A Study on the Effect of Seaquakes on a Floating Body

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Summary

Effect of seaquake on a floating body in an open sea and in an enclosed basin was studied theoretically and experimentally. First, sea bottom and breakwaters were replaced by the distributions of highly pulsating bubbles, and then formulas for surge, sway and heave accelerations of the floating body were derived in term of the acceleration of sea bottom or breakwaters. The theoretically predicted responses of the floating body were well supported by laboratory experiments using a small water tank on a vibrator. From the present study it was found that the vertical oscillation of large area of sea bottom or of the enclosed basin of any water depth induces the vertical acceleration on the floating body as if it were on the ground. Horizontal shake of breakwaters induces both vertical and horizontal accelerations on the floating body, and their magnitudes decrease substantially with increase of distance from the breakwaters.

1. Introduction

For seismically active region, seaquake effect on a floating structure should be considered in the design process. Hove et al. have reported a number of well documented cases showing that ships have been severely damaged or shaken by seismic waves in the open sea. They have observed as follows:

1. Earthquake effects are just as severe to structures in the open sea as to structures on ground.
2. The depth of water has negligible effect on the damage potential.
3. In some cases the ship appeared to be lifted up or out of water and they have stressed that the damage potential appears to have such wide distribution in the open sea as on ground and also pointed out that the mechanics behind the characteristics of seakeage are not well explained. Recently, Hagiwara et al. have conducted a comprehensive experimental study on the motion responses of a floating power plant to the seismic activities with a guide based on a simple hydrodynamic theory. They used a 1/170 scale model afloat in an enclosed tank (2.0 m x 1.5 m) fixed on a vibrator. As a result it was observed as noted by Hove et al. that the vertical acceleration of the body takes the same value as that of the water tank. Further, they found a possibility of isolation from the high frequency horizontal acceleration by taking a distance from the breakwaters. At present, as noted by these authors cited above, a hydrodynamic study on the motion responses of a floating body to the seaquake is an area of studies to be pursued for the development of reliable design methodology for floating structures in seismically active regions. The cases presented by Hove et al. were based on the reports from captains and crew who experienced the seaquakes incidentally. It is, therefore, rather difficult to extract further detail seismological and hydrodynamic information from their reports. Fortunately, however, there is a very rare and invaluable observation by the seismologists Mogi and Mochizuki, who experienced severe seaquakes many times on a hydrographic observation ship, and made detailed measurements of high frequency seismic waves of 50~300 Hz by use of a hydrophone just above the focal region of Izu-Hanto-Toho-Oki Earthquake of M 6.7 on June 29, 1980.

The present author noticed this high frequency property of seismic waves, and then attempted to model the seismic activities on the sea bottom by distributing pulsating bubbles such as caused by underwater explosion. In fact, most of people, who experienced seaquakes, felt as if their ships were hit by underwater explosions. In the present study, a formula for unsteady force acting on a rigid floating body induced by a pulsating bubble in a water was formulated first and then the sea bottom or breakwaters under seismic activities were

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replaced by the distribution of the pulsating bubbles. It turned out that the present theoretical model explains well the observed responses of floating bodies to the seaquakes.

2. Unsteady forces acting on a floating body induced by a pulsating bubble

In 1953, Chertock made a study on the flexural response of a submerged body to a pulsating gas bubble. In this study, by using Green's theorem, analysis was made on the forces acting on a body in an unsteady incident flow without having to solve the relevant diffraction problem. Ogilvie made a generalization of this method and showed applicability of this method to a wide variety of hydrodynamic problems.

For a high frequency fluid motion with free surface, the so called memory effect due to free-surface waves is negligible. Therefore, by use of mirror images with respect to the free-surface, we may treat the floating body problem as an unbounded fluid problem. In the present study, for the sake of simplicity, three axial translation modes, surge, sway and heave of a floating rigid body to a highly pulsating submerged bubble was considered following Chertock, who analysed only the vertical motion for a flexural body. First, it is assumed that the flow generated by a pulsating bubble is an incompressible motion. Further it is assumed that there exists a velocity potential \( \Phi(x, y, z, t) \) which satisfies Laplace's equation and is expressed as a sum of the following two components

\[
\Phi(x, y, z, t) = \Phi_0(x, y, z, t) + \sum_{i=1}^{\infty} q_i(t) \varphi_i(x, y, z)
\]

where \( \Phi_0 \) represents a motion due to the pulsating bubble and the second term represents the velocity potential due to the floating body. \( q_i(t) \) is the \( i \)-th mode coordinate and \( \dot{q}_i(t) \) is the its time derivative, and \( \varphi_i \) represents \( i \)-th mode potential.

With a moving coordinate system as shown in Fig. 1, \( x \)-axis coincides with the direction of surge and \( y \)-axis sway and \( z \)-axis heave. The equation of motion of the floating body is written in general:

\[
M \ddot{q}_i(t) = \int_{\mathcal{S}_B} \rho n dS
\]

where \( M \) is the mass of the floating body, \( \rho \) is the fluid pressure acting on a body with the wetted surface \( S_B \), and \( n \) is the outward normal vector from the fluid. The right hand side of the equation (2) is rewritten by use of a relation for an unbounded fluid:

\[
\int_{\mathcal{S}_B} \rho n dS = -\rho \frac{d}{dt} \int_{\mathcal{S}_B} \Phi_0(\xi, \eta, \zeta, t) n dS
\]

where \( \rho \) is the density of water. Substituting (1) into (3), we have from (2) as:

\[
M \ddot{q}_i(t) = -\rho \frac{d}{dt} \int_{\mathcal{S}_B} \Phi_0(\xi, \eta, \zeta, t) n dS - \rho \sum_{i=1}^{\infty} \dot{q}_i(t) \int_{\mathcal{S}_B} \varphi_i(\xi, \eta, \zeta) n_i dS
\]

where \( n_i \) is the \( i \)-th component of \( n \). \( \Phi_0 \) and \( \varphi_i \) are the solutions of the following boundary value problem:

\[
F \Phi_0 = 0, \quad F \varphi_i = 0 \quad \text{for } z < 0
\]

\[
\partial \Phi_0 / \partial n = 0, \quad \partial \varphi_i / \partial n = n_i \quad \text{on } S_B
\]

\[
\partial \Phi_0 / \partial n = -v_g, \quad \partial \varphi_i / \partial n = 0 \quad \text{on } G
\]

Regarding the condition on the bubble surface, Chertock stated as follows: “The condition \( \partial \varphi_i / \partial n = 0 \) on \( G \) makes \( \varphi_i \) a function of time as well as the space coordinates, because the surface \( G \) varies with time. However, the further analysis is restricted for cases where the bubble is sufficiently far from \( S_B \) so that its presence has negligible effect on defining the potential \( \varphi_i \). In that case \( \varphi_i \) will be the same as the potential due to the prescribed motion of \( S_B \) when the bubble is absent, and \( \varphi_i \) can be taken as a function of \( x, y, z \) only”. We follow this approximation hereafter.

By use of the relation \( \partial \varphi_i / \partial n = n_i \) on \( S_B \), the integral of the second term of the right hand side of the equation (4) is written as:

\[
\int_{\mathcal{S}_B} \varphi_i n dS = \int_{\mathcal{S}_B} \varphi_i \frac{\partial \varphi_i}{\partial n} dS = a_{ij} \rho
\]

where \( a_{ij} \) is the added mass due to the motion of the floating body. Then the equation (4) is written as

\[
(M + a_{ij}) \ddot{q}_i(t) = -\rho \frac{d}{dt} \int_{\mathcal{S}_B} \Phi_0 n dS
\]

where it is considered the cases that \( a_{ij} = 0 \) for \( i \neq j \).

By use of the Green's second identity to two functions \( \Phi_0 \) and \( \varphi_i \), we have

\[
\int_{\mathcal{S}_B + \infty} \left( \Phi_0 \frac{\partial \varphi_i}{\partial n} - \varphi_i \frac{\partial \Phi_0}{\partial n} \right) dS = 0
\]
Using the boundary conditions stated above, we have
\[ \int_S \Phi n_1 dS = - \int_O \Phi_1 v_1 dS \]
Here we consider as stated before the case where the distance between the floating body and the bubble is far enough so that we may introduce the following approximations:

1) the bubble is regarded as a sphere.
2) \( v_g \) is uniform over the sphere.

Then we have an approximation
\[ \int_S \Phi n_1 dS = - \phi_{1g} \int_O v_g dS = - \phi_{1g} \frac{dV}{dt} \]
where \( V \) is the volume of the bubble. \( \phi_{1g} \) is the value of potential \( \phi_i \) at the center of the bubble.

The desired equation of motion of the floating body is thus obtained from (6):

\[ (M + a_{11}) \ddot{q}_1(t) = - \phi_{1g} \frac{d^2 V}{dt^2} \quad (7) \]

To determine the potential \( \phi_{1g} \) of the eq. (7) we use again the assumption that the distance between a floating body and a bubble is far enough so that we may use an asymptotic expression of \( \phi_i \) at the bubble. Now a potential \( \phi(x, y, z) \), which represents the flow around a floating body and satisfies \( \phi = 0 \) at \( z = 0 \), is expressed in general by the Green's theorem as:

\[ \phi(x, y, z) = \frac{1}{4\pi} \int_S \left[ \frac{1}{r_1} - \frac{1}{r_2} \right] \frac{\partial \phi}{\partial n} - \phi \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) dS \quad (8) \]

where
\[ r_1 = [(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2]^{1/2} \]
\[ r_2 = [(x+\xi)^2 + (y-\eta)^2 + (z+\zeta)^2]^{1/2} \]

By defining
\[ r = (x^2+y^2+z^2)^{1/2} \]
and considering a point \( (x, y, z) \) far from the floating body, we have a Taylor expansion of (8) up to the order of \( O(1/r^3) \) as follows:

First, we may obtain the following expansions.
\[ \frac{1}{r_1} - \frac{1}{r_2} = \frac{2x}{r^3} + \frac{2y}{r^3} + \frac{6\zeta x}{r^3} + \frac{6\zeta y}{r^3} + O\left( \frac{1}{r^4} \right) \]
\[ \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) = \frac{\partial \zeta}{\partial n} \frac{2x}{r^3} + \frac{\partial \zeta}{\partial n} \frac{6\zeta x}{r^3} + O\left( \frac{1}{r^4} \right) \]
\[ \frac{\partial}{\partial n} \left( \frac{6\zeta y}{r^3} + O\left( \frac{1}{r^4} \right) \right) \]

and then,
\[ \phi(x, y, z) = \frac{1}{4\pi} \left[ \int_S \left\{ \frac{\partial \phi}{\partial n} - \phi \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \right] \frac{2x}{r^3} \]
\[ + \frac{1}{4\pi} \int_S \left\{ \frac{\partial \phi}{\partial n} - \phi \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \frac{6\zeta x}{r^3} \]
\[ + \frac{1}{4\pi} \int_S \left\{ \frac{\partial \phi}{\partial n} - \phi \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \frac{6\zeta y}{r^3} \]
\[ \times \frac{6\zeta y}{r^3} + O\left( \frac{1}{r^4} \right) \]

The first term of the right-hand side is a velocity potential due to a dipole whose axis directs \( z \)-axis, and the second and the third terms are higher order and due to quadrupoles, which are composed in such a way that two dipoles, one directing \( x \) (or \( y \)) -axis under the free-surface and other directing negative \( x \) (or \( y \)) -axis above the free-surface, come close together along \( z \)-axis. Thus we may assume that in a highly oscillating problem the first term represents heave motion of a floating body, and the second term surge motion and the third term sway motion respectively. Then we may write:

\[ \phi(x, y, z) = \phi_1(x, y, z) + \phi_2(x, y, z) + \phi_3(x, y, z) \quad (9) \]

where
\[ \phi_1 = \frac{1}{4\pi} \int_S \left\{ \frac{\partial \phi_1}{\partial n} - \phi_1 \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \frac{6\zeta x}{r^3} \]
\[ \phi_2 = \frac{1}{4\pi} \int_S \left\{ \frac{\partial \phi_2}{\partial n} - \phi_2 \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \frac{6\zeta y}{r^3} \]
\[ \phi_3 = \frac{1}{4\pi} \int_S \left\{ \frac{\partial \phi_3}{\partial n} - \phi_3 \frac{\partial}{\partial n} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right\} dS \frac{2\zeta}{r^3} \]

where \( \psi \) is the displacement volume, \( a_{11} \) is added mass due to surge motion, \( a_{22} \) due to sway motion, \( a_{33} \) due to heave motion and \( \zeta_0 \) is a representative value of \( \zeta \) on the body. Substituting (9) into (7), we have the following equations for the three modes of motions:

Surge motion:
\[ (M + a_{11}) \ddot{q}_1(t) = - \frac{1}{4\pi} \left( \rho \psi + a_{11} \zeta_0 \right) \frac{d^2 V}{dt^2} \frac{6\zeta x}{r^3} \]

Sway motion:
\[ (M + a_{22}) \ddot{q}_2(t) = - \frac{1}{4\pi} \left( \rho \psi + a_{22} \zeta_0 \right) \frac{d^2 V}{dt^2} \frac{6\zeta y}{r^3} \]

Heave motion:
\[ (M + a_{33}) \ddot{q}_3(t) = - \frac{1}{4\pi} \left( \rho \psi + a_{33} \zeta_0 \right) \frac{d^2 V}{dt^2} \frac{2\zeta}{r^3} \]

Finally, by use of the condition that the body is floating
\[ M = \rho \psi \]
we have then the acceleration of the floating body as:

Surge motion:
\[ \ddot{q}_1(t) = - \frac{1}{4\pi} \zeta_0 \frac{d^2 V}{dt^2} \frac{6\zeta x}{r^3} \]

Sway motion:
\[ \ddot{q}_2(t) = - \frac{1}{4\pi} \zeta_0 \frac{d^2 V}{dt^2} \frac{6\zeta y}{r^3} \]

(10)
Heave motion:
\[ \ddot{z}(t) = -\frac{1}{4\pi} \frac{d^2 V}{dr^2} \frac{2z}{r^3} \quad (12) \]

From these results it is found that the heave acceleration is determined without any information of body geometry, while surge and sway motions depend on the value of \( \zeta_0 \), which is a representative geometrical parameter of depthwise dimension of the floating body.

3. Acceleration of a floating body due to seaquakes

3.1 Acceleration due to vertical vibration of sea bottom

In the previous section, the response of a floating body due to an underwater bubble is considered. In the present section, the unsteady vertical motion of sea bottom, which is caused by the so-called P-waves due to seismic activity of ground, is represented by the distribution of pulsating bubbles on the sea bottom.

For the sake of simplicity uniform horizontal sea bottom of depth \( z = -f \) is considered. Let the time dependent vertical displacement of sea bottom be defined by \( h(t) \). Then a volume \( dV(t) \) for an elemental area \( dxdy \) is written as:

\[ dV = h(t) dxdy \]

When a region \( (x_1, y_1 ; x_2, y_2) \) on the sea bottom is displaced, the accelerations of the floating body are expressed for:

Surge motion:
\[ \ddot{q}_1 = \frac{3}{2\pi} \frac{f_{zc}}{h} \int_{x_1}^{x_2} \int_{y_1}^{y_2} x dxdy \frac{x}{(x^2 + y^2 + f^2)^{3/2}} \quad (13) \]

Sway motion:
\[ \ddot{q}_2 = \frac{3}{2\pi} \frac{f_{zc}}{h} \int_{x_1}^{x_2} \int_{y_1}^{y_2} y dxdy \frac{x}{(x^2 + y^2 + f^2)^{3/2}} \quad (14) \]

Heave motion:
\[ \ddot{q}_3 = \frac{f}{2\pi} \frac{f_{zc}}{h} \int_{x_1}^{x_2} \int_{y_1}^{y_2} dxdy \frac{1}{(x^2 + y^2 + f^2)^{3/2}} \quad (15) \]

Further, when the floating body is right above the epicenter, we may put \( x_2 = -x_1 = x_0 \), \( y_2 = -y_1 = y_0 \) and the surge and sway motions are not caused due to asymmetric character of integrands of (13) and (14), and only the acceleration due to heave motion appears. From the integration of (15), we have

\[ \ddot{q}_3 = \frac{2}{\pi} \tan^{-1} \left( \frac{x_0y_0}{f \sqrt{x_0^2 + y_0^2 + f^2}} \right) \quad (16) \]

Even though the floating body is not right above the epicenter, it is understood from the equations (13) through (15) that the heave motion dominates.

For a large earthquake the focal region is large enough so that we may assume

\[ \frac{x_0}{f}, \frac{y_0}{f} \to \infty \]

Then, the equation (16) becomes

\[ \frac{\ddot{q}_3}{h} \to 1 \quad (17) \]

This result means that the acceleration of the floating body is the same as that of the sea bottom and the phase of motion is identical with that of the vertical motion of the sea bottom as if the floating body is on the ground, and the effect of sea depth does not appear. Further, since the motion starts from a state of rest, the initial vertical displacement of the floating body is the same as that of the sea bottom.

If the focal region is limited within a narrow band such as an earthquake fault, the acceleration of the floating body decreases rapidly with increase of distance from the epicenter as shown in the following: Let \( 2x_0 \) be the length of fault and \( B \) the breadth. Then we have from (15):

\[ \text{Fig. 2 Vertical acceleration due to earthquake fault} \]

\[ \text{Fig. 3 Acoustic emission activity observed above earthquake fault (from reference 3)} \]
As an example, use is made of the data of earthquake fault estimated by Mogi and Mochizuki for the 1980 Izu-Hanto-Toho-Oki Earthquake. They estimated as: $2B = 20$ km, $B = 1.5$ km (read from Fig. 16 of the paper by Mogi and Mochizuki 1980) and $f = 1.25$ km (read from Fig. 14 of the same paper). Calculated curve of $q_3/h$ against the distance $y$ from the center line ($y = 0$) is shown in the upper figure of Fig. 2.

It is observed that the acceleration responses decrease rapidly with the distance from the epicenter. This trend agrees well with the trend of the acoustic emission activity observed by Mogi and Mochizuki as shown in Fig. 3.

3.2 Acceleration of a floating body in an enclosed water basin

3.2.1 Vertical shake

Suppose a rectangular basin, approximately representing a harbour surrounded by breakwaters, in which a body is afloat. For the vertical motion caused by the P-waves of earthquake, the relation $q_1/h = 1.0$ holds for any water depth because of the infinite mirror images of highly oscillating sea bottom due to the parallel vertical walls $xz$ and $yz$ as shown in Fig. 4. As mentioned in the introduction of the present paper, the experimental studies by Hagiwara et al. showed that the vertical acceleration of a floating body took the same values as those of the water tank for any frequency zone (2 Hz ~ 30 Hz), and the water depth was negligible effect on the responses\(^2\). These experimental results are well predicted by the present theory. Additional experimental studies were conducted by the present author to verify the present theory. These results are shown in the later section together with the predictions for heave and sway motions due to horizontal shake.

3.2.2 Horizontal shake

For the horizontal shake, which is caused by S-waves due to seismic activities, the heave and sway accelerations of a floating body are derived from (11) and (12) as follows by replacing breakwaters with the pulsating bubbles distributed vertically on two parallel $xz$ planes at $y = -y_1$ and $y = y_2$, where $(y_1 + y_2)$ is the distance between the breakwaters and kept constant.

**Sway acceleration**

$$q_2 = \frac{\zeta_0}{4\pi} \int_{-\infty}^{0} dx \int_{-2d}^{0} dz \left[ -by \tilde{h}_z \right] + \int_{-\infty}^{0} dx \int_{-2d}^{0} dz \left[ \frac{by_2(-\tilde{h})z}{(x^2 + y_1^2 + z^2)^{3/2}} \right]$$

$$= \frac{\tilde{h}}{2\pi} \left[ \frac{2h}{9} \left( \frac{y_1}{d} \right)^2 + \frac{y_2}{d} \right]$$

**Heave acceleration**

$$q_y = \frac{\zeta_0}{4\pi} \int_{-\infty}^{0} dx \int_{-2d}^{0} dz \left[ \frac{2\tilde{h}_z}{(x^2 + y_1^2 + z^2)^{3/2}} \right] + \int_{-\infty}^{0} dx \int_{-2d}^{0} dz \left[ \frac{(-\tilde{h})z}{(x^2 + y_1^2 + z^2)^{3/2}} \right]$$

$$= \frac{\tilde{h}}{2\pi} \left[ \frac{4(\frac{y_1}{d})^2}{9} - \ln \left( \frac{4 + (\frac{y_1}{d})^2}{9} \right) \right]$$

where the integral range for $x$ extends to infinity. This is due to the consideration of infinite number of mirror images about the parallel $zx$ planes which represent breakwaters perpendicular to the horizontally shaking breakwaters. Further, the integral range for $z$ extends to $z = -2d$. This is due to the consideration of mirror images about the bottom of the basin.

From (18) and (19) it is found that the response accelerations decrease with increase of distance from the breakwaters as already found experimentally by Hagiwara et al.\(^2\). The heave acceleration takes asymmetric value about the center and becomes null at the center ($y_1 = y_2$). On the other hand, the sway acceleration is symmetric about the center. Calculated values based on these expressions are shown in the following section together with measured data.

3.2.3 Experimental studies

To verify the theoretical predictions a small water tank (400 mm × 400 mm) made of acrylate resins and a vibrator (250 N, 0 ~ 50 Hz) were used. The experimental arrangement for the present study is shown in Fig. 5. The input acceleration was measured by accelerometers $P_0$ at the vibrator and $P_1$ at the opposite side of the tank. Their mean values were used for the analysis as the given acceleration. Accelerometers for sway motion $P_2$ and heave motion $P_3$ were set at the center of inner bottom of a floating box. Fig. 6 shows some examples of recorded accelerations. The upper figure of the right hand side of Fig. 6 shows the heave
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acceleration due to vertical shake. As the theory predicts, the amplitude and phase of response acceleration are almost the same as those of given acceleration. The quantitative evaluation is given later. The figures in the left hand side of Fig.6 shows a comparison of response accelerations for three different positions of the floating body. The heave acceleration at the center (horizontal shake A) is almost negligible as the theory predicts and the small value of sway acceleration is observed. In the records of horizontal shake B and C, the position of the floating body is opposite about the center of the tank. As the theory predicts, the sign of heave acceleration changes for these two points, while the sway acceleration keeps the same phase and amplitude of response. From the comparison of horizontal shake B and D, it is observed that the smaller water depth \( d \) gives smaller response accelerations.

In the followings quantitative comparisons between the predicted and measured values are made. Fig.7 shows the ratio of heave acceleration to the given acceleration for vertical shake. The positions of the floating body are changed. Though a little higher values are observed near the walls, the experimental data agree well with the given acceleration as a whole, and are independent of water depth and frequency. Fig.8 through Fig.11 show the comparisons between the predicted and measured accelerations in the case of horizontal shake. Calculations were made based on the expressions (18) and (19). In calculating sway acceleration \( \zeta_0 \) is assumed to be one half of the draft \( T \) of a floating body, viz., \( \zeta_0 = -T/2 \). Fig.8 shows the effect of water depth on motion responses. The shallower draft gives lower values of heave and sway accelerations. The theoretical values agree qualitatively with measurements. However quantitative agreement becomes poorer towards the walls. This may be due to the approximation employed in the present theory, which has been developed under the assumption that the floating
body is far from the pulsating walls. Fig. 9 shows the effect of draft of a floating body to the motion responses. The theory indicates that the draft has no effect on the heave acceleration. In fact the measured data for $T=50$ mm and $30$ mm are almost the same and support this theoretical prediction.

On the other hand, as the theory predicts the effect is apparent for sway acceleration. The trend of calculated curves corresponds well to the measurements. Fig. 10 demonstrates the independency of frequency of horizontal shaking to the motion responses, and Fig. 11 demonstrates that the
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changes of breadth of floating body used in the present study has negligible effect on motion responses. These experiments also support the theoretical predictions, viz., the phase of oscillation induced on a floating body takes the same value as that of the breakwater, and the accelerations are independent of the breadth of the floating body.

3.3 Acceleration of a floating body near the vertical shore open to the sea

Motion response of a floating body near the vertical shore open to the sea can be derived by removing the effect of the one side of breakwaters of an enclosed basin. That is, from (18) and (19) we have as follows.

Sway motion:

\[ \ddot{q}_s = -\frac{\kappa}{\pi d} \left( \frac{\zeta_0}{y/d} \right) \left( \frac{1}{y/d} - \frac{\dot{y}}{4 + \left( \frac{y}{d} \right)^2} \right) \]  

Heave motion:

\[ \ddot{q}_h = \frac{\kappa}{2\pi} \ln \left( \frac{4 + \left( \frac{y}{d} \right)^2}{\left( \frac{y}{d} \right)^2} \right) \]

Fig. 12 shows calculated values of response accelerations to the given acceleration versus the distance parameter \( y/d \). In this calculation \( \zeta_0/d \) is assumed to be 0.5. With increase of distance from the shore the response acceleration is reduced substantially. Further, it is noted that the heave response is larger than the sway response, though the shore is shaken horizontally.

4. Concluding remarks

As an extension of Chertock's analysis for the flexural response of a submerged body to a pulsating gas bubble, the effect of seake on a floating body was studied by replacing the sea bottom or breakwaters with distribution of highly pulsating bubbles. From the present theoretical and experimental study the following results are obtained:

1. For large area of high frequency motion of sea bottom a floating body is accelerated vertically as if the body is on the ground, and the depth of water has negligible effect. This result is also applied to a body floating on an enclosed basin.

2. Effect of seake caused in the narrow banded region such as the earthquake fault decreases rapidly with increase of distance from epicenter.

These theoretical results correspond well with the observations on board ships and in laboratory experiments.

3. For horizontal shake of an enclosed basin, heave and surge or sway accelerations coexist. With increase of the distance from the wall these accelerations decrease and when a floating body is located at the center of the basin, the heave acceleration becomes null, and the shallower water depth gives smaller values of acceleration responses.

In the present study a floating body is assumed as a rigid body. However, in the design stage of structure, the flexural responses of the structure to the seakes are required. The study of this flexural response is left as a next step of studies together with the improvement of the present asymptotic theory.

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