Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

**K14/2**

# An aseismic design of equipment submerged in a pool on a base-isolated building

**Shin T.M.**
*Korea Atomic Energy Research Institute, Korea*

## ABSTRACT

For submerged internal equipment like spent fuel storage racks in the nuclear power plant, building base-isolation may cause an adverse effect on the seismic response of the equipment exceptionally. Through a seismic analysis of simplified internal equipment model in a base-isolated building, it is discussed about the potential increase of response in extreme case. As design methods to minimize the increased response in this case, an optimization of fluid gap size for the control of hydrodynamic effect and base isolation of the submerged equipment are introduced.

## 1. INTRODUCTION

Base-isolation of a building (or primary structure) has shown a remarkable performance in seismic response attenuation of its internal (or secondary) equipment through many studies[1,2]. The internal equipment concerned about in the case are mostly in air condition. However, there are some equipment like spent fuel storage racks in nuclear power plant which have to be operated under the submerged condition, and thus experience hydrodynamic resistances against excitations by earthquake[3]. It is known that the fluid coupling between a body and a rigid wall reduces both natural frequencies and modal participation factors of the body compared with the case when they are in air[4]. Noting that most of the base isolation devices generally reduce the fundamental frequency of the building structure, it is easy to expect that building base isolation may have adverse effects by bringing about resonance upon submerged internal equipment.

This paper illustrates such a case through dynamic analyses of a simplified model of submerged internal equipment in a base-isolated building. To reduce the increased response in the case, an optimization of fluid gap size for the control of hydrodynamic effect is attempted. As an alternative for the case that gap control is limited, in addition, a concept of base isolation of the submerged equipment in a base-isolated building is introduced .

## 2. DYNAMIC MODELING

## *2.1 Coupled System Model Considering Hydrodynamic Effect*

Based on the approach given by Fritz[5], the hydrodynamic forces of the fluid coupling, $H$, between the internal equipment and the building shown in Fig.1, can be written as follows :

$$\begin{Bmatrix} F_s \\ F_p \end{Bmatrix} = \begin{bmatrix} -m_H & m_I \\ m_I + m_H & -m_{II} \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{X}_p \end{Bmatrix} \tag{1}$$

where

$F_p$ : Force acting on the pool structure by the submerged equipment movement
$F_s$ : Force acting on the submerged equipment by the pool structure movement
$m_H$ : Hydrodynamic mass associated with the submerged equipment
$m_I$ : Mass of fluid displaced by the submerged equipment
$m_{II}$ : Mass of fluid which would be enclosed by the pool structure without the submerged equipment
$x_s$ : Motion of the submerged equipment relative to the pool structure
$X_p$ : Absolute motion of the pool structure

For the dynamic analysis of interaction between the submerged internal equipment and the building, a cylindrical piece of equipment having a solid or hollow square cross-section is chosen. The equipment is assumed to be fully submerged in a rectangular pool which is located in a building. Sloshing effect of the contained fluid to the seismic response of submerged equipment or building pool structures is assumed to be negligible. Fluid coupling between the submerged equipment and rigid wall of the pool is caused entirely by the inertia of the fluid which is assumed to be incompressible and inviscid.

For a normal hexahedron with a square cross-section surrounded by a rigid concentric outer wall with narrow fluid gap as shown in Fig.1c, the ratio of submerged natural frequency $f_{sH}$ of the equipment to the one in air $f_s$ is given by[6]

$$\frac{f_{sH}}{f_s} = \frac{1}{\sqrt{1 + \frac{m_I}{24 m_s} \cdot \frac{(1+r)^3}{(1-r)r^2} \cdot (\frac{1}{1-e^2} + 3)}} \qquad \text{for } 0.5 \le r < 1, \quad e \ne 1 \tag{2}$$

where $r$ is the ratio of the equipment width, $w_s$, to the pool width, $w_p$, given by $r = w_s / w_p$, and the eccentricity, $e$, is defined as the ratio of $E$, the equipment initial deviation from the concentric center, to the gap size, $g$, given by $e = E / g$. These dimensionless variables, $r$ and $e$, are defined as control variables of fluid gap optimization for the reduction of submerged equipment response.

In order to simply express the interaction of a submerged equipment with the fluid, let us consider a single degree of freedom system as shown in Fig.1. In this simple system, the displacement relative to the building floor would be an important measure as an indicator of structural integrity because the relative displacement is, in general, proportional to the strain inside a structure. For a multi-story building which is base-fixed and dynamically behaves like a simple beam[6], it can be approximately modeled as a single degree of freedom system as shown in Fig.1a. From the fact that the first mode of the base-isolated building is almost entirely a rigid body mode, in which there is no deformation in the superstructure, the base-isolated building can be simplified as 2-DOF system model consisted of the isolator at the base and the superstructure of building as shown in Fig. 1b.

### 2. 2 *Equation of Motion for the Coupled System*

Dynamic models of submerged internal equipment located on buildings with two different base conditions are shown in Fig. 1a and Fig. 1b. The base-fixed building has a lumped mass $M_p$, a stiffness $K_p$, a damping coefficient $C_p$, and the submerged equipment has mass $m_s$ and stiffness $k_s$, a damping coefficient $c_s$ as shown in *Fig. 1a.* Hydrodynamic coupling $H$ between the internal equipment and the pool structure on the building is modeled using equation (1). Let $U_g$, $U_p$, and $u_s$ be respectively the ground motion, displacement of the building structure to the base, and that of the submerged equipment relative to the building floor. Then, the equations of motion for the internal equipment in base-fixed building model become

$$\begin{aligned} &M'\ddot{U}_p + C_p\dot{U}_p + K_pU_p = -M'\ddot{U}_g - m_{sI}\ddot{u}_s \\ &m_{sH}\ddot{u}_s + c_s\dot{u}_s + k_su_s = -m_{sI}(\ddot{U}_g + \ddot{U}_p) \end{aligned} \qquad (3)$$

where $M' = M_p + m_{II} + m_{sI}$ , $m_{sI} = m_s - m_I$, $m_{sH} = m_s + m_H$ .

Now let us assume the building is base-isolated. And the base is assumed to have mass $M_b$, stiffness $K_b$, a damping coefficient $C_b$. Let $U_b$ be the base displacement relative to the ground and other assumptions and notations be the same as in the case of base-fixed building. Then the equations of motion for the total system are given by

$$\begin{aligned} &M^t\ddot{U}_b + C_b\dot{U}_b + K_bU_b = -M^t\ddot{U}_g - M'\ddot{U}_p - m_{sI}\ddot{u}_s \\ &M'\ddot{U}_p + C_p\dot{U}_p + K_pU_p = -M'(\ddot{U}_g + \ddot{U}_b) - m_{sI}\ddot{u}_s \\ &m_{sH}\ddot{u}_s + c_s\dot{u}_s + k_su_s = -m_{sI}(\ddot{U}_g + \ddot{U}_b + \ddot{U}_p) \end{aligned} \qquad (4)$$

where $M^t = M_b + M'$ .

## 3. SEISMIC ANALYSIS AND DISCUSSION

### 3.1 *Descriptions of Analysis Method*

The fundamental natural frequency and damping ratio of the base-fixed building model in Fig. 1a are respectively assumed to be 3.3Hz and 0.02. To analyze the influence of base-isolation type on the seismic response of the submerged internal equipment, four different types of base isolation devices ; Laminated Rubber Bearing(LRB), Pure-Friction(P-F) isolator, isolator by Electricite de France (EDF) and Resilient-Friction Base Isolation system(R-FBI) are considered. The natural frequencies and damping ratios of the base-isolators are as shown in Table 1[2]. A value of 0.01 is taken for the common mass ratio of the submerged equipment to the floor, and 0.01 for the damping ratio of the submerged equipment based on $m_{sH}$. The peak seismic responses are calculated for the in-air natural frequency of 0 Hz to 20 Hz.

The sixth order Runge-Kutta scheme and double precision were chosen for numerical integration of the equations of motion in FORTRAN. The input earthquake is El Centro 1940. Since displacement of the submerged equipment relative to the floor would be an indicator of strain in real elastic structures, the response of the equipment is discussed mainly in terms of the relative displacement response.

### *3.2 Influences of Building Base-Isolation on Equipment Response*

Fig. 2 shows two different effects of the building base-isolation on the seismic responses of internal equipment in air and in submerged condition. The peak seismic responses of the internal equipment for $f_s$= 0 Hz - 20 Hz are investigated. As reported from many studies, both of the EDF and LRB building base-isolations significantly reduce the seismic response of the in-air equipment regardless of the natural frequency of the equipment for $f_s$= 1.5 Hz - 20 Hz as shown in Fig.2a. On the contrary, the base-isolation of the building turns out to give adverse effect on the response of the submerged equipment. Fig. 2b shows amplification of the peak responses of the submerged internal equipment by EDF or LRB base-isolation of the building for the added mass effect $\frac{m_{sH}}{m_s} = 64$. It can be seen that in the EDF and LRB base-isolations the response rises near the submerged resonance frequencies $f_{sH}$= 0.9 Hz and 0.5 Hz respectively, which correspond to $f_s$= 7.5 Hz and 4 Hz for $\frac{m_{sH}}{m_s} =$ 64. That is, the response increase at the resonance peak for the LRB and EDF base-isolations and the level of increase is about 4 to 6 times at worst cases.

Fig.3 shows the effect of building base isolation on the peak sliding displacement of the submerged internal equipment for the added mass effect $\frac{m_{sH}}{m_s} = 25$ when the equipment is assumed to be free standing and the friction coefficient to be a value of 0.2. Though the increase or decrease of the peak responses depends upon the natural frequency of the equipment, the maximum increase of the sliding displacement reaches about 4 times. Considering that the peak sliding displacement is one of the important factor in seismic design for the free standing equipment, the adverse effect on the submerged equipment by building base isolation should be overcome through an appropriate design strategy.

### *3.3 Response Reduction by Fluid Gap Optimization*

In order to prevent the submerged internal equipment from resonating with the base-isolated building, an appropriate control of the hydrodynamic effect can be attempted. The hydrodynamic effect can be controlled by adjusting the fluid gap size and initial location of the equipment relative to the surrounding structure. Because this adjustment can be practical after the design constraints such as possibility of collision with adjacent structures and minimum space required for interfacing systems are evaluated, optimization of fluid gap was made with those constraints. And the possible range of fluid gap is assumed to be 0 to 25 cm for analysis purpose in this case.

Fig. 4 shows the level of response reduction by the gap optimization. The original peak displacements are calculated for the added mass effect $\frac{m_{sH}}{m_s} = 25$ , which corresponds to a constant fluid gap condition. Then, the fluid gap can be determined to minimize the peak responses of the submerged equipment for each cases by optimization. The minimized responses and the corresponding optimal gaps of equipment in base-fixed building are shown in Fig. 4a. The optimal gap turns out to be constantly 0.5 or 1.0 cm, which is almost the lower bound, regardless of the natural frequency. The response reduction can be obtained in the level of about 1/4 - 1/40 throughout the frequency range. In LRB base-isolated building, the optimal gap varies fully within the range of 0.5 cm to 25 cm to minimize the response. The effect of response reduction, the maximum level of which is about 1/20, is noted for $f_s < 5.0$ Hz, while it is negligible for $f_s > 5.0$ Hz because the response has already decreased much for the range.

### *3.4 Response Reduction by Base Isolation of Submerged Equipment*

In case that the level of response control by fluid gap optimization is limited, application of base-isolation simultaneously to the submerged equipment may be an alternative. If the submerged equipment is subject to a considerable hydrodynamic effect, the added mass effect will help to prevent the base-isolated equipment resonating with floor excitations in the base-isolated building. Thus, the fundamental frequency of the base-isolated submerged equipment becomes much lower than that of the base-isolated building.

As reviewed and discussed in section 3.2, the seismic response of the submerged equipment can be highly aggravated by EDF or LRB base-isolation of the building structure. To get the best combination between the base-isolators for the building structure and the base-isolators for the submerged equipment, the seismic responses of the equipment in five different base conditions are analyzed and compared. In Fig. 5, the peak acceleration and displacement responses are compared for the equipment base-isolation using four different types in EDF base-isolated structure. For the case of EDF base-isolated building structure, EDF base-isolation of the submerged equipment shows the least and constant absolute acceleration response as shown in Fig. 5a, and LRB base-isolation of the equipment does the least relative displacement as shown in Fig. 5b.

The peak acceleration and displacement responses of the submerged equipment with the LRB base-isolated building structure are shown in Fig. 6a and Fig. 6b. Even though the response amplitudes are slightly different, the overall trends for the internal equipment isolators are quite similar to those for EDF isolation, that is, EDF base-isolation of the submerged equipment shows the best performance for the acceleration response attenuation and LRB base-isolation of the submerged equipment shows the best for the displacement response attenuation of the system.

## 4. CONCLUSIONS

When base isolation is applied to the building structure, the main frequency components of the floor vibrations of the building structure are shifted to low range, and hence, hydrodynamic effects on the equipment, which are very desirable in base-fixed building structures, bring about adverse effects. Therefore, in the base-isolation design of building structures on which submerged equipment are installed, great care should be taken so that there might not occur resonance of the submerged equipment with the fundamental natural frequency of the building structure. In summary,

1) The peak displacement response of the submerged internal equipment, which is subject to a considerable hydrodynamic effect, can be significantly increased by the base-isolation in the building structure while the response of the in-air equipment decreased.

2) By an optimization of the fluid gap, the seismic response of the submerged equipment can be largely reduced. Closer fluid gap with no impact possibility turns out to be better in base-fixed structure, but the optimal size of fluid gap is largely dependent on the equipment natural frequency in base-isolated structure.

3) The LRB or EDF base-isolation of the submerged equipment can remarkably reduce the seismic response by using the hydrodynamic mass effect for further lowering the natural frequency of the equipment, and it can be a good alternative in the case where the response reduction by fluid gap design is limited.

## REFERENCES

1. Tsai, H., J. M. Kelly 1989. Seismic response of the superstructure and attached equipment in a base-isolated building. *Earthquake Eng. Struct. Dyn.* 18: 551-564.

2. Fan, F., G. Ahmadi 1992. Seismic response of secondary systems in base-isolated structures. *Eng. Struct.* 14: 35-48.

3. Singh, S., S. F. Putman & J. Pop 1990. Structural evaluation of onsite spent fuel storage: recent developments. *3rd Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping* : V/4-1-V/4-18. Orlando: Florida.

4. Scavuzzo, R., W. F. Stokey & E. F. Radke 1979. Dynamic fluid-structure coupling of rectangular pools. *ASME PVP*-39: 77-86.

5. Fritz, R. 1972. The effect of liquids on the dynamic motions of immersed solids. *J. eng. ind. Trans. ASME*: 167-173.

6. Shin, T., K.J. Kim 1996. Seismic response amplification of submerged secondary system in base-isolated structures. *CST96 3rd Int. Conf. On Computational Structural Technology*: 269-281. Budapest: Hungary.

Table 1. Values of model parameters used for various base-isolators

| Base Isolation System | Natural Frequency $f_n$ (Hz) | Damping Ratio $\xi_n$ (Loss Factor) | Friction Coeff. $\mu$ |
|---|---|---|---|
| Laminated Rubber Bearing (LRB) | 0.5 | 0.08 (0.16) | - |
| Pure-Friction (P-F) | - | - | 0.1 |
| Resilient-Friction (R-FBI) | 0.25 | 0.08(0.16) | 0.05 |
| Electricite De France(EDF) | 1.0 | 0.08(0.16) | 0.2 |

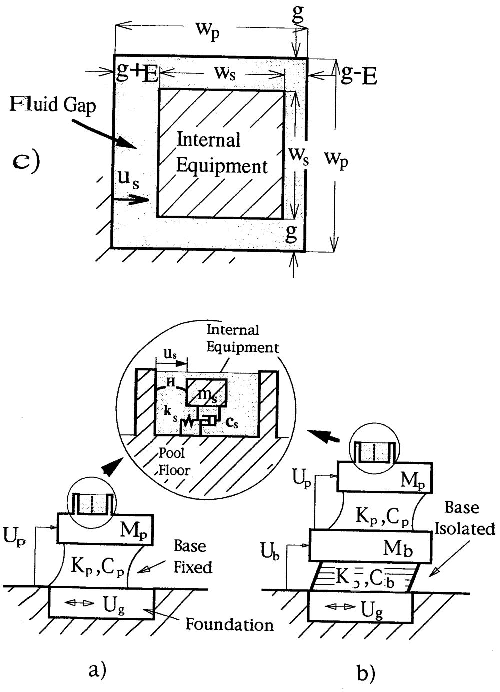
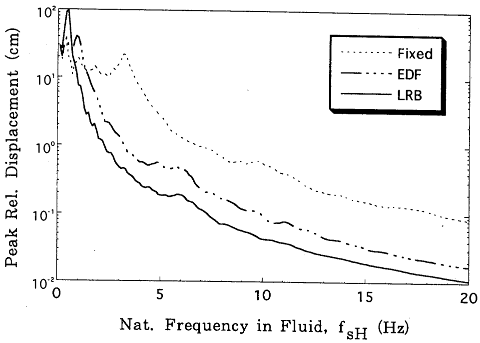
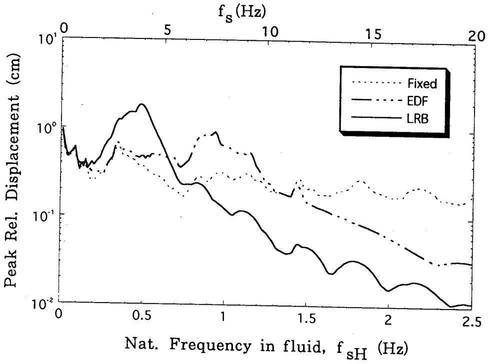


Fig. 1 Coupled model of submerged equipment a) on base-fixed building, b) on base-isolated building



a) In-Air Internal Equipment



b) Submerged Internal Equipment ($m_{sH}/m_s$=64)

Fig. 2 Effect of building base isolation on the peak responses of submerged equipment

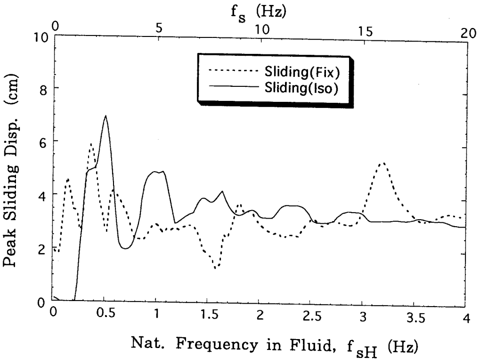
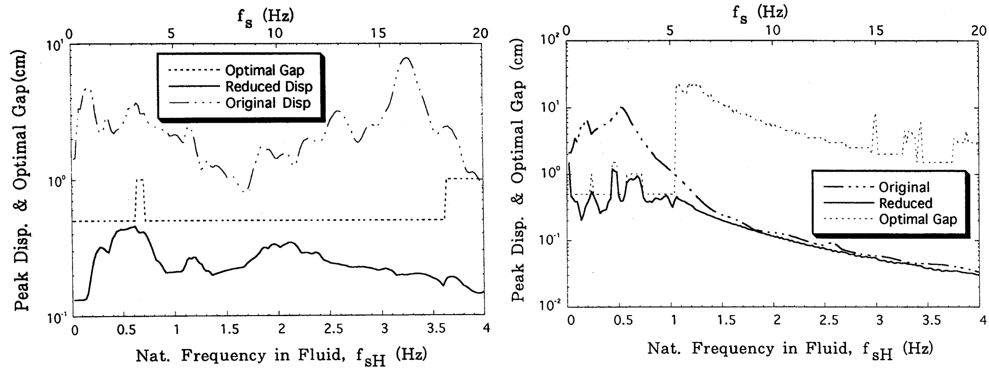


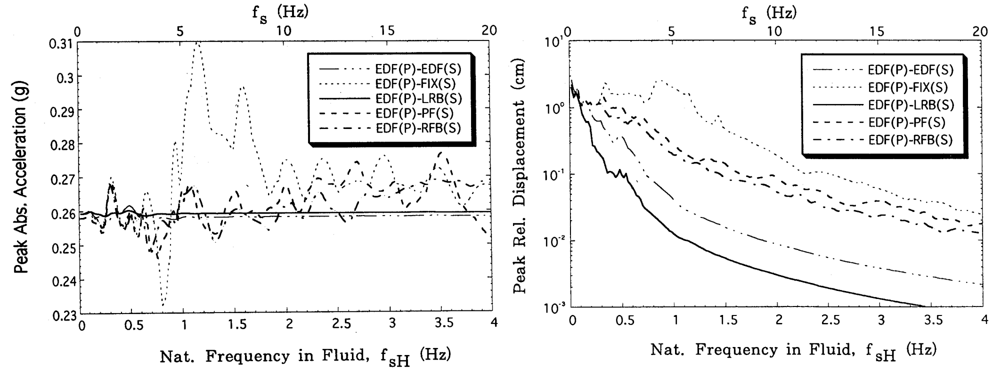
Fig. 3 Effect of building base isolation on the peak sliding displacements of submerged equipment at $f_{sH}$ = 0 - 4 Hz



a) In Base-Fixed Building

b) In Base-isolated Building

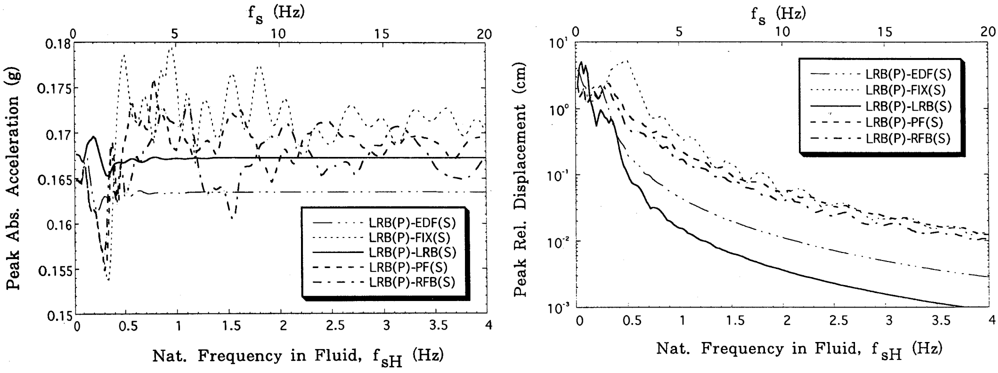
Fig. 4 Response reduction of submerged equipment at $f_{sH}$ = 0 - 4 Hz by fluid gap optimization



a) Acceleration Response

b) Displacement Response

Fig. 5 Peak responses of base-isolated equipment in EDF base-isolated building at $f_{sH}$ = 0 - 4 Hz



a) Acceleration Response

b) Displacement Response

Fig. 6 Peak responses of base-isolated equipment in LRB base-isolated building at $f_{sH}$ = 0 - 4 Hz