It is shown that the numerical results obtained using the analytical model are in an excellent comparison with the test results. Thus, the proposed method is considered to be efficient and reliable for evaluation of the seismic response of a base isolated spent fuel storage system.

1. INTRODUCTION

The safety of spent fuel storage structures is extremely important, because the failure of the structures, containing cooling water and spent fuel which are of high level in radioactivity, may have disastrous consequences on lives and environments. An alternative to increase the seismic resistance of the spent fuel storage structure and its anchorages is to reduce the seismic forces to which the structure is subjected by incorporating base isolators. In general, a linear vicously damed model, roughly defining the characteristics of base isolators, can not accurately represent the isolated system in which the structure is affected by the hysteresis and the strain hardening induced from base isolators. Therefore, it would be desirable to conduct experimental studies on the isolated systems.

The base isolated spent fuel storage structures were tested by the Pseudo-dynamic(PSD) test method using a substructuring technique in which the isolated system is devided into the tested and computed parts. The experiments were performed to evaluate the mechanical characteristics og base isolator, and the seismic analyses on the base isolated spent fuel storage structures were conducted using the various numerical models obtained from test results. The numerical results using several hysteresis models and experimental results are in good agreements. Thus, the proposed method is considered to be efficient and reliable for evaluation of the seismic response of a base isolated spent fuel storage system.

2. MODELLING OF A FLUID-STRUCTURE SYSTEM

2.1 *Rectangular liquid storage structures*

The rectangular structure is mounted onto the base isolators on the ground and partially filled with fluid shown in Fig 1. The behaviors of the stuctures during earthquake are basically 3-dimensional. However, for the complicity, the 2-dimensional structure as shown in Figure 2 is considerd in this study. The wall of the structures are modelled by using beam elements. In the actual analysis, only a half of the fluid-structure system is considered, because the motion of the system under horizontal earthquake loading is anti-symmetric with respect to the vertical plane at the center.

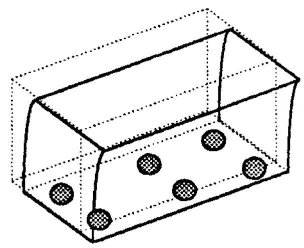


Fig. 1 Base-Isolated Liquid Storage Structure

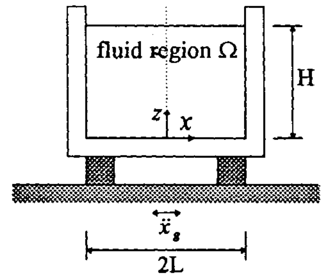


Fig. 2 Model of Rectangular storage structure

2.2 *Velocity potential and hydrodynamic forces*

For the irrotational flow of an incompressible inviscid fluid, the velocity potential, $\phi(x,z;t)$, satisfies the Laplace equation in the fluid region.

$$\nabla^2\phi(x,z;t)=0 \quad in\ \Omega \tag{1}$$

Then, the fluid-wall boundary conditions can be expressed as follows:

$$\phi_{,x}(\pm L,z;t)=\dot{W}(z;t) \tag{2}$$

$$\phi_{,z}(x,0;t)=0 \tag{3}$$

$$\phi_{,z}(x,H;t)=\dot{\xi}(x;t) \tag{4}$$

$$\rho\dot{\phi}(x,H;t)+\rho g\xi(x;t)=0 \tag{5}$$

where $\xi(x;t)$ is the elevation of the free surface over the mean surface level; $W(z;t)$ is the horizontal displacement of the wall; $\phi_{,x}$ represents $\partial\phi/\partial x$; ρ is the mass density of fluid; and g is the acceleration of gravity. The general solution for the Eq. (1). which satisfies the boundary condition on the tank wall, Eq. (2), can be expressed as,

$$\phi(x,z;t)=\sum_{n=1}^{\infty}A_n(z;t)\sin\lambda_n x+x\dot{W}(z;t) \tag{6}$$

where $\lambda_n=(2n-1)\pi/2L$ and $A_n(z;t)$ is the time varying coefficients of the n-th term in the sine series which is to be determined using the other boundary conditions. The free surface elevation can be also expressed in terms of the sine series as,

$$\xi(x;t)=\sum_{n=1}^{\infty}\eta_n(t)\sin\lambda_n x \tag{7}$$

where $\eta_n(t)$ represents the generalized free surface amplitude associated with $\sin\lambda_n x$.

Substituting Eqs. (6) and (7) into Eqs. (1), (3), (4) and (5), one can obtain expressions for $A_n(z;t)$ in terms of $\dot{W}(z;t)$ and $\eta_n(t)$. The horizontal displacement of the wall is represented by the using third order polynomial of z within each beam element. Once the solution for $A_n(z;t)$ is obtained, substituting it into the free surface boundary conditions, one can obtain the relationship between $\{\eta\}$ and $\{\ddot{d}\}$ as,

$$[M_{ff}]\{\ddot{\eta}\}+[K_{ff}]\{\eta\}=[S]\{\ddot{d}\} \tag{8}$$

where diagonal matrices $[M_{ff}]$ and $[K_{ff}]$ can be interpreted as mass and stiffness matrices associated with the free surface motion; and $[S]$ is the coefficient matrix of the exciting force associated with the wall motion. The hydrodynamic pressure exerted on the wall can be expressed in terms of velocity potential. Then, the nodal hydrodynamic force vector, $\{F\}$, can be obtained as,

$$\{F\}=-[M_a]\{\ddot{d}\}-[S]^T\{\eta\} \tag{9}$$

where $[M_a]$ is the hydrodynamic added mass matrix associated with the horizontal movement of the liquid; and $[S]$ is the matrix relating the horizontal force on the wall with the free surface motion.

2.3 *Equation of motion for the base isolated spent fuel storage system*

Combining Eqs. (8) and (9), the equation of the fluid structure system can be obtained as,

$$\begin{bmatrix} M_{ss}+\overline{M}_a & 0 \\ -\overline{S} & M_{ff} \end{bmatrix}\begin{Bmatrix} \ddot{d} \\ \ddot{\eta} \end{Bmatrix}+\begin{bmatrix} K_{ss} & \overline{S}^T \\ 0 & K_{ff} \end{bmatrix}\begin{Bmatrix} d \\ \eta \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{10}$$

where $\{d\}$ is the nodal horizontal displacement vector of the wall; $[\overline{M}_a]$ and $[\overline{S}]$ are the matrices corresponding to $[M_a]$ and $[S]$ but with proper dimensions. By expressing the displacement vector of the free nodes, $\{d\}$, as the sum of the ground movement, $\ddot{x}_g$, and the relative displacement to the ground movement, $\{x_r\}$, i.e.,

$$\{d\}=\{1\}x_g+\{x_r\} \tag{11}$$

Decomposing the displacement vector $\{x_r\}$ into the components at the base isolator $\{x_b\}$ and at the nodes on the wall $\{x_w\}$, Eq. (11) can be rewritten as,

$$\begin{bmatrix} M_{bb} & M_{bw} & 0 \\ M_{bw}^T & M_{ww} & 0 \\ -\overline{S}_b & -\overline{S}_w & M_{ff} \end{bmatrix}\begin{Bmatrix} \ddot{x}_b \\ \ddot{x}_w \\ \ddot{\eta} \end{Bmatrix}+\begin{bmatrix} K_{bb} & K_{bw} & \overline{S}_b^T \\ K_{bw}^T & K_{ww} & \overline{S}_w^T \\ 0 & 0 & K_{ff} \end{bmatrix}\begin{Bmatrix} x_b \\ x_w \\ \eta \end{Bmatrix}=-\begin{bmatrix} M_{bb} & M_{bw} \\ M_{bw}^T & M_{ww} \\ -\overline{S}_b & -\overline{S}_w \end{bmatrix}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix}\ddot{x}_g \tag{12}$$

or $\quad [M]\{\ddot{x}\}+[K]\{x\}=-[M^*]\{1\}\{\ddot{x}_g\}$

where K_{bb} is the stiffness coefficient for the base motion which can be expressed as the sum of the stiffness coefficient associated with the tank wall, K_{bb}^w and the base isolator, K_{Isol}. Decomposing Eq. (12) into the substructure of isolation system and superstructure of storage tank, Eq. (12) can be simply expressed as Eq. (13).

$$[M]\{\ddot{x}\}+[C^I]\{\dot{x}\}+[K^I]\{x\}+\{R^E\}=-[M^*]\{1\}\{\ddot{x}_g\} \tag{13}$$

where :

$$[C^I]=\begin{bmatrix} 0 & 0 & 0 \\ 0 & c_w & 0 \\ 0 & 0 & c_f \end{bmatrix},\quad [K^I]=\begin{bmatrix} K_{bb}^w & K_{bw} & \overline{S}_b^T \\ K_{bw}^T & K_{ww} & \overline{S}_w^T \\ 0 & 0 & K_{ff} \end{bmatrix},\quad \{R^E\}=\begin{Bmatrix} c_b\dot{x}_b+K_{Isol}x_b \\ 0 \\ 0 \end{Bmatrix}=\begin{Bmatrix} R_{Isol} \\ 0 \\ 0 \end{Bmatrix}$$

3. PSEUDO-DYNAMIC TESTS OF BASE ISOLATED SPENT FUEL STORAGE STRUCTURES

3.1 *Pseudo-dynamic test method*

The Pseudo-dynamic test method is a relatively new experimental technique for evaluating the seismic performance of structural models in a laboratory by means of on-line computer controlled simulation. Thus, in fundamental PSD technique, the structural model is represented as a discrete system and solved for its seismic response by using the direct integration, while their restoring forces are not numerically modeled but directly measured from a test conducted in parallel with the direct integration.

On behalf of evaluating the seismic performance of base-isolated spent fuel storage tanks as a base isolation system, the PSD test incorporating a substructuring technique, which have been mostly developed and applied by Dermitzakis et al. and Nakashima et al., was employed in this study. Thus, the base-isolators would be only tested on the tested part whose hysteretic behavior was complicated and not well-defined, whereas the liquid tanks as the computed part would be numerically treated in a computer with the mechanical model. For this purpose, as an integration method adaptable to the PSD test, an implicit-explicit method proposed by Hughes et al. was used. This method combined with the general Newmark method and an explicit predictor-corrector method is to apply an explicit method to the tested part and an implicit method to computed part. Implementation scheme of the PSD test can be described as three main operations: (a) numerical integration, (b) displacement control, (c) data acquisition.

3.2 *Description of test models*

The base-isolated reinforced concrete structure for the storage of spent fuel is investigated. The width (2L) and the wall thickness(h) are taken as 12m and 1.2m, respectively. The fluid is assumed to be filled upto 13m above the base. The material properties of the concrete storage structure are: Young's modulus(E)=19.6 GPa, Poisson's ratio(ν)=0.2 and mass density(ρ_s)=2.4×10^3Kg/m^3. The properties of fluid elements are: bulk modulus(K)=2.0 GPa, mass density(ρ)=1.0×10^3Kg/m^3. The test models were subsequently tested using the El Centro 1940 NS accelerogram. The voscous damping ratio of convective and impulsive modes were assumed to be 5% and 0.5% respectively. The frequencies associated with convective and impulsive modes of fixed base spent fuel storage structure are illustrated in Table 1.

Table 1. Frequencies of fixed-base storage structure (Hz)

	1st	2nd	3rd	4th
Convective mode	0.255	0.442	0.570	0.675
Impulsive mode	3.276	17.880	43.047	124.064

The base isolators, shown in Fig. 3, were loaded horizontally along transverse direction. The tests were performed using the test apparatus which exerted two hydraulic actuators on horizontal and vertical directions simultaneously as shown in Fig. 4. Vertical loads and horizontal displacements exerting on a pair of base isolators are controlled by each actuator from which the displacements and restoring forces of the isolators are measured immediately.

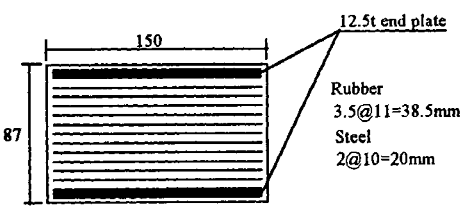


Fig. 3 LRB base isolator

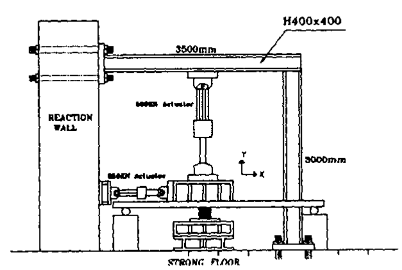
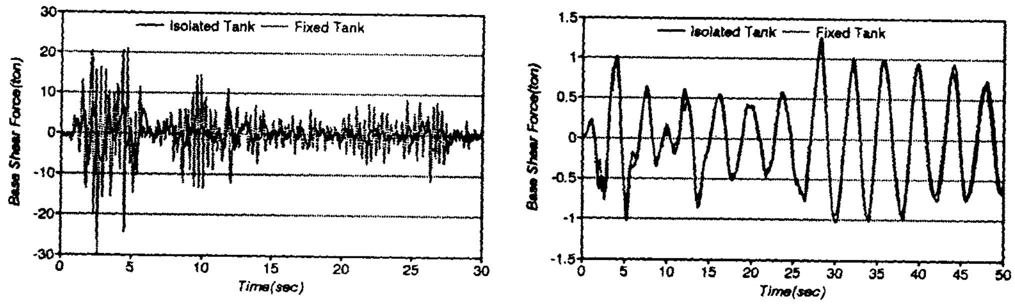


Fig. 4 Test layout

3.3 *Test result*

The Pseudo-dynamic tests incorporating a substructuring technique were performed on the test models subjected by seismic excitations. The seismic response obtained by the PSD tests of the test model are shown from Fig. 5 to Fig. 6. From Fig. 5, it can be observed that the base shear force associated with impulsive component exerting on the tank wall would be well reduced by an effect of base isolation. However, the base shear forces associated with convective components would be slightly increased as using base isolation system. Fig. 6 shows the max. base shear forces and max. wave heights for isolation frequency, f_b, obtained from the test of the isolated tank. In the isolated tank, the convective forces, partly attributed to the tank wall, are almost not reduced but slightly increased. On the other hand, the impulsive forces more dominant rather than the convective forces are reduced to much lower ones due to energy dissipation of base isolators. Thus, it is shown that base isolators have more effect on the impulsive force and lead to much lower resultant seismic forces. Moreover, from Fig. 6, it can be observed that the the max. wave height associated with free surface motion would be increased by an effect of base isolation.



(a) Impulsive mode (b) convective mode

Fig. 5 Base shear force in fixed-base and isolated structure under input ground motion.

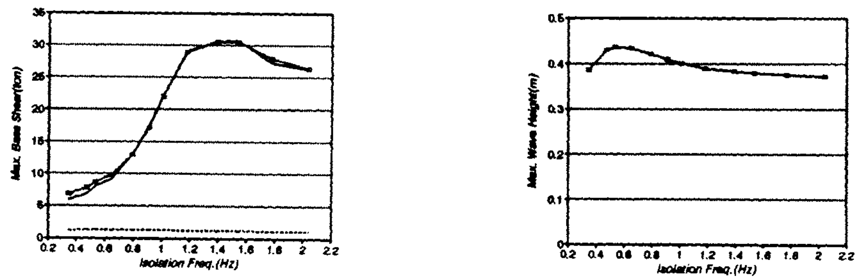
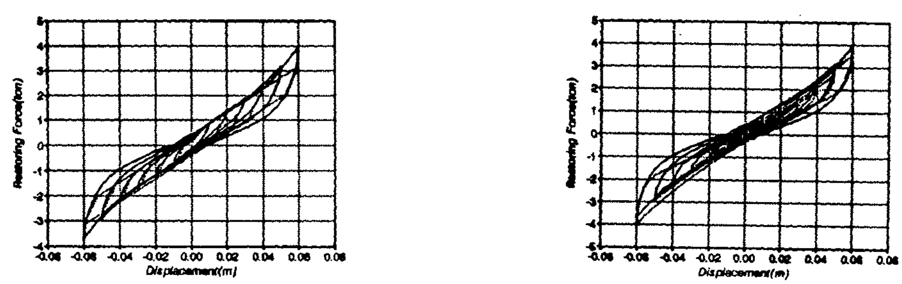


Fig. 6 Relationships of max. base shear forces and max. wave height for isolation frequency on isolated storage structures.

4. HYSTERESIS MODEL PARAMETER OF BASE ISOLATOR

Fig. 7 shows the hysteresis loops for various shear strains, from 10 to 50mm. From this result, hysteretic restoring force characteristics of the base isolator are modelled by the bi-linear model and Bouc-Wen model.



(a) Bi-linear Model (b) Bouc-Wen Model

Fig. 7 Comparison of numerical models with test results

Bi-linear model

From experimental results, the parameters of test piece used in the numerical analysis are determined as follows,

Q_d=0.395 ton, K_I=144.96ton/m K_d=46.10 ton/m

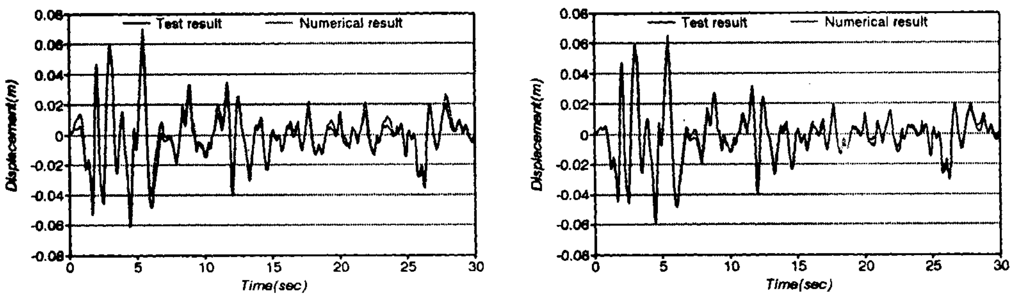
Bouc-Wen model

$$R=\alpha kd+(1-\alpha)kz$$
$$\dot{z}=A\dot{d}+\beta|\dot{d}||z|^{n-1}z-\gamma\dot{d}|z|^{n}$$

From experimental results, the parameters for this model are obtained as follows,
K=36.08 ton/m, α=0.96, A=80.5182, β=161.787m^{-1}, γ=-185.2024m^{-1},

5. SIMULATION ANALYSIS

The numerical analysis results are shown in Fig. 8 compared with the experimental results. From the comparison, it has been indicated that the bi-linear model and the Bouc-Wen model reproduce the experimental result very well. One can note that the Bouc-Wen Model gives better agreements with the experimental results than the bi-linear model, while the bi-linear model is much simpler in computation viewpoint than the Bouc-Wen model.



(a) Bi-linear Model (b) Bouc-Wen Model

Fig. 8 Comparison of analytical results with test results for response time history of the base isolated structure

6. CONCLUSIONS

A number of Pseudo-dynamic(PSD) tests and the numerical analyses have been conducted on the spent fuel storage structure supported by base isolators under earthquake loadings. The seismic performances of the base isolated spent fuel storage structure have been evaluated by using the PSD test method incorporating a substructuring technique. From the test results, it can be considered that the resultant seismic forces exerting on the tank wall would be well reduced by using the isolation system.

Sinse the numerical results obtained using the proposed model show excellent comparisons with the test results, the proposed test method is considered to be efficient and reliable for evaluation of the seismic response of a base isolated spent fuel storage system.

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