건물기초의 절연이 내부수중구조물의 지진응답에 미치는 영향

Influence of Building Base-Isolation on Seismic Response of Submerged Internal Systems

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요　약

건물기초를 지진절연하면 건물뿐만 아니라 그 내부구조물의 지진응답도 크게 감소한다는 사실이 많은 연구를 통해 확인되어 왔다. 그런데 이러한 내부구조물이 유체내에 잠기고 부가질량효과가 크게 작용되는 조건에 놓이는 경우 오히려 지진응답이 증가할 수 있다. 본 논문은 건물 내 수중구조물의 지진해석을 통해 그러한 예를 제시하고자 한다. 해석결과 지진절연된 건물의 경우 이러한 내부 수중구조물의 지진응답이 상당히 증가할 수 있기 때문에 이에 대한 조치가 필요함을 보였고, 적절한 설계에 의하여 부가질량효과를 조절함으로써 어느 정도 응답을 줄일 수 있다는 사실을 알 수 있었다.

Abstract

The base-isolation of building, as appeared in many studies, has shown remarkable performance in seismic response attenuation of the internal system as well as the building structure itself. But for the case that the internal system is submerged and hence subject to a considerable hydrodynamic effect, the seismic response of the system due to the base-isolation of building can be greater than the case that they are in air. This paper presents the dynamic analysis of a submerged internal system on base-isolated building to show such an example. The results show that an additional treatment is required to reduce the adverse effects on the seismic response of such a system when the building is base-isolated, and that the system response can be reduced to some extent by an appropriate control of fluid gap between the system and the building structure.

Keywords : base-isolation, submerged internal system, seismic response

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1. Introduction

Base isolation has become a basic technique to protect structures and their contents from strong earthquake impacts in recent years. In aseismic design of structures containing internal equipment which are critical to public safety or value such as nuclear power plants, storage tanks or pumping stations of water, protection of the internal system can be as important as the building structure itself. Kelly and Tsai[2,3] illustrated considerable effects of the base isolation on the response reduction of the internal systems as well as the building structures. Fan and Ahmadi[4,5] carried out comparative studies on the performance of various base isolation systems and numerical simulation studies on the seismic responses of secondary system in base-isolated structure. The main concern in those studies so far has been about the seismic response of internal systems under in-air condition.

Some equipment, however, may have to be located in the fluid and operated in submerged condition[1,10]. It is well known such equipment experience hydrodynamic resistances against excitations by earthquakes. As Scavuzzo *et al.*[7] described, the fluid coupling between the two concentrically located bodies reduces both the natural frequency and modal participation factor of the inner body when compared with the case where they are in air. Noting that most of the base isolation devices generally reduce the fundamental frequency of the building structure, it is easy to understand that the base isolation may have adverse effects by bringing about resonances upon a submerged internal system.

This paper illustrates such a case through comparative dynamic analyses of a submerged internal systems in a base-fixed building and in a base-isolated building. The equations of motion are set up to comparatively analyze the seismic response of the internal system for both conditions of the building base. Significance of the seismic response amplification due to the base-isolation of building is emphasized through an extreme case analysis where the submerged natural frequency of the system is tuned to the base isolation frequency. The size and initial location of the submerged system relative to the surrounding structure and their effect on excessive response is studied. Response characteristics of the submerged internal systems subject to variable hydrodynamic effect are compared for the building structures with various types of base isolation.

2. Formulation of Equations of Motion

2.1 Hydrodynamic Effects on Seismic Response

The dynamic behavior of a submerged oscillating body is heavily dependent on hydrodynamically added mass and added damping. Lots of studies have been carried out on this issue. An extensive study was made by Fritz[6] on the dynamic analysis of two bodies coupled by liquid. He proposed a method to evaluate reaction forces on moving rigid bodies when they are completely immersed in fluids. Chen *et al.*[8] and Dong[9] dealt with dimensional effects on added mass and added damping for water submersion. Scavuzzo *et al.*[7] studied dynamic behavior of rectangular modules submerged in rectangular pools through normal mode analysis. They assumed fluid to be incompressible and inviscid, and used the potential theory for the derivation of hydrodynamic mass.

The natural frequency of a submerged body is determined by the sum of the body mass and the hydrodynamic mass which is called the virtual mass or apparent mass. And the amount of hydrodynamic mass is a function of fluid density, the geometric dimension of the two interacting structures, the gap between them, and so on. Based on the approach given by Fritz[6], the hydrodynamic forces by the fluid coupling H between the internal system and the pool structure shown in Figure 1 and Figure 2, can be written as follows :

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

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

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

m_H : Hydrodynamic mass associated with the internal system

m_I : Mass of fluid displaced by the internal system

m_{II} : Mass of fluid based on the volume enclosed by the pool structure which is coupled to the internal system

u_s : Motion of the internal system relative to the pool structure

U_p : Absolute motion of pool structure

For the dynamic analysis of interaction between the submerged internal system and the building structure, a cylindrical piece of equipment having solid or hollow square cross section is chosen as the internal system. The system is assumed to be fully submerged and surrounded by a rectangular pool or a rigid tank and be located on a certain floor in a building structure. Fluid coupling between the system and the pool wall is assumed to be caused entirely by the intertia of the fluid, which is assumed to be incompressible and inviscid.

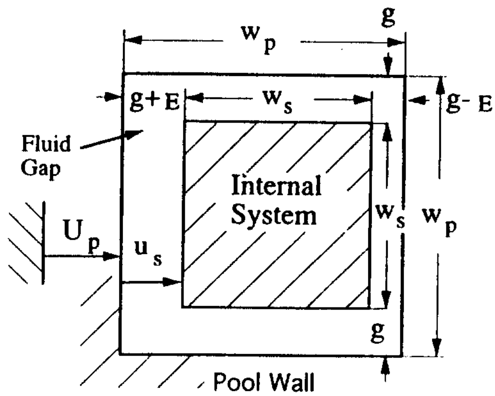


Fig. 1 Top View for Description of Fluid Gap between Submerged Internal System and Pool Structure

For a long concentric rectangular body with square section surrounded by a rigid outer wall with narrow fluid gap as shown in Figure 1, the hydrodynamic mass along the horizontal x-direction given by Scavuzzo *et al.*[7] can be rewritten as

$$m_H = \frac{m_I}{24} \cdot \frac{(1+r)^3}{(1-r)r^2} \cdot \left[\frac{1}{1-e^2}+3\right] \qquad (2)$$

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 $e=E/g$. It is assumed that the contribution of displacement in y or z direction to the hydrodynamic mass along x direction is negligible. And a submerged natural frequency f_{sH} of the system is simply determined as

$$f_{sH}=\frac{1}{2\pi}\cdot\sqrt{\frac{k_s}{m_s+m_H}} \tag{3}$$

where m_s and k_s are mass and stiffness of the submerged system.

From equations (2) and (3), the submerged natural frequency of the system shown in Figure 1 can be expressed using a ratio to the in-air one as

$$\frac{f_{sH}}{f_s}=\frac{1}{\sqrt{1+\frac{m_I}{24m_s}\cdot\frac{(1+r)^3}{(1-r)r^2}\cdot(\frac{1}{1-e^2}+3)}}$$
$$\text{for } r\neq1,\ e\neq1 \tag{4}$$

where f_s is in-air natural frequency of the submerged system. It is assumed in this case that the fluid gap is enough narrow so that the approximations used to derive the equation (2) are justified. Thus, the natural frequency of the submerged system having such a fluid gap with surrounding structure can be said to be a function of size ratio and eccentricity.

2.2 Dynamic Characteristics of Submerged System

In consideration of the forces acting on the system by base excitation and fluid coupling given in equation (1), a simple equation of motion for the submerged one degree of freedom linear system shown in Figure 1 can be expressed as

$$m_{sH}\ddot{u}_s+c_{sH}\dot{u}_s+k_su_s=-m_{sI}\ddot{U}_p \tag{5}$$

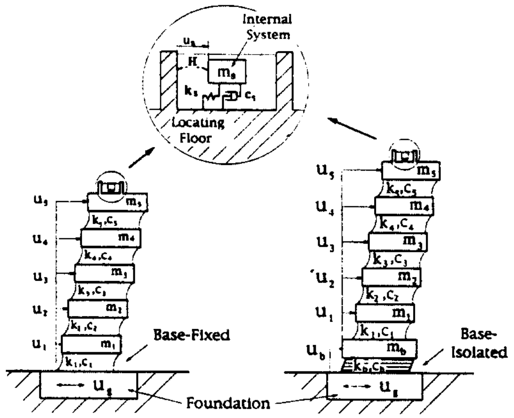
where $m_{sH}=m_s+m_H$, $m_{sI}=m_s-m_I$, and $c_{sH}=c_s+c_H$ in which c_s is damping of the system and c_H is the added damping. With the change of the system environment from in-air to in-fluid, both mass and damping coefficient increase, meaning that the natural frequency of the submerged system decreases. Furthermore, the excitation force corresponding to the base excitation decreases. Thus, when an internal system is submerged in fluid on a building structure, absolute acceleration of the internal system as well as displacement relative to the building structure is expected to be smaller than those in air as long as the main frequency components of the floor excitations do not change above the natural frequency of the internal system in air.

When base isolation is applied to the building, the main frequency components of the floor vibrations of the building are shifted to low range, and hence hydrodynamic effects on the internal system, which is very desirable in base-fixed buildings, may bring about adverse effects.

2.3 Equation of Motion for Coupled System

2.3.1 Submerged internal system in base-fixed building

The analysis model of the submerged system located on the 5th-floor of a base-fixed five-story structure is shown in Figure 2a. The building and internal system are taken as lumped spring-mass model. The building structure has lumped mass m_i and stiffness k_i on the i-th floor, and the submerged system has mass m_s and stiffness k_s. Hydrodynamic coupling between the system and the 5-th floor is modeled using equation (1). Let u_g be the ground motion u_i be the i-th floor displacement relative to the foundation, and u_s be the submerged system displacement relative to the floor where it is located. The effect by relative motion between pool wall and locating floor in the building is assumed to be negligible.



a) b)

Fig. 2 Model of Submerged Internal System in a 5-Story Building
a) Internal System Model in Base-Fixed Building
b) Internal System Model in Base-Isolated Building

Then, the undamped equations of motion for the submerged system in a base-fixed building become

$$\mathbf{M\ddot{u}}+\mathbf{Ku}+((m_{sI}+m_{II})\ddot{u}_5+m_{sI}\ddot{u}_s)\mathbf{e}_5= -(\mathbf{Mr}+(m_{sI}+m_{II})\mathbf{e}_5)\ddot{u}_g \qquad (6a)$$

$$m_{sI}\ddot{u}_5+m_{sH}\ddot{u}_s+k_su_s=-m_{sI}\ddot{u}_g \qquad (6b)$$

where $\mathbf{r}=\{1\ 1\ 1\ 1\ 1\}^T$

$\mathbf{e}_5=\{0\ 0\ 0\ 0\ 1\}^T$

$\mathbf{u}_5=\{u_1\ u_2\ u_3\ u_4\ u_5\}^T$

in which $\mathbf{M}$ and $\mathbf{K}$ are mass and stiffness matrices of the building structure respectively.

2.3.2 Submerged internal system in base-isolated building

Now, let's assume the building structure containing the submerged system considered above become base-isolated. Then, the analysis model will be as shown in Figure 2b. The isolated base is assumed to have mass m_b and stiffness k_b, and let u_b be the displacement relative to the ground. If the other assumptions and definitions are the same as the case of base-fixed structure, equations of motion for the total system expressed by using the properties defined in equation (6) are given as

$$M_t\ddot{u}_b+(\mathbf{Mr})^T\mathbf{\ddot{u}}+(m_{sI}+m_{II})\ddot{u}_5+m_{sI}\ddot{u}_s+k_bu_b =-M_t\ddot{u}_g \qquad (7a)$$

$$(\mathbf{Mr})\ddot{u}_b+\mathbf{M\ddot{u}}+\mathbf{Ku}+\{(m_{sI}+m_{II})\ddot{u}_b+(m_{sI}+m_{II})\ddot{u}_5+m_{sI}\ddot{u}_s\}\mathbf{e}_5 =-\{\mathbf{Mr}+(m_{sI}+m_{II})\mathbf{e}_5\}\ddot{u}_g \qquad (7b)$$

$$m_{sI}(\ddot{u}_b+\ddot{u}_5)+m_{sH}\ddot{u}_s+k_su_s=-m_{sI}\ddot{u}_g \qquad (7c)$$

where $M_t=m_b+\sum_{i=1}^{5}m_i+m_{II}+m_{sI}$.

3. Numerical Analysis

3.1 Description of Analysis Method

In this section, dynamic characteristics of the submerged internal system in base-fixed and in base-isolated buildings are studied through the numerical simulation. The five-story building model shown in Figure 2a which is assumed to have the same mass, stiffness, and damping in various stories, is used for the base-fixed building. The five natural frequencies and dampings of the building structure in this case are f_1=3.30Hz, f_2=9.63Hz, f_3=15.18Hz, f_4=19.51Hz, f_5=22.25Hz, and ξ_1=0.02, ξ_2=0.058, ξ_3=0.092, ξ_4=0.118, ξ_5=0.135. The same model for the base-isolated building is shown in Figure 2b. The internal system is modeled as a single degree-of-freedom linear oscillator with stiffness k_s and damping c_s which is subject to hydrodynamic coupling H as shown in Figure 2.

The system is assumed to be located in the fifth floor, and a value of 0.01 for the mass ratio of the system to the floor is used throughout this study. 1% is assumed for the damping ratio considering the hydrodynamic mass simply because the cross section is a rectangle as in the Scavuzzo *et al.*'s work[7]. The laminated rubber bearing(LRB), which is modeled as a linear spring-viscous damper system, is used for the typical base-isolation system except in the section where the effect of various base isolations is considered. The El Centro 1940 earthquake is used for the representative seismic input throughout this study.

Considering the sixth order Runge-Kutta scheme, a double precision FORTRAN routine for numerical evaluation of the equation of motion is developed. A time step of 0.005 second is used to integrate the governing equations for the case including sliding and non-sliding phase having transition periods for some isolation systems using friction, and 0.005 for the other general cases. The first 24 seconds of the response time histories are used to calculate the peak responses of the system throughout this study. Since displacement of the submerged system relative to the floor would be an indicator of strain in real elastic structures, the response of the internal system is discussed mainly in terms of the relative displacement response although the response in terms of the absolute acceleration is discussed as well. The units of the displacement and acceleration are respectively cm and g.

3.2 Response Time History of Submerged Internal System

In Figure 3, time domain responses of the submerged internal system are shown in terms of absolute accelerations as well as relative dis placements. The level of absolute acceleration responses become greatly reduced for the base design change as shown in Figure 3a, which is similar to the result of Kelly and Tsai[2,3]. The relative displacement, however, gets amplified as shown in Figure 3b, which may be mainly due to the added mass effect of the submerged body. If acceleration response spectrum of the internal system is a major concern, base-isolation could still be beneficial even when the internal system is submerged as long as its limit in the displacement relative to the floor is not violated. But the level of relative displacement increase in the internal system in this case can cause a significant effect on the structural integrity of the system itself.

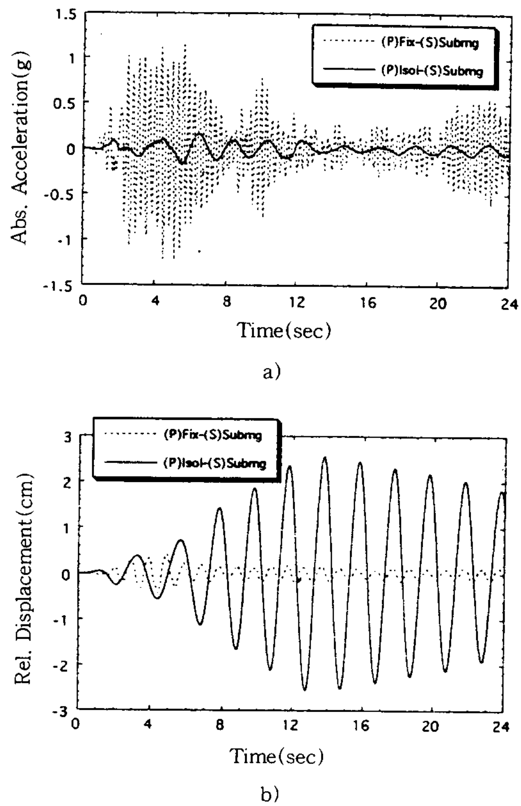
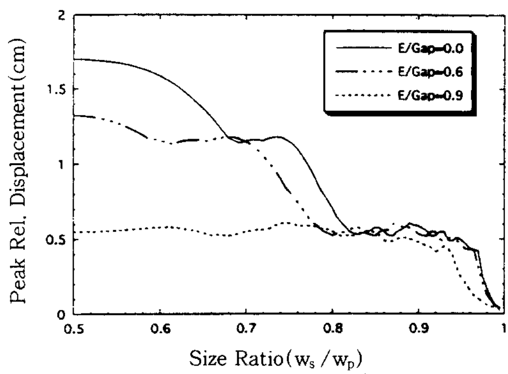


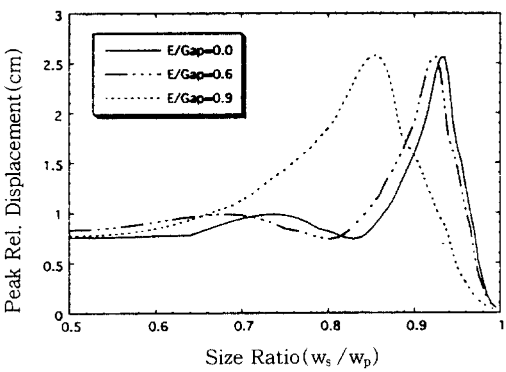
Fig. 3 Response Time Histories of Submerged System (f_{sH}=0.5 Hz) for E1 Centro 1950 Earthquake
a) Absolute Acceleration
b) Relative Displacement

3.3 Effects of Size and Eccentricity

Figure 4 shows effects of fluid gap between the submerged internal system and the building structure on the peak displacement response of the system for the base-fixed as well as base-isolated structures with the eccentricity as a parameter. With the fluid gap close to zero or the size ratio close to one, the natural frequency of the submerged system drop very rapidly to zero, which may be the main reason for the peak response spectrum to become close to zero rapidly near the size ratio equal to 1 as shown in both Figure 4a and 4b.



a)



b)

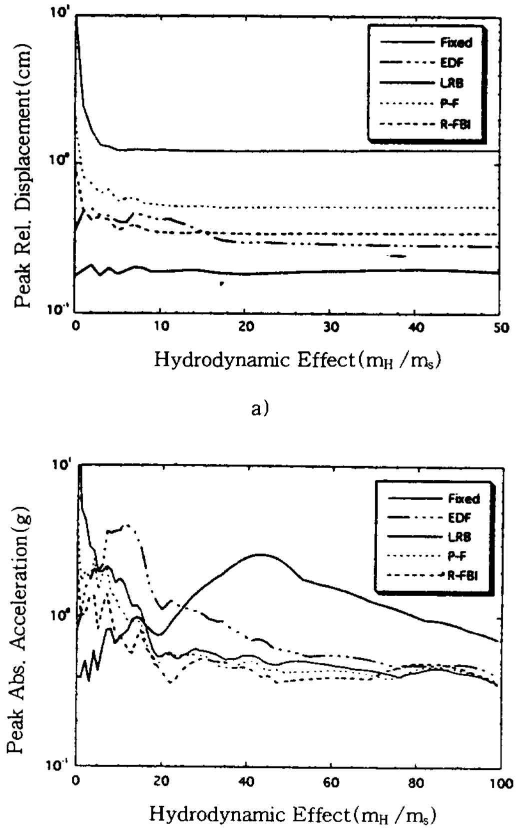
Fig. 4 Variation of Peak Displacement Response of Submerged Internal System with Size Ratios for Different Eccentricity for El Centro 1940 Earthquake.
a) Rel. Displacement of Internal System in Base-Fixed Structure
b) Rel. Displacement of Internal System in Base-Isolated Structure

Figure 4a shows that effects of eccentricity in base-fixed building are greater when the fluid gap is large and become negligible as the fluid gap approach zero. That is, larger the eccentricity, smaller the peak responses. But the situation is quite different for base-isolated structures. As Figure 4b shows, in case where natural frequency of the submerged system f_{sH} happen to coincide with the base isolation frequency, the optimum size ratio range for base-fixed structures makes the peak response worst for base-isolated structures. The peak displacement response of a submerged internal system could be amplified by a factor of about 5 when base-fixed design is replaced with base-isolation design for the building without any further considerations. Figure 4b shows also that the peak response of the submerged system in the base-isolated structure can be reduced to a great extent by appropriate control of the fluid gap and eccentricity but the lowest level in base-isolated structure is still higher than the one in base-fixed structure.

3.4 Influences of Base-Isolation Type

Figure 5 shows peak responses of the submerged internal system with respect to the hydrodynamic mass effect $\frac{m_H}{m_s}(=\frac{m_{sH}}{m_s}-1)$ for 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).

The governing equations and parameter values for the base-isolation devices are adopted from Fan and Ahmadi[4,5] and the latter is shown in Table 1.



a)

b)

Fig. 5 Peak Responses of Submerged Internal System with Hydrodynamic Effect for 4 Different Types of Base-Isolations in Building Structures
a) Absolute Acceleration
b) Relative Displacement

Table 1 Values of Parameters used for Various Base Isolators

Base Isolation System	Natural Frequency f_n(Hz)	Damping Ratio ξ_n	Friction Coefficient μ
Laminated Rubber Bearing(LRB)	0.5	0.08	–
Pure-Friction(P-F)	–	–	0.1
Resilient-Friction(R-FBI)	0.25	0.08	0.05
Electricite De France(EDF)	1.0	0.08	0.2

The in-air natural frequency f_s of the internal system was let to be the same as the fundamental natural frequency of the base-fixed building. Figure 5a shows peak acceleration responses. For the base-fixed building, an increase of $\frac{m_H}{m_s}$ from 0 to 4 reduces the peak acceleration response from 10g to 1.3g and further increase of $\frac{m_H}{m_s}$ affects little the peak acceleration response. This is of course because the internal system resonates to excitations by the building structure when $\frac{m_H}{m_s}$ is close to 0 and gets detuned rapidly with increase of $\frac{m_H}{m_s}$.

For both of the P-F and R-FBI base isolations, the peak acceleration response decreases to one third as $\frac{m_H}{m_s}$ increases from 0 to 9 and keeps almost constant for $\frac{m_H}{m_s}>9$, which is qualitatively similar to the case of fixed-base. For the EDF and LRB base isolations, however, the response increases a little near $\frac{m_H}{m_s}=0$ and then shows some fluctuations for $0<\frac{m_H}{m_s}<15$.

The peak displacement response which is a direct measure of the seismic effect on the submerged system shows quite different trends for the EDF and LRB as shown in Figure 5b. On the contrary to the acceleration responses, the displacement responses for these two types exceed those for the other three types including the base-fixed case over most of the hydrodynamic mass ranges. For the EDF and LRB, the resonance peaks appear around $\frac{m_H}{m_s}=11$ and 43 for which f_{sH} equals to 1 and 0.5 Hz respectively and the submerged internal system resonates to the excitations in the base-isolated building. In the EDF and LRB base-isolations, the peak displacement response of the internal system could increase

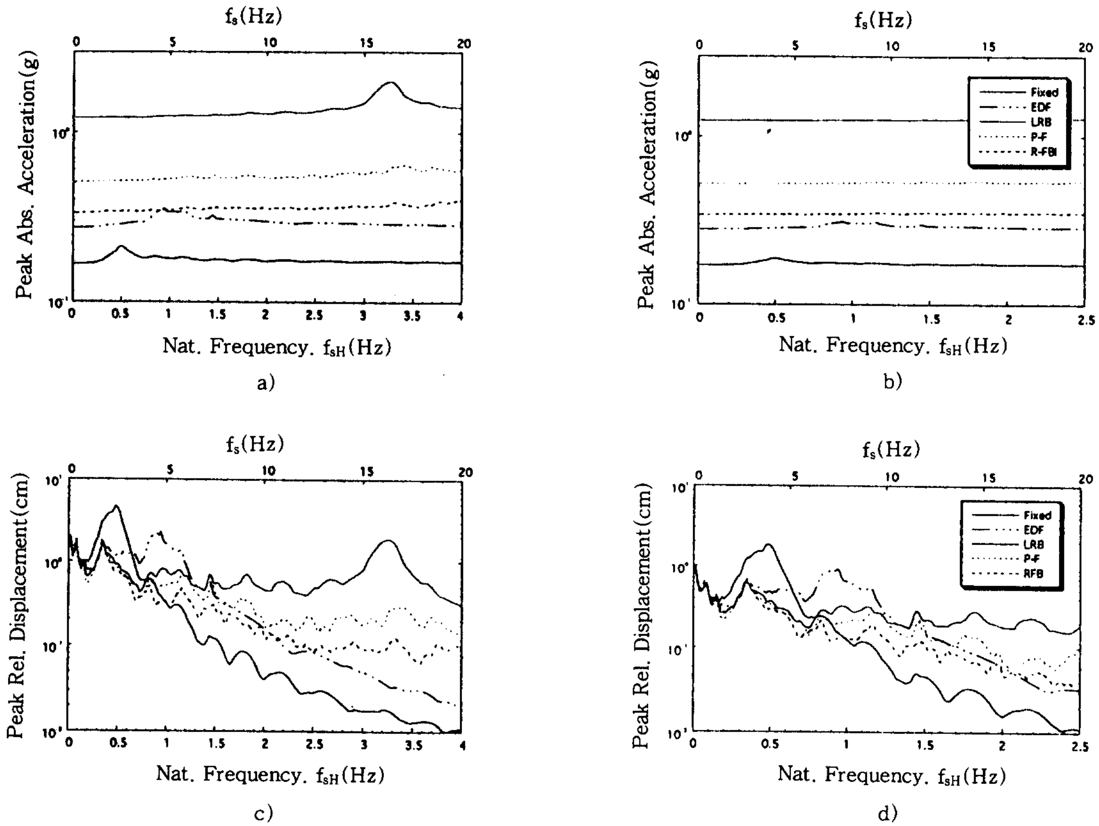


Fig. 6 Peak Responses of Submerged Internal System with Submerged Natural Frequency(m_{sH}/m_s=25 and 64, E1 Centro 1940 Earthquake) a) Absolute Acceleration for m_{sH}/m_s=25 b) Absolute Acceleration for m_{sH}/m_s=64 c) Relative Displacement for m_{sH}/m_s=25 d) Relative Displacement for m_{sH}/m_s=64

about 4 or 5 times by submerging. It is noted that the internal system response in the P-F and R-FBI base-isolations is smaller than the one in the base-fixed structure regardless of the level of hydrodynamic effect.

Figure 6 shows variations of the peak responses of the submerged internal system with natural frequencies for several base-isolation types and given values of $\frac{m_{sH}}{m_s}$=25 and $\frac{m_{sH}}{m_s}$=64, which is an observation similar to the one shown in Figure 5.

The peak acceleration responses of the submerged system do not change much from the floor responses in the building. That is, the peak acceleration responses keep almost constant except over some resonance frequencies in case of the fixed-base, EDF and LRB base-isolations as shown in Figure 6a and 6b.

The level of responses decreases in the order of fixed-base, P-F, R-FBI, EDF, and LRB base-isolations, which matches well with the in-air results for f_s>15Hz by Fan and Ahmadi[5]. Figure 6c and 6d display the peak displacement responses of the internal system. 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=4.5 Hz and 2.5 Hz for $\frac{m_{sH}}{m_s}$=25 and f_s=7.5 Hz and 4 Hz for $\frac{m_{sH}}{m_s}$=64. That is, the in-air frequency range of the internal system whose seismic response can be adversely affected by base-isolation increases with the hydrodynamic mass effect. The response increase at the resonance peak for the LRB and EDF base-isolations is about 4 to 6 times. The P-F and R-FBI base-isolations do not show any bad effects on the submerged internal system responses.

4. Conclusions

Through the analyses, it has been pointed out how much the base isolation of building structure could increase the seismic response of the submerged internal system at worst. In the base-isolation design of building on which submerged internal systems are installed, a great care should be taken not to cause resonance of the system with the fundamental frequency of the base-isolated building. Based on the presented results, the following conclusions may be summarized for the submerged internal systems surrounded by the building structure ;

1) The peak displacement response of the submerged internal system can be significantly increased by the base-isolation in building and, for the LRB and EDF base-isolations in the building structure, it could increase at worst by a factor of about 4 and 6 respectively.

2) By an appropriate control of the hydrodynamic effect, the seismic response of the submerged internal system in the base-isolated building structure can be reduced to some extent.

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