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EXPERIMENTAL STUDY ON SEAQUAKE RESPONSE CHARACTERISTICS OF FLOATING STRUCTURES

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ABSTRACT

Seaquake response characteristics of floating structures in a deep basin are experimentally evaluated by using an underwater shaking table. Effects of mooring systems or material properties of the bottom board of the floating structure on its motion are also examined. Further, an analysis using the Finite Element Method program is executed to be compared with experimental results. As a result, acceleration response characteristics of floating structures subjected to seaquake under some conditions are made clear. It is also certified that the Finite Element Method adopted in this study is effective for estimating the seaquake response of floating structures.

KEYWORDS

Seaquake; Compressible Wave; Underwater Shaking Table; Floating Structure; Tension Leg Mooring; Finite Element Method; Helmholtz Equation; Resonance.

INTRODUCTION

Floating structures are generally considered to be isolated from horizontal seismic motion. However, there is no seismic isolation of floating structures when vertical seismic motion is considered because of the phenomenon called "seaquake". Seaquake is the phenomenon in which compressible waves in sea water strongly influence on ships or floating structures as vertical shock. They are induced by the vertical seismic motion of the sea bottom. Further, the seaquake response of floating structures depends on the relationship between the frequency of seismic wave and the depth of sea water. It is considered that the motion of floating structures due to seaquake coincides with that of the sea bottom when the water depth is small enough. However, the seaquake response characteristics of floating structures change in case of deep water depth or the high frequency of seismic wave in relation to the compressibility of water. To reproduce this situation by use of the underwater shaking table, experiments must be carried out under deep water conditions. Some researches have dealt with experimental or analytical subjects with respect to seaquake. However, there are few studies in which the experiments on the seaquake response of floating structures on deep water have been described. In the present study, the seaquake response characteristics of floating structures in the deep basin are experimentally evaluated by using the underwater shaking table. Further, the effects of mooring systems or material properties of the bottom board of the floating structure on its motion are also discussed. In addition, the analysis using the Finite Element Method is performed to be compared with the experimental results.

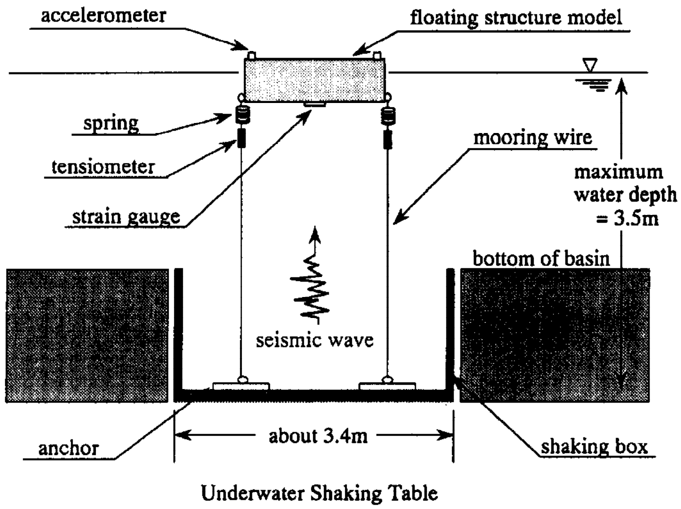


Fig. 1 General view of experiment (with tension leg moorings)

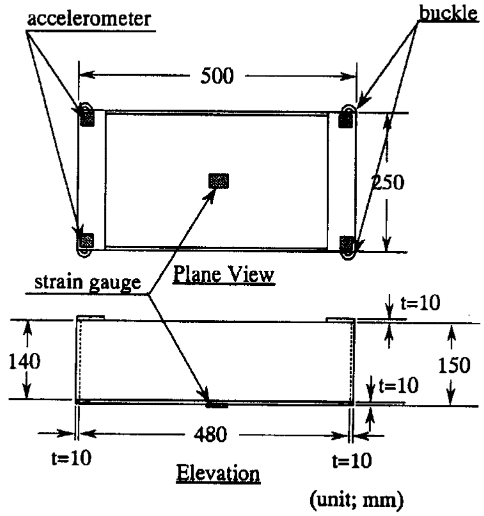


Fig. 2 Model of floating structure

Table 1 Types of models

type	length (cm)	width (cm)	height (cm)	mass (kg)	bottom board
TYPE-A	50	25	15	6.25	acrylic
TYPE-B	50	25	15	6.25	rubber

Table 2 Cases of experiments

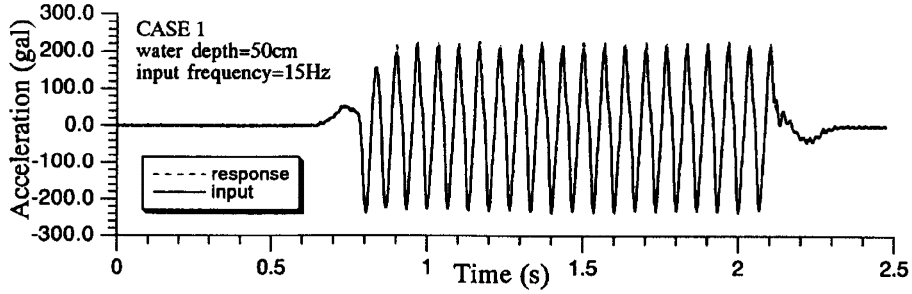
case	model	mooring	draft (cm)	spring stiffness (kN/m)
CASE 1	TYPE-A	No mooring	5	-
CASE 2	TYPE-A	Tension leg	10	0.98
CASE 3	TYPE-B	No mooring	5	-
CASE 4	TYPE-B	Tension leg	10	0.98

SEAQUAKE RESPONSE EXPERIMENT

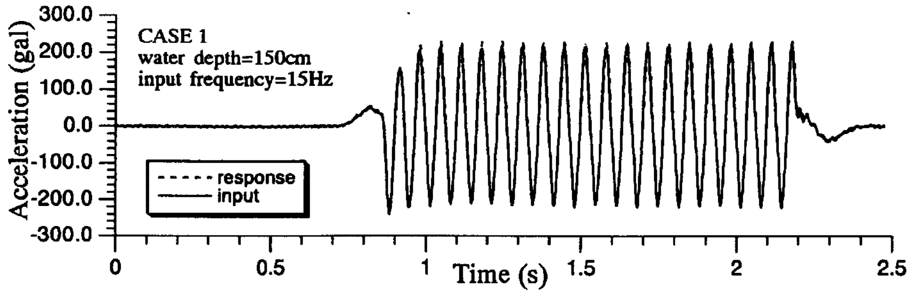
The underwater shaking table belonging to Port and Harbour Research Institute (PHRI) is generally used for estimating seismic response of a breakwater in model experiment. In this study, this equipment was employed to produce compressible waves into water. The underwater shaking table used here has a square cover with the dimension of 3.4m x 3.4m on a shaking box. To conduct experiments in deep water, the cover was taken off and the seaquake response experiments were carried out in range of the maximum water depth of 3.5m.

The experimental set up is illustrated in Figure 1. This figure shows a model of a rectangular floating structure with tension leg moorings and the underwater shaking table without the cover of the shaking box. Figure 2 shows the plane view and elevation of the floating structure model. As can be seen in these figures, four accelerometers are placed at four corners on the floating structure. At the center of the bottom board of the floating structure, a strain gauge is attached in order to measure stresses of the bottom board. Mooring systems consist of springs, mooring wires and anchors. A tensiometer is equipped with the point of each mooring wire. Meanwhile, three accelerometers are installed at three corners on the shaking box in order to measure input accelerations.

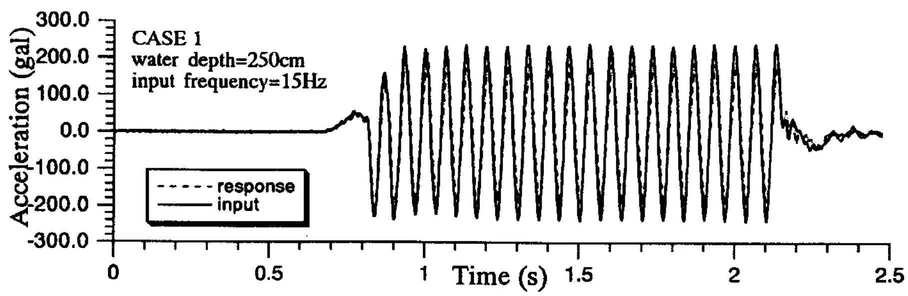
Table 1 shows two types of floating structure models which have the same dimensions. The difference of these models is that TYPE-A has the acrylic bottom board while TYPE-B the rubber one. It is considered that the former is rigid while the latter soft. Each type of models has some weights inside it and its mass is adjusted in advance. Table 2 shows four cases of model experiments including two types of floating structure models and two types of mooring systems. The experiments without mooring systems were performed by means of unfastening mooring wires. In the experiments, input accelerations are vertical steady sinusoidal waves and each input frequency varies from 5 to 35Hz at variants of 10Hz. Further, the water depths are 0.5, 1.5, 2.5 and 3.5m.



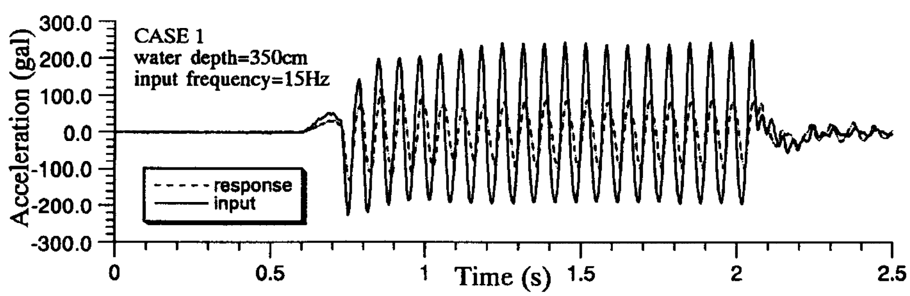
(a) CASE 1,water depth=50cm, input frequency=15Hz



(b) CASE 1, water depth=150cm, input frequency=15Hz



(c) CASE 1, water depth=250cm, input frequency=15Hz



(d) CASE 1, water depth=350cm, input frequency=15Hz
Fig.3 Time histories of input and response accelerations

EXPERIMENTAL RESULTS AND DISCUSSION

Time Histories of Acceleration Response of Floating Structure

Figures 3 (a) - (d) show the time histories of input accelerations and response ones of the floating structure model for the case of CASE 1. One of three input waves measured on the shaking box is drawn as a solid line in each figure. Meanwhile, one of four response waves obtained on the floating structure is drawn as a broken line. These figures at the top, second, third and bottom steps represent the cases of the water depths of 50, 150, 250 and 350cm, respectively. The input frequency is 15Hz in all the figures. As can be seen in these figures, the response accelerations are smaller in comparison with the input ones for the water depths of 250 and 350cm. It can be considered that the main causation of this inclination is related to the shape of the experimental facility

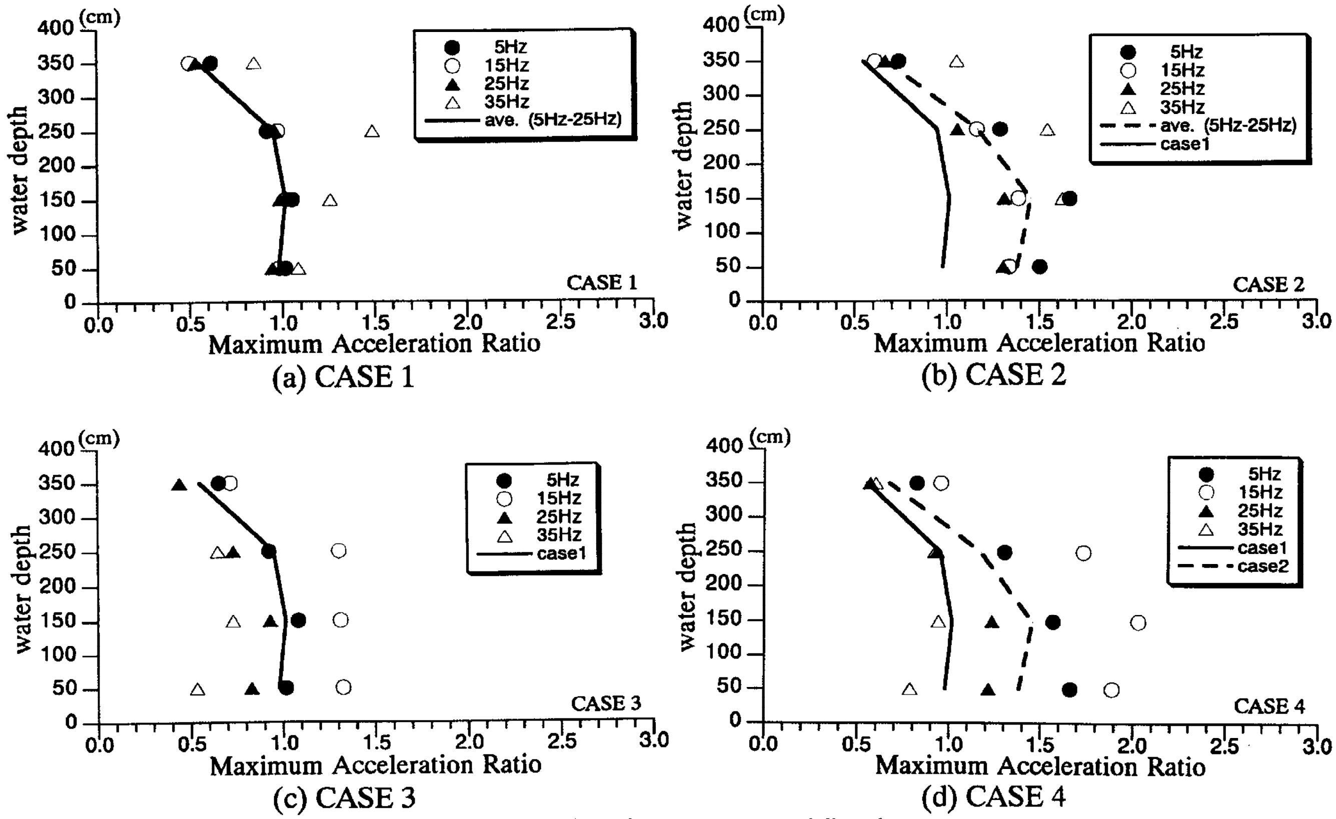


Fig.4 Maximum acceleration response of floating structure

used here. Namely, since the water exists inside the shaking box for the water depth of less than 150cm, it means that the experiments were accomplished in the enclosed water area. On the other hand, for the water depth of more than 150cm, it can be regarded as that they were carried out in the open water area because of the water spreading in the whole basin. Consequently, it can be considered that this phenomenon appears from the reason that the energy of the input seismic wave gets scattered and lost in the open water area.

Maximum Acceleration Response of Floating Structure

Maximum values of input and response accelerations are calculated and arranged from measured waves in this section. Figures 4 (a) - (d) show the ratios of the maximum response accelerations of the floating structure to the maximum input ones and they are represented for the cases of CASE 1, CASE 2, CASE 3 and CASE 4, respectively. In these figures, input accelerations are computed as the mean values of three obtained input waves for the purpose of minimizing their measurement errors. On the other hand, one of four measured values for response accelerations is plotted in each figure. Further, solid and broken lines in these figures indicate the mean values of the maximum acceleration ratios in range of the input frequency of 5 to 25Hz for CASE 1 and CASE 2, respectively.

In Figure 4 (a), the maximum acceleration ratios are almost equivalent to 1.0 for the water depth of less than 250cm. However, they decrease rapidly as the water depth exceeds 250cm. In other words, the response accelerations are nearly equal to the input ones in the enclosed water area and smaller in the open water area. The main reason of this tendency is mentioned in the previous section. Further, the maximum acceleration ratios are large for the cases of the input accelerations of high frequency. For instance, the maximum acceleration ratio in case of 35Hz is about 1.6 times as large as that of 5Hz for the water depth of 250cm. It can be supposed that the lack of the rigidity of the acrylic bottom board causes these results.

From the comparison of Figures 4 (a) and (b), it can be recognized that the acceleration responses of the rigid floating structure with tension leg moorings are larger than those without mooring systems for all the cases.

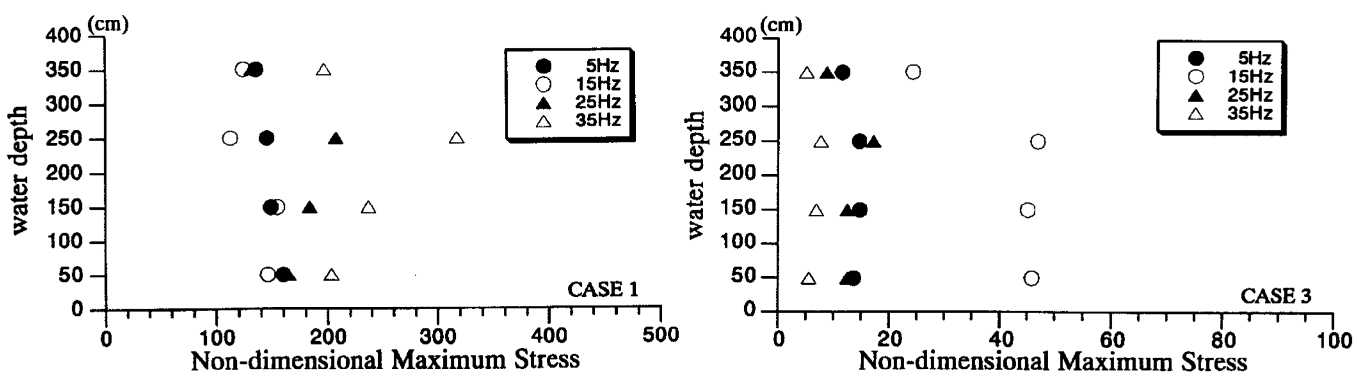
Herein, the rigid floating structure means the model with the acrylic bottom board. However, the responses of the floating structures with and without mooring systems are almost equivalent to each other for the case of the water depth of 350cm. Moreover, the maximum acceleration ratios are larger when the input frequency is 5Hz because of the effects of the mooring wires in Figure 4 (b).

As shown in Figure 4 (c), it can be found that the bottom board made of rubber reduces the seaquake response of the floating structure in CASE 3 in comparison with CASE 1 for the high frequency of 25 and 35Hz. For the case of the input frequency of 15Hz, the maximum acceleration ratios of CASE 3 are larger than those of CASE 1. Its main reason can be considered to be that the natural frequency of the rubber bottom board is close to 15Hz.

From Figure 4 (d), the reduction of the acceleration response of the floating structure can be recognized for the input waves of the high frequency of 25 and 35Hz as compared with CASE 2. At the same time, it is found that there is the increase of the seaquake response caused by tension leg moorings in the same way as shown in Figure 4 (b).

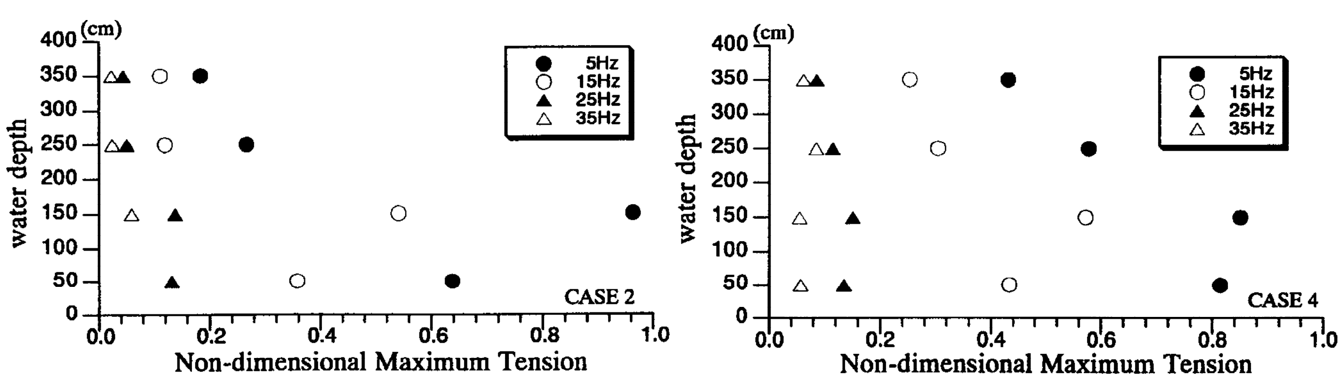
Maximum Stress of Bottom Board and Maximum Tension of Mooring Wire

Figures 5 (a) and (b) show the non-dimensional maximum stresses of the bottom board of the floating structure for the cases of CASE 1 and CASE 3, respectively. In these figures, the normalized maximum stresses are calculated by using the formula $E\varepsilon BL/(Ma)$, where E is Young's modulus of the bottom board, ε is the strain at the center of the bottom board, B is the width of the floating structure, L is the length of the floating structure, M is the mass of the floating structure, and a is the maximum value of the input acceleration. The acrylic and rubber Young's moduli are 2,744 and 49Pa, respectively. On the other hand, Figures 6 (a) and (b) show the non-dimensional maximum tensions of the mooring wire for the cases of CASE 2 and CASE 4, respectively. The maximum tensions are also normalized by the formula $T/(Ma)$, where T is the tension of the mooring wire.



(a) CASE 1 (b) CASE 3

Fig.5 Non-dimensional maximum stress of bottom board of floating structure



(a) CASE 2 (b) CASE 4

Fig.6 Non-dimensional maximum tension of mooring wire of floating structure

It can be seen from Figure 5 (a) that the maximum stresses are large when the input frequency is 35Hz. In other words, it means that the vibration of the acrylic bottom board is generated in case of the high input frequency. As shown in Figure 4 (a), it influences on the motion of the floating structure and causes the increase of its acceleration response. From Figure 5 (b), the maximum stresses become larger as the input frequency is 15Hz and it can be supposed that the resonance of the rubber bottom board appears at that time. Therefore, the acceleration response is larger in case of the input frequency of 15Hz as shown in Figure 4 (c).

From the comparison of Figures 6 (a) and (b), the maximum tensions of CASE 2 have the same inclination as those of CASE 4. As the input frequency is 5Hz, the maximum tensions are larger in both cases. The natural frequency of the floating structure with tension leg moorings is suggested to exist near 5Hz. Further, it turned out that its natural frequency is close to about 3Hz with the simple calculation. Consequently, it can be understood that the coincidence of the natural frequency of the floating structure and the input seismic frequency causes the resonance of the floating structure.

NUMERICAL SIMULATION OF SEAQUAKE

The analytical method of seaquake response described below is based on the hypothesis that seaquake can be regarded as compressible waves propagating in sea water. Accordingly, the boundary value problem around the floating structure can be represented using Helmholtz equation. We consider as one example that the sea bottom vibrates in the vertical direction and generates compressible waves into sea water. Further it is assumed that the fluid is inviscid and compressible and that its motion is irrotational. Therefore, the velocity potential Φ exist and the following equation and conditions has to be solved to gain the solution of this boundary value problem. First, the governing equation of the velocity potential in sea water can be written by equation (1).

$$\partial^2\Phi/\partial x^2+\partial^2\Phi/\partial z^2+(\omega/c)^2\Phi=0 \quad (1)$$

where x is the coordinate axis in the horizontal direction, z is the coordinate axis in the vertical direction, ω is the angular frequency and c is the velocity of sound in water, respectively. Secondly, the boundary condition at the sea surface is expressed as follows:

$$\Phi=0 \quad (2)$$

In the same way, the boundary condition at the sea bottom is given by

$$\partial\Phi/\partial z=0 \quad (3)$$

The continuity condition of the velocity of the seismic motion at the sea bottom is described by equation (4).

$$\partial\Phi/\partial n=V \quad (4)$$

where n is the normal unit vector perpendicular to the sea bottom and V is the velocity amplitude of the motion of the sea bottom. Further, equation (4) must also be satisfied at the surface of the floating structure, provided that n is the normal unit vector perpendicular to the surface of the floating structure and that V is the velocity amplitude of its motion. In addition, the velocity potential Φ needs to satisfy the Sommerfeld's radiation condition. Moreover, the fluid pressure p is expressed in the following form using the velocity potential Φ.

$$p=-\rho(\partial\Phi/\partial t)-\rho gz \quad (5)$$

where ρ is the density of sea water, t is time and g is the gravitational acceleration, respectively. Substituting equation (5) into equations (1) - (4), these equations are expressed in terms of the fluid pressure. Then, the solution of the boundary value problem with respect to the fluid pressure can be obtained by calculating those equations numerically. At the same time, the response of the floating structure can be gained by solving the equation of motion under taking account of the interaction between the floating structure and fluid.

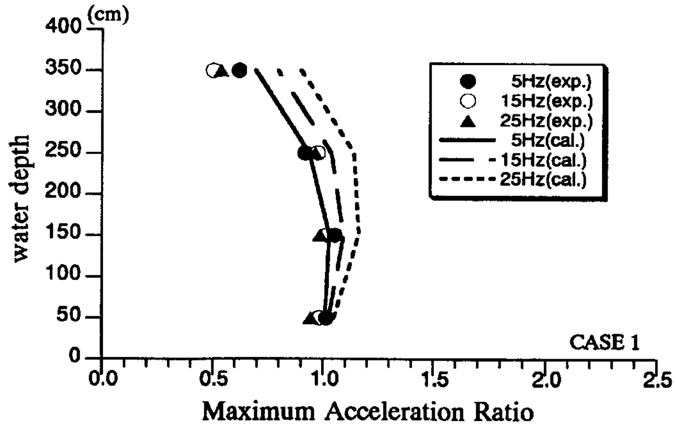


Fig. 7 Comparison of experimental and calculated results (CASE 1)

The boundary value problem mentioned above can be solved by use of the Finite Element Method or the Source Distribution Method. In this study, BEAD (Bank Earthquake Analysis with Dynamic water pressure) program developed in PHRI was employed to simulate seaquake. This is a sort of two-dimensional Finite Element Methods. It has been generally used to analyze the dynamic water pressure acting on a breakwater and its acceleration response during earthquake.

NUMERICAL RESULTS AND DISCUSSION

Comparison of Experimental and Numerical Results

The calculation using BEAD program was conducted for CASE 1, because this program can be used only for the floating structure without mooring systems. The numerical results are compared with experimental ones as shown in Figure 7. The ratios of the maximum response accelerations of the floating structure to the maximum input ones are drawn in this figure. Three symbols indicate the experimental values, while three lines the simulated ones.

As can be seen in Figure 7, the numerical values are almost in good agreement with the experimental ones. However, the good coincidence of the experimental and numerical values can not be seen in deep water depth, for example, when the water depth is 350cm. It means that the energy dissipation of the seaquake response in the experiments is larger than in the simulation. This is considered to be because of the two-dimensional effects of the numerical simulation. Moreover, it is also found that the experimental values are almost equal one another. On the contrary, the numerical values become larger with the input frequency increasing. The main reason of this discrepancy is supposed to be that the calculation simulates more ideal situation of the seaquake response as compared with the experiments. It is suggested from the inclination of the numerical results that the acceleration response of the floating structure becomes close to the resonance peak as the input frequency increases. The resonance of the seaquake response of the floating structure is discussed in the next section. Consequently, it is concluded that this analytical method is reasonable to estimate the seaquake response of the floating structure within the range of the input frequency and water depth adopted in the experiments.

Resonance Phenomenon of Floating Structure

The resonance phenomenon of the floating structure due to seaquake depends on the relation between the seismic frequency and the depth of sea water. The condition for the appearance of the resonance is described in terms of the frequency f and the water depth H as follows:

$$f=Vp/(4H) \tag{6}$$

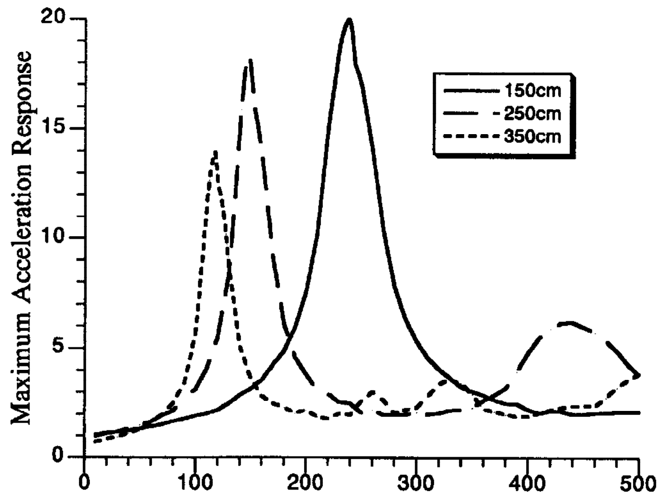


Fig.8 Frequency response curves of acceleration of floating structure under experimental boundary conditions

where *Vp* is the velocity of the seismic wave in the water which is approximately 1500m/s. As can be understood from this equation, it is difficult to reproduce the resonance phenomenon in shaking table tests, because the velocity of the seismic wave is common in the model and the prototype. One example explaining this situation is shown in Figure 8. The numerical results obtained by use of BEAD program are drawn in this figure. Each line represents the maximum acceleration response of the floating structure for three water depths. It can be seen that the resonance appears when the input frequency is about 110Hz in case of the water depth of 350cm. The maximum input frequency that the underwater shaking table in PHRI can generate is 50Hz. Besides, the maximum water depth in the basin is 3.5m. Therefore, the resonance of the floating structure due to seaquake could not be created in the experiments. The deeper basin or the underwater shaking table which has the ability of the higher frequency generation are needed to reproduce the resonance phenomenon accurately in experiments.

CONCLUSION

The seaquake response of the rigid floating structure without mooring systems is almost constant without relation to water depth in the enclosed water area in the experiments. On the other hand, it decreases with the water depth increasing in the open water area. Further, by using soft material for the bottom board, we can change the natural frequency of the floating structure and reduce its response due to high frequency seaquake. The seismic isolation of floating structures may be improved with the application of this idea. Moreover, the seaquake response of the floating structure with tension leg moorings is larger in comparison with that without mooring systems. Therefore, it should be avoided to moor floating structures with tension legs to keep their seismic isolation. Finally, the calculated results obtained by using the Finite Element Method are almost in good agreement with experimental ones for the rigid floating structure without mooring systems. This method can be used to estimate the seaquake response of floating structures. In the future, we would like to reproduce the resonance phenomenon of the floating structure due to seaquake in model experiments.

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