Journal of KSNVE, Vol. 7, No. 4, pp. 655~661, 1997.

〈**Original Paper**〉

Seismic Response Characteristics of Submerged Systems with Large Hydrodynamic Effect in Base-isolated Structure

지진절연 건물내 유체동적효과가 큰 수중계의 지진응답특성

Tae-Myung Shin* and Kwang-Joon Kim**
신 태 명 · 김 광 준

(Received April 7, 1997 ; Accepted May 8, 1997)

Key Words : Base-isolation(지진절연), Submerged System(수중계), Hydrodynamic Effect(유체동적효과), Seismic Response(지진응답)

ABSTRACT

Base-isolation of a primary structure generally decrease the seismic response of its own and the secondary structure. It may cause an adverse effect on the seismic response of secondary system when the system is submerged and subject to a considerable hydrodynamic effect. In this paper, it is shown how, and how much, the base isolation of the primary structure can affect the secondary system response in extreme cases through dynamic analysis of a simplified coupled model for a submerged secondary system and a base-isolated primary structure. As an aseismatic design approach to reduce the response of the submerged system, optimization of the fluid gap, which controls the hydrodynamic mass effect, is performed. As an alternative approach in case where the control of fluid gap is unrealistic, application of base isolation to the submerged system is suggested. Effectiveness of various combinations of the primary base and secondary base isolations are compared.

요 약

건물내 동적계가 수중에 있고 유체동적효과가 클 경우, 건물을 지진절연하면 일반적인 경향과는 달리 계의 지진응답이 오히려 증가될 수 있다. 본 논문에서는 건물내 수조에 잠긴 계에 대하여 단순화된 복합모델의 동적해석을 통하여 건물의 지진절연이 건물내 수중계의 지진응답에 어떻게 그리고, 최대로 얼마나 영향을 주는지를 보인다. 이 때 응답을 줄이기 위한 내진설계방안으로서 유체질량효과를 조절하는 유체간극의 최적화를 수행하여 그 효과를 살펴보았고, 간극조절이 곤란한 경우의 대안으로서 지진절연된 건물내 수중계를 다시 지진절연하는 방안을 제안하였으며 적절한 이중절연방식의 조합에 대한 효율을 비교하였다.

1. Introduction

Base-isolation of a primary structure (or building) has shown a remarkable performance in seismic response attenuation of a secondary system (or internal equipment) through many studies$^{(1,2)}$. The secondary system concerned about in the case are mostly in air condition. However, there are some secondary systems like spent fuel storage racks in

---

*Member, Mechanical Design, NSSS, KOPEC
**Member, Department of Mechanical Engineering, KAIST

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 primary structure, it is easy to expect that the primary base isolation may have adverse effects by bringing about resonance upon submerged secondary system.

This paper illustrates such a case through dynamic analyses of a simplified model of submerged secondary system in a base-isolated primary structure. 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 secondary system in a base-isolated primary structure 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 submerged system and the pool structure shown in Fig. 1, can be written as follows :

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

where

F_p : Force acting on the pool structure by the submerged system movement

F_s : Force acting on the submerged system by the pool structure movement

m_H : Hydrodynamic mass associated with the submerged system

m_I : Mass of fluid displaced by the submerged system

m_{II} : Mass of fluid which would be enclosed by the pool structure without the submerged system

x_s : Motion of the submerged system relative to the pool structure

X_p : Absolute motion of the pool structure

For the dynamic analysis of interaction between the submerged secondary system and the primary structure, a cylindrical piece of system having a solid or hollow square cross-section is chosen. The system is assumed to be fully submerged in a rectangular pool which is located in a primary structure. Sloshing effect of the contained fluid to the seismic response of submerged system or pool structures is assumed to be negligible[6]. Fluid coupling between the submerged system 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 system to the one in air f_s is given by[7]

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

where r is the ratio of the system 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 system 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 system response.

In order to simply express the interaction of a submerged system 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 primary structure 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 the purpose of dynamic analysis for a coupled system consist of primary structure and secondary system, the primary structure can be approximately modeled as a single degree of freedom system if it behaves like a simple beam(7) as shown in Fig. 1a. From the fact that the first mode of the base-isolated primary structure is almost entirely a rigid body mode, in which there is no deformation in the superstructure, the base-isolated primary structure can be simplified as 2-DOF system model consisted of the isolator at the base and the superstructure as shown in Fig. 1b.

2.2 Equation of Motion for the Coupled System

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

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

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

Now let us assume the primary structure 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 primary structure. Then the equations of motion for the total system are given by

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

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

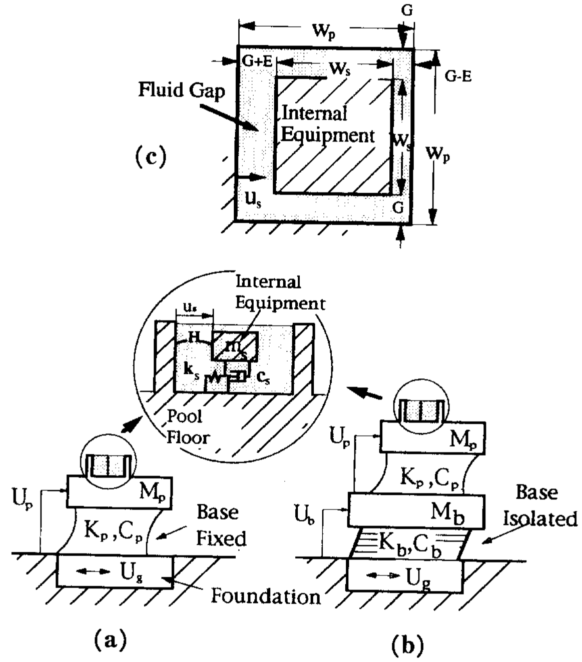


Fig. 1 Coupled model of submerged system
(a) on base-fixed primary structure,
(b) on base-isolated primary structure
(c) and primary structure in section view

3. Seismic Analysis and Discussion

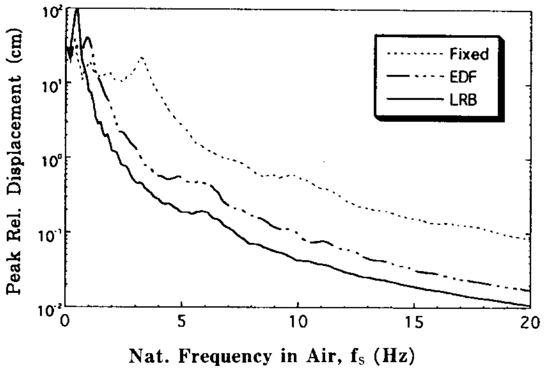
3.1 Descriptions of Analysis Method

The fundamental natural frequency and damping ratio of the base-fixed primary structure 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 secondary system as shown in Fig. 1b, 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 sown in Table 1. A value of 0.01 is taken for the common mass ratio of the submerged system to the floor, and 0.01 for the damping ratio of the submerged system based on m_{sH}. The peak seismic responses are calculated for the in-air natural frequency of 0 Hz to 20 Hz.

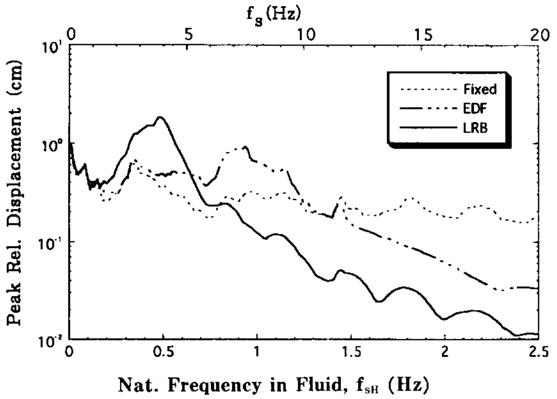
The sixth order Runge-Kutta scheme and double precision were chosen for numerical integration of the equations of motion in FORTRAN. The input

Table 1 Values of model parameters used for various base-isolators[2]

Base isolation system	Natural frequency f_n(Hz)	Damping ratio ζ_n (loss factor)	Friction coefficient μ
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



(a) In-Air Internal Equipment



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

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

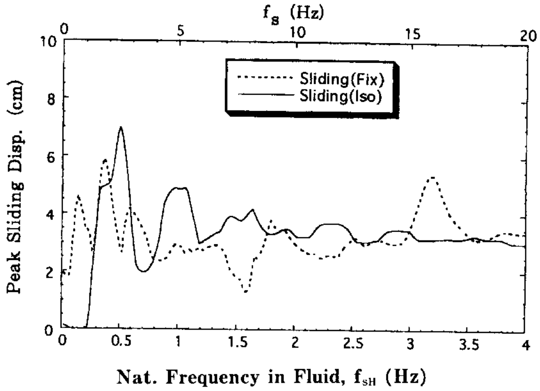


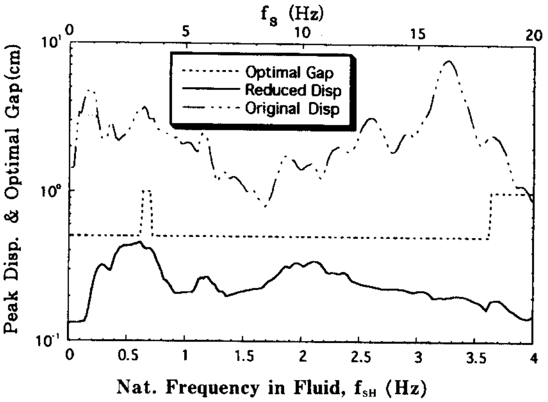
Fig. 3 Effect of primary base isolation on the peak sliding displacements of submerged system at $f_{sH}=0 \sim 4$ Hz

earthquake is El Centro 1940. Since the displacement of the submerged system relative to the floor would normally be an indicator of strain, the response of the system is discussed mainly in terms of the relative displacement response.

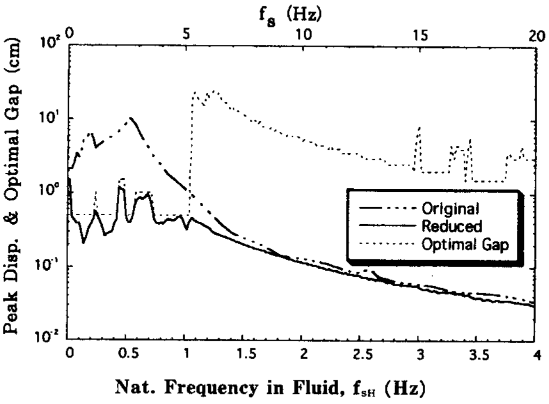
3.2 Influences of Primary Base Isolation on Secondary System Response

Figure 2 shows two different effects of the primary structure base-isolation on the seismic responses of secondary system in air and in submerged condition. The peak seismic responses of the secondary system for $f_s=0$ Hz ~ 20 Hz are investigated. As reported from many studies, both of the EDF and LRB base-isolations of the primary structure significantly reduce the seismic response of the in-air system regardless of the natural frequency of the system for $f_s=1.5$ Hz ~ 20 Hz as shown in Fig. 2a. On the contrary, the base-isolation of primary structure turns out to give adverse effect on the response of the submerged system. Fig. 2b shows amplification of the peak responses of the submerged secondary system by EDF or LRB base-isolation of the primary structure 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 about $f_{sH}=0.9$ 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.

Figure 3 shows the effect of primary structure base isolation on the peak sliding displacement of the submerged secondary system for the added mass effect $\frac{m_{sH}}{m_s}=25$ when the system 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 system, 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 system, the adverse effect on the submerged system by primary structure base isolation should be overcome through an appropriate design strategy.



(a) In Base-Fixed Building



(b) In Base-isolated Building

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

3.3 Response Reduction by Fluid Gap Optimization

In order to prevent the submerged secondary system from resonating with the base-isolated primary structure, 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 system 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.

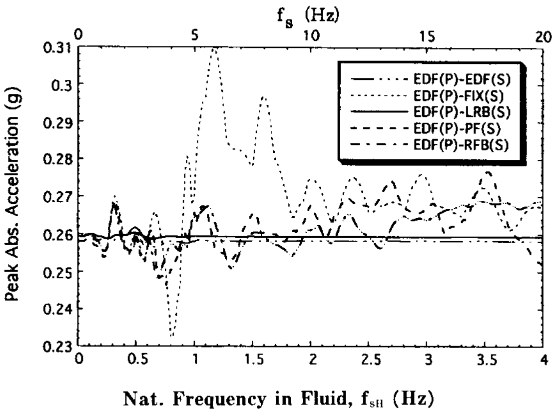
Figure 4 shows the level of response reduction by the gap optimization. The original peak displacements are calculated for the added mass effect $\frac{m_{sH}}{m_s}=25$, which corresponds to a constant fluid gap condition. Then, the fluid gap can be determined to minimize the peak responses of the submerged system for each cases by optimization. The minimized responses and the corresponding optimal gaps of system in base-fixed primary structure are shown in Fig. 4a. The optimal gap turns out to be constantly 0.5 cm 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 primary structure, 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

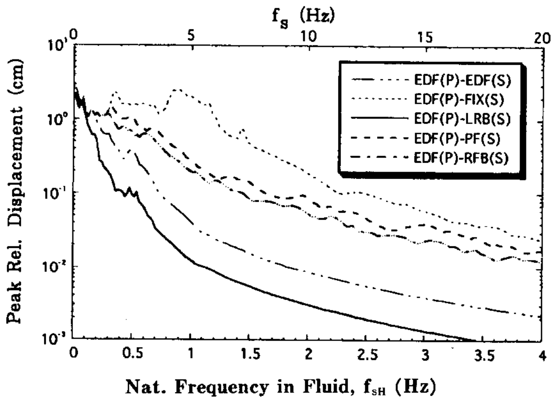
In case that the level of response control by fluid gap optimization is unrealistic, application of base-isolation simultaneously to the submerged system may be an alternative. If the submerged system is subject to a considerable hydrodynamic effect, the added mass effect will help to prevent the base-isolated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

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

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

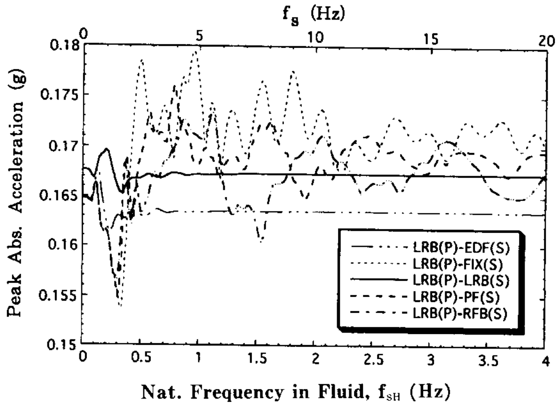


(a) Acceleration Response

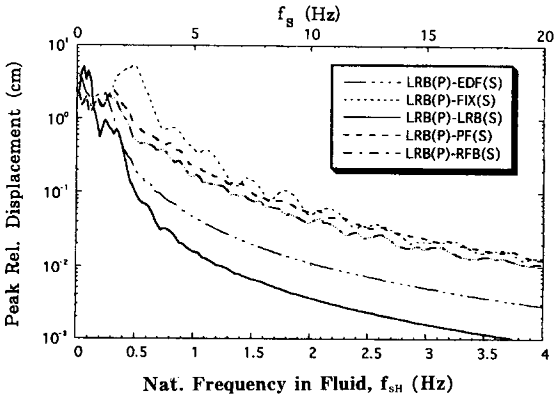


(b) Displacement Response

Fig. 5 Peak responses of base-isolated system in EDF base-isolated primary structure at $f_{sH}=0\sim4$ Hz



(a) Acceleration Response



(b) Displacement Response

Fig. 6 Peak responses of base-isolated system in LRB base-isolated primary structure at $f_{sH}=0\sim4$ Hz acceleration response attenuation and LRB base-isolation of the submerged system shows the best for the displacement response attenuation of the system.

4. Conclusions

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

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

(2) By an optimization of the fluid gap, the seismic response of the submerged system 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 system natural frequency in base-isolated structure.

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

References

(1) Tsai, H., and Kelly, J. M., 1989, "Seismic Response of the Superstructure and Attached System in a Base-Isolated Building", Earthquake Eng. Struct. Dyn., Vol. 18, pp. 551～564.

(2) Fan, F., and Ahmadi, G., 1992, "Seismic Response of Secondary Systems in Base-Isolated Structures", Engineering Structures, Vol. 14, pp. 35～48.

(3) Singh, S., Putman, S. F., and Pop, J., 1990, "Structural Evaluation of Onsite Spent Fuel Storage: Recent Developments", 3rd Symposium on Current Issues Related to Nuclear Power Plant Structures, System and Piping, V/4-1-V/4-18, Orlando: Florida.

(4) Scavuzzo, R., Stokey, W. F., and Radke, E. F., 1979, "Dynamic Fluid-Structure Coupling of Rectangular Pools", ASME PVP-39, pp. 77～86.

(5) Fritz, R., Feb. 1972, The Effect of Liquids on the Dynamic Motions of Immersed Solids", Trans. ASME Journal of Engineering for Industry, pp. 167～173.

(6) Kim and et al., 1993, "Performance of Base-Isolated Spent Fuel Storage Pool Structures", SMIRT-12, K24/4, pp. 345～350.

(7) Shin, T. M. and Kim, K. J., 1997, "Seismic Response of Submerged Secondary Systems in Base-isolated Structures", Engineering Structures, Vol. 19, No. 6, pp. 452～464.