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〈Original Paper〉

Seismic Sliding Characteristics of Rectangular Structures submerged in a Rectangular Pool

수조내 사각단면구조물의 미끄럼 지진응답 특성

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Key Words : Sliding Characteristics(미끄럼 특성), Hydrodynamic Effect(유체동적 효과), Seismic Design (내진 설계), Submerged Equipment(수중 구조물)

ABSTRACT

According to the conventional method of analysis for the seismic sliding of equipment submerged in a pool, in general, only the initial condition of fluid gap is used to estimate the hydrodynamic effect between the two structures throughout the seismic analysis. This is based on the assumption of small displacement relative to the fluid gap thickness during earthquakes. In a narrow fluid gap condition, however, this method may lead to a result of unconservative side. Through example seismic analyses for equipment submerged in a pool of a building, in this paper, it is studied when and how much the sliding response can be underestimated. And method of updating the hydrodynamic effect in each step of time integration is proposed to avoid excessive error in estimation of peak sliding response in such a case.

요 약

수조 내에 잠긴 구조물에 대한 미끄럼 지진응답의 해석시 비선형 모델에 포함되는 유체동적 효과를 계산할 때에 종래의 방법은 수조와 구조물 사이의 초기 간격 조건만으로 계산한 다음, 이를 지진 작용 시간동안 일정한 값으로 가정하여 사용하였다. 이는 지진시 수중구조물의 예상변위가 유체 간격에 비해 아주 작다고 가정하였기 때문이다.

그러나 유체 간격이 비교적 크지 않은 조건에서는 이 방법은 자칫 비보수적인 결과를 초래할 수 있다. 본 논문에서는 건물내 수조에 잠긴 구조물에 대한 지진해석의 한가지 예를 통하여 어떠한 경우 얼마나 미끄럼변위를 과소평가 할 수 있는지를 보인다. 그리고, 이러한 경우 최대 미끄럼변위의 예측시 예상되는 과도한 오차를 피하기 위하여는 시간적분을 위한 각 적분 단위시간마다 유체동적 효과를 지속적으로 계산하여 개정해 주어야 한다는 사실을 확인하였다.

1. Introduction

Prediction of peak sliding during earthquakes is one of the major activities in seismic design of free-standing equipment submerged in a pool structure. To assure no impact between structures, in general, the

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equipment are kept separate from the pool wall with enough margin of space based on the result of sliding and tipping analysis. To predict the sliding displacement of submerged equipment precisely, a complicated nonlinear seismic analysis using well defined model should be performed(1).

In this paper, discussions are made on the conventional method of consideration of the hydrodynamic effect between the submerged equipment and the pool structure in the sliding model for seismic analysis. A nonlinear seismic analysis is performed using a coupled model of building and submerged equipment to illustrate a potential underestimation of sliding displacement by the conventional method in a narrow fluid gap. And, in addition, relation between the ratio of peak sliding to the fluid gap versus the level of underestimation is plotted to suggest a guideline to reduce errors in predicting peak sliding displacement.

2. Dynamic Characteristics of Submerged Sliding Equipment

To explain the dynamic characteristics of submerged sliding equipment surrounded by pool structure in a building, a cylindrical piece of equipment having a 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 is assumed to be negligible(2). 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(3).

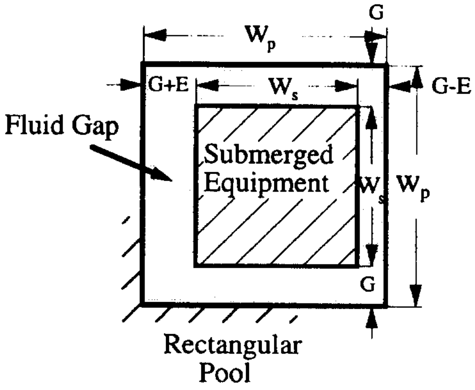

Fig. 1 Section view of equipment and pool

For a normal hexahedron with a square cross-section surrounded by a rigid concentric outer wall with narrow fluid gap as shown in Fig. 1, the ratio of submerged natural frequency f_{sH} of the equipment to the one in air f_s can be expressed as (4,5,6)

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

$$\text{for} \quad 0.5 \le r < 1,\ e < 1 \qquad (1)$$

where m_I is mass of fluid displaced by equipment, and m_s is mass of submerged equipment. The dimensionless parameter r is the ratio of the equipment width, w_s, to the pool width, w_p, as shown in Fig. 1, 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 $e=E/G$.

r and e are variables to determine the hydrodynamic effect on the submerged equipment at a specific time. Therefore, it is easily explained that a relative displacement of equipment by sliding in a fluid gap can change not only the hydrodynamic effect but also the dynamic characteristics of the equipment.

In conventional method to analyze the seismic sliding response of equipment subject to a fluid gap, however, the hydrodynamic effect is considered as constant value calculated using only the initial condition even in a nonlinear analysis(1,7). When equipment resonates with one of the peak frequency of building floor response, the change of hydrodynamic effect does not remain negligible any more. Therefore, by updating the hydrodynamic effect step by step during time integration, more accurate result can be guaranteed.

3. Equation of Motion for the Coupled Model

A dynamic model of rectangular equipment submerged in a pool of a building structure is shown in Fig. 2(c). To simulate the building dynamic effect on the equipment to a reasonable extent, the building structure including pool is modeled as two mass system to have lumped mass M_p, damping C_p, and stiffness K_p on each floor. The submerged equipment is modeled as two lumped mass sliding system of m_s, with damping c_s and stiffness k_s between them. μ is a constant friction coefficient between the equipment and the pool bottom. Hydrodynamic coupling between the equipment and the pool in the 2-nd floor is modeled using the equation by Fritz$^{(3)}$.

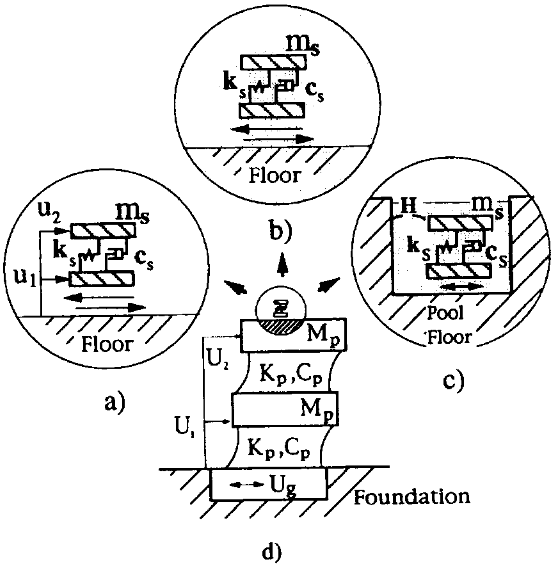

Fig. 2 Schematic view of equipment models (a) In air, (b) Submerged in infinite fluid, (c) Submerged in gap condition, coupled with (d) Building structure including pool

Let U_g, U_i, and u_i be respectively the ground motion, displacement of the i-th floor relative to the base, and that of the distributed i-th mass of the submerged system relative to the top floor. m_H and m_{II} are respectively, hydrodynamic mass associated with the equipment and mass of fluid enclosed by pool structure without equipment. Then, the equations of motion for the total system become

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\ \dot{\mathbf{U}} + \mathbf{K}\mathbf{U} + (m_{II}\ddot{U}_2 - (m_I + m_H)\ddot{u}_1 - F_\mu)\mathbf{e}_2 = -(\mathbf{M}\mathbf{r} + m_{II}\mathbf{e}_2)\ddot{U}_g \tag{2a}$$

$$(\mathbf{m} + \mathbf{m}_H)\ddot{\mathbf{u}} + \mathbf{c}\ \dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -(\mathbf{m} - \mathbf{m}_I)\mathbf{r}(\ddot{U}_g + \ddot{U}_2) - F_\mu \mathbf{e}_1 \tag{2b}$$

where

$\mathbf{r} = \{1\ \ 1\}^T$, $\mathbf{e}_1 = \{10\}^T$, $\mathbf{e}_2 = \{01\}^T$,

$F_\mu = 2 \cdot \mu \cdot m_S \cdot g \cdot \mathrm{sgn}(\dot{u}_1)$, $\mathbf{U} = \{U_1 U_2\}^T$, $\mathbf{u} = \{u_1 u_2\}^T$. $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are mass, damping, and stiffness matrices of the building structure, and $\mathbf{m}$, $\mathbf{c}$, $\mathbf{k}$ are mass, damping, and stiffness matrices of the equipment, respectively. $\mathbf{m}_H$ and $\mathbf{m}_I$ are also mass matrices similar to $\mathbf{m}$ of which m_s substituted by m_H and m_I. g and sgn() mean the acceleration of gravity and the signum function, respectively.

For the in-air equipment as shown in Fig. 2(a), the equations of motion can be obtained by removing only the hydrodynamic terms in both sides of Equation (2a) and (2b). For the submerged equipment with no fluid gap with other structures as shown in Fig. 2(b), the equation of motion for the building model is the same as in-air equipment case because no hydrodynamic interaction can be assumed, and the equation of motion for the equipment is the same form as Equation (2b).

4. Description of Analysis Method

In this section, dynamic characteristics of the submerged sliding equipment are studied through numerical simulations. Considered are as follows ; comparison of peak sliding responses of equipment with various natural frequencies in 3 different conditions, difference between conventional method and updating method for the natural frequency and sliding displacement with respect to time, difference of displacement for various friction coefficients, difference of peak displacement for various natural frequencies of equipment, and relation between the dimensionless peak displacement and the level of underestimation.

A building model of two stories shown in Fig. 2(d) is assumed to have the same mass, stiffness, and damping in each story. Natural frequencies and damping ratios of the building structure in this case study are given by $f_1 = 3.30$ Hz, $f_2 = 8.64$ Hz and $\zeta_1 = 0.02$, $\zeta_2 = 0.052$, the submerged equipment is modeled as a two degree-of-freedom sliding oscillator subject to hydrodynamic coupling H, and located on the top floor as shown in Fig. 2. A value of 0.01 is taken for the common mass ratio of the secondary system to the floor except the case of study for its effect. Typical parameters used in the analysis are ; 0.01 for the damping ratio of the equipment based on m and m_H, 0.02 for the friction coefficient between equipment and pool bottom except the case of study for its effect, $r = 0.8$ and $e = 2/3$ as width ratio and initial eccentricity, fluid gap thickness of 18 cm except the case of study for its effect, and Pacoima Dam (S16E, 1971) earthquake for the seismic input.

The sixth order Runge-Kutta scheme and double precision were chosen for numerical integration of the equations of motion in FORTRAN. A time step of 0.0005 second was used for the numerical integration when sliding and non-sliding phases were involved due to the friction mechanism. The input time histories during the first 24 seconds were used to calculate the peak responses of the system. The units of the displacement and acceleration are respectively cm and g.

5. Analysis Result and Discussion

Figure 3 compares the peak sliding responses of equipment in 3 different conditions, in-air, submerged (m_H/m = 1), and submerged with fluid gap (m_H/m = 16) in a building structure. Only by submersion from in-air condition, the amplitude of peak sliding decreases to about half in average. And decreases by one order from in-air to a fluid gap condition so that the sliding displacement can be negligible in relatively large gap. The peak absolute acceleration shows almost reverse trend to the displacement as

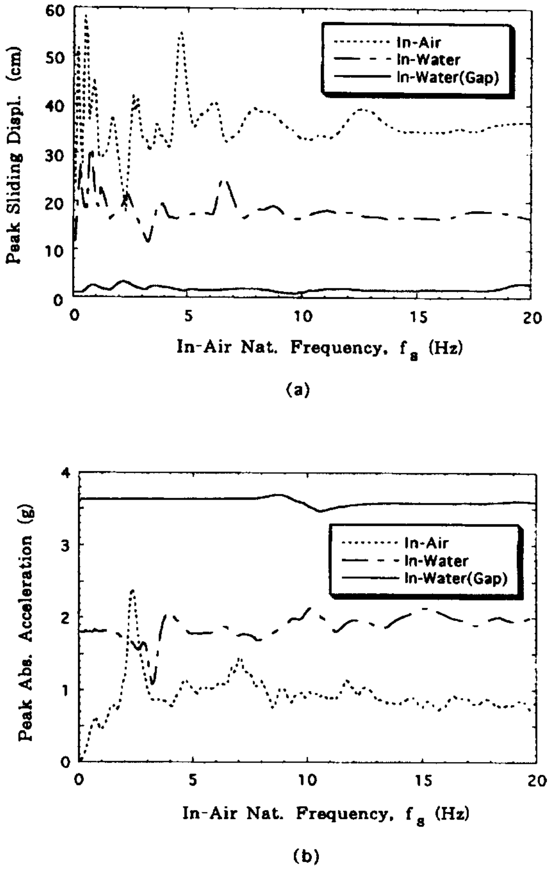

Fig. 3 Comparison of seismic sliding responses
(a) Peak sliding displacements
(b) Peak absolute accelerations

shown in Fig. 3(b). The peak of in-air acceleration response near $f_s = 2.5$ Hz is estimated as an high energy effect of input earthquake on this particular frequency range.

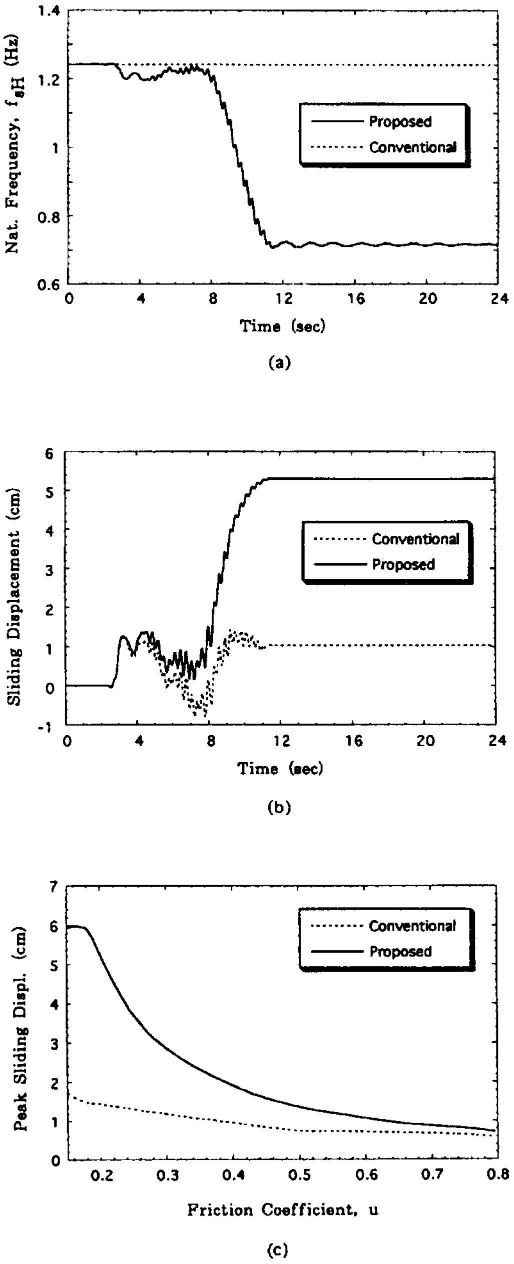

Fig. 4 Potential errors by conventional method
(a) Natural frequency time history
(b) Displacement time history
(c) Peak Sliding Displacement

Figure 4 shows time histories of natural frequency and sliding response, and peak response sensitivity for various friction coefficients for a typical equipment of $f_s =$ 5.7 Hz, which is a natural frequency to cause peak response and is close to the natural frequency of an actual equipment. Figure 4(a) depicts how much the natural frequency of submerged equipment can vary during earthquake. Because the conventional method assumed constant hydrodynamic effect, no change was considered for the natural frequency. The change of equipment natural frequency as shown in Fig. 4(a), however, reaches a considerable level by applying renewed values at each time step. This affects also to the peak sliding displacement. The displacement obtained by the conventional method is almost 1/3-1/4 of that by proposed method as shown in Fig. 4(b). Therefore, at some point the conventional method may lead to a fault prediction of sliding path when compared with updating method. Figure 4(c) shows the difference of peak sliding displacement between the two methods for various friction coefficients from 0.15 to 0.8. According to the conventional method, minor increase is found for the decrease of friction coefficient in peak sliding response. The response calculated by updating method, however, shows a quadratic increase as the friction coefficient decrease. And then, for the friction coefficient less than about 0.2, the sliding displacement does not show any remarkable change. Therefore, below at the friction ratio of 0.2, the ratio of underestimation reaches almost less than 1/4.

In Fig. 5, it describes how much error the conventional method can have in predicting the peak sliding response for various natural frequencies of submerged equipment. Figure 5 is plotted by connecting the peak response points each of which is obtained from the result of time integral for initial natural frequencies of $0 < f_s < 4.2$ Hz of

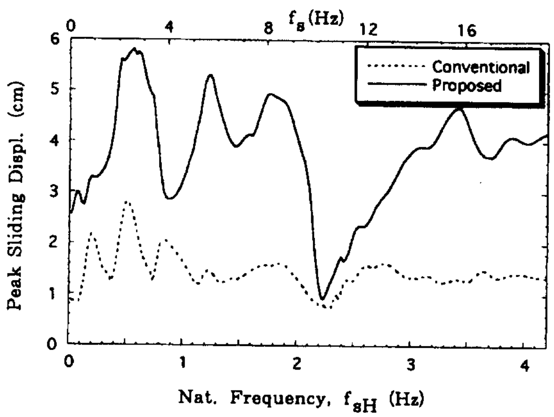

Fig. 5 Comparison of peak sliding by two methods

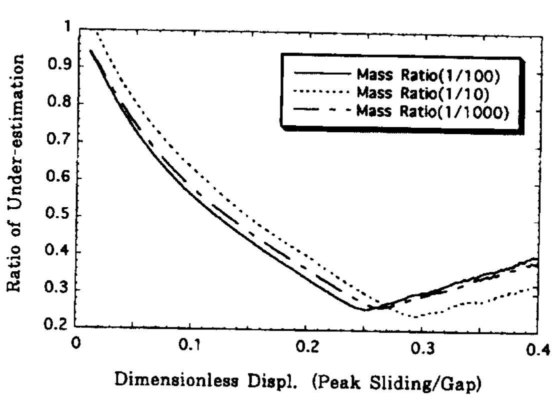

Fig. 6 Level of underestimation vs. sliding amplitude

submerged equipment. And it corresponds to in-air natural frequency of $0 < f_s < 18$ Hz as shown on upper abscissa in Fig. 5. Except for some range of frequency near f_{sH} = 2.2 Hz, the conventional method gives output on unconservative side by ratio of 1/3-1/4 in average when compared with updating method. The sliding characteristics of submerged rigid block in the same condition can be presumed from the response trend near f_s = 18 Hz.

To investigate in what level of sliding displacement updating of hydrodynamic effect is required, relation of underestimation rate versus dimensionless displacement is plotted for various mass ratios m_s / M_p of in Fig. 6. The vertical axis is about the ratio of peak response by conventional method to updating method, and the horizontal axis is about the ratio of peak sliding displacement to fluid gap thickness. The curve is obtained from the peak responses of equipment of f_s = 5.7 Hz by changing the fluid gap thickness. It is interesting that even for a case of very small displacement relative to the gap thickness the conventional method may be able to underestimate the peak sliding. And the ratio of underestimation rather increases passing a critical point where the rate reaches the minimum value of about 1/4 as the ratio of peak sliding to gap thickness increase from 0 to 0.4. The effect of mass ratio is not so distinguishable, but it moves the curve left or right depending upon the equipment natural frequency.

6. Conclusions

From the result of nonlinear seismic analysis for the equipment submerged in a pool on a building structure, it is recommended that the hydrodynamic effect should be updated on a step by step basis for time integration not to underestimate the peak sliding displacement. The ratio of underestimation depends upon the natural frequency of submerged equipment and the ratio of peak sliding to fluid gap thickness. The error of sliding response prediction by conventional method rapidly increases by the decrease of friction coefficient. In design viewpoint, at least more than 4 times of peak displacement is recommended to keep as a minimum space for the fluid gap to avoid impact between the two structures during earthquakes in use of the conventional method.

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