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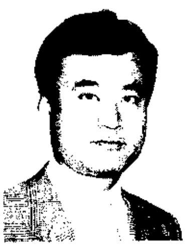
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1 Introduction

The floating type structural system is applicable to large offshore structures including airports, power plants and multi-purpose facilities. Such a large scale floating structure should be in service at least 100 years because of the large capital investments and utilization, so it also should be designed to be safe and stable against several natural hazards and accidents during its service life.

For the floating structures supported with mooring cables, an earthquake load is not always critical in their structural design, while the very large floating structures (VLFS) may suffer critical damage during their long period of service because in extreme cases, the severe seismic loads on the dolphin may be enough to break the connecting devices to the floating structures, or may destroy the dolphin itself.

In order to develop the seismic assessment of the VLFS, the following major issues should be discussed.

(1) Prediction of expected maximum earthquakes during its service period
(2) Seismic response analysis of dolphin system
(3) Seismic response analysis of the VLFS system under spatial phase delay of seismic wave arrivals
(4) Assessment of progressive failure of VLFS with increasing damaged dolphins

This study presents and discusses a method for estimating the seismic response and risk of the VLFS supported with many dolphins in a seismic environment.

For the first three issues, there are several scenarios for the frequency domain with the power spectral density of the earthquake motion. The discussion also focuses on the risk of a progressive failure of the VLFS which might be triggered by an increase in the number of damaged dolphins.

2 Analysis

2.1 Structual Modeling

When the VLFS is not allowed to exceed the limited displacement, the floating structure must be supported with many dolphins as shown in **Fig. 1**, instead of the mooring cables currently used.

The dolphin system is more sensitive to seismic excitation through the structural piles driven into the baserock than is the mooring system.

The connecting device, which is composed of spring and damper, is furnished between the dolphin and the

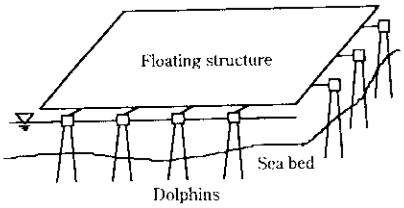

Fig. 1 Floating structural system supported with dolphins[4)]

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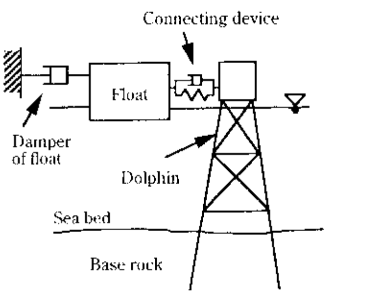

Fig. 2 Dolphin structural model[4)]

floating structure as shown in **Fig. 2**.

The dolphin connected to the VLFS can be modeled as a single-degree-of-freedom system whose amplification factor is given by the following equation[1)]:

$$H_j(\omega) = \frac{1 + 2ih_{2j}\frac{\omega_{2j}}{\omega} - \left(\frac{\omega_{2j}}{\omega}\right)^2}{(\omega_{1j}^2 + \omega_{2j}^2 - \omega^2) + 2i(h_{1j}\omega_{1j} + h_{2j}\omega_{2j})\omega} \cdots (1)$$

where ω_{1j} and ω_{2j} are the characteristics frequencies of the j-th dolphin and its connecting device system, respectively, while h_{1j}, and h_{2j} are their damping factors.

The characteristic values of the connecting device of the j-th dolphin are given by

$$\omega_{2j} = \sqrt{\frac{k_j}{m_j}},\quad h_{2j} = \frac{c_j}{2\sqrt{m_j k_j}} \cdots\cdots\cdots\cdots\cdots (2)$$

where m_j, c_j, k_j are the mass of the top of the dolphin, the spring constant and the damping coefficient of the connecting device, respectively.

The VLFS is assumed to move along the horizontal surface and to neglect the local elastic deflection of the floating structure at the applied force point, so the rigid model is introduced to simulate the motion of the floating structure. **Figure 3** is the configuration of the floating structure, in which the dolphins are arranged along the x-direction (i = 1 to n) and along the y-direction (j = 1 to m), respectively.

The earthquake excitation is transmitted to the floating structure from the baserock through the inertia forces F_i and G_j of the dolphins.

$$\left.\begin{aligned} F_i &= k_i^*\{v_i - (x_i - x_f)\theta - v\} + \\ &\quad c_i\{\dot{v}_i - (x_i - x_f)\dot{\theta} - \dot{v}\} \\ G_j &= k_j^*\{u_j - (y_j - y_f)\theta - u\} + \\ &\quad c_j\{\dot{u}_j - (y_j - y_f)\dot{\theta} - \dot{u}\} \end{aligned}\right\} \cdots\cdots\cdots\cdots (3)$$

where u, v, θ are the motions (two dimensional translations and rotation) at the gravity center (x_f, y_f) of the VLFS, while u_j is the response in the x-direction at the top of the j-th dolphin, and v_i is the response in the y-direction at the top of the i-th dolphin. Since the global stiffness of the i-th dolphin and its connecting device must be taken into consideration in the response analysis of the following section, the spring constant k_i* in Eq. (4) can be given by

$$k_i^* = m_i\omega_{ni}^2,\quad \omega_{ni} = \frac{\omega_{1i}\omega_{2i}}{\sqrt{\omega_{1i}^2\omega_{2i}^2}} \cdots\cdots\cdots\cdots\cdots (4)$$

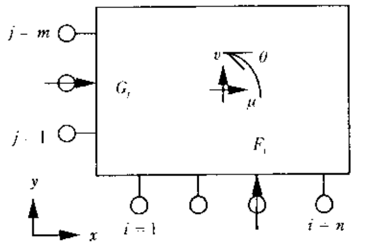

Fig. 3 Configuration of the floating structure

The incident seismic wave is assumed herein to propagate into the VLFS in the direction of ψ radian from the x-axis, and its exciting motion is considered to be perpendicular to the propagating direction of the seismic shear wave.

The frictional resistance of the VLFS induced by the surrounding water is estiamted as the damping coefficient of the VLFS.

2.2 Earthquake Motion

The statistical approach can provide the expression of accelerogram as the nonstationary random process whose spectral content is statistically predicted with the historical earthquake database in the following form[2)]:

$$\ddot{z}(t, x) = \sum_{k=1}^{2} \sqrt{2S(\omega_k, t, x)\,\Delta\omega}\,\exp\{i(\omega_k t + \phi_k)\} \cdots (5)$$

where $\omega_k = k\Delta\omega$, $\Delta\omega = \omega_u/n$, and ω_u is the upper bound of frequency, while ϕ_k is the phase angle to be randomly distributed in $(0, \pi)$.

The effect of spatial randomness on the spectral content can be estimated with the coherency function coh(ω, x) in the following form[3)]:

$$S(\omega, t, x) = S_0(\omega, t)\ \mathrm{coh}\,(\omega, x) \cdots\cdots\cdots\cdots (6)$$

where $S_0(\omega, t)$ is the nonstationary power spectral density at a specific site, and the coherency function coh is given with parameter α and the separate distance Δ by

$$\mathrm{coh}\,(\omega, x) = \exp\left[-\frac{\alpha\omega|\Delta|}{2\pi c_s}\right] \cdots\cdots\cdots\cdots\cdots (7)$$

2.3 Formulations

The equation of motion of the VLFS can be formulated in the following simultaneous equations:

$$\left.\begin{aligned} M\ddot{u} + C\dot{u} &= \sum_j G_j \\ M\ddot{v} + C\dot{v} &= \sum_i F_i \\ I\ddot{\theta} + C_\theta\dot{\theta} &= \sum_i F_i(x_i - x_f) - \sum_j G_j(y_j - y_f) \end{aligned}\right\} \cdots (8)$$

in which M, I, C and C_θ are the mass, inertia moment, and damping coefficients (for translation mode and rotation mode) of the VLFS. Using the response vector $Q=\{u, v, \vartheta\}$ and its generalized motion vector q and characteristic matrix $[\phi]$, we may obtain the following equation of motion in the generalized coordinates:

$$\{\ddot{q}\} + [2h_n\omega_n]\{\dot{q}\} + [\omega_n^2]\{q\} = [\phi]^T\{W(t)\} \cdots (9)$$

in which

$$\{Q(t)\} = [\phi]\{q(t)\},\ \vartheta = L\theta,\ L=\sqrt{\frac{I}{M}} \cdots\cdots (10)$$

The term $\{W(t)\}$ of the right-hand side in Eq. (9) can be expanded in the temporal and frequency regions, so that each term is given by the following equations:

$$\{W(t)\} \equiv \begin{Bmatrix} W_x(t) \\ W_y(t) \\ W_\theta(t) \end{Bmatrix} = \begin{bmatrix} \sum_k a(\omega_k, t)\left\{\sum_j K_y(\omega_k, y_j, \psi)\right\} \\ \sum_k a(\omega_k, t)\left\{\sum_i K_x(\omega_k, x_i, \psi)\right\} \\ \sum_k \frac{a(\omega_k, t)}{L}\begin{Bmatrix} \sum_i K_x(\omega_k, x_i, \psi)(x_i - x_f) - \\ \sum_j K_y(\omega_k, y_j, \psi)(y_j - y_f) \end{Bmatrix} \end{bmatrix} \cdots\cdots\cdots\cdots\cdots (11)$$

in which

$$a(\omega_k, t) = \sqrt{2S_0(\omega_k, t)\,\Delta\omega}\,\exp\{i(\omega_k, t + \theta_k)\} \cdots (12)$$

and

$$K_x(\omega_k, x_i, \psi) = \frac{m_i}{M} b_x(\omega_k, x_i, \psi)(2ih_i\omega_{ni} + \omega_{ni}^2)H_i(\omega_k)$$

$$K_y(\omega_k, y_j, \psi) = \frac{m_j}{M} b_y(\omega_k, y_j, \psi)(2ih_j\omega_{ni} + \omega_{ni}^2)H_j(\omega_k)$$

$$b_x(\omega_k, x_i, \psi) = \cos\psi\,\exp\left[-\frac{1}{2}\frac{\omega_k}{2\pi}\frac{\alpha|x_i - x_f|}{\frac{c_s}{\cos\psi}} - i\,\omega_k\frac{x_i - x_f}{\frac{c_s}{\cos\psi}}\right]$$

$$b_y(\omega_k, y_j, \psi) = -\sin\psi\,\exp\left[-\frac{1}{2}\frac{\omega_k}{2\pi}\frac{\alpha|y_j - y_f|}{\frac{c_s}{\sin\psi}} - i\,\omega_k\frac{y_j - y_f}{\frac{c_s}{\sin\psi}}\right] \cdots\cdots\cdots\cdots\cdots (13)$$

where c_s and ψ are the velocity and the incident angle of the propagating seismic wave, respectively.

3 Structural System Reliability

If a severe earthquake damages many dolphins, the system response could be unstable. Once the VLFS initiates the rotational motion, the residual dolphins might be damaged in succession, so that the progressive failure of the dolphins occurs.

Let us define the event of the system failure that the rotational response of the VLFS exceeds the critical value θ_{cr} given in the following form:

$$\text{event } E \equiv \langle \theta_{D(d1,\,d2,\ldots\ldots,\,dm)} \gtrsim \theta_{cr} \rangle \cdots\cdots\cdots\cdots (14)$$

where the response $\theta_{D(d1,\,d2,\ldots,\,dm)}$ of the VLFS is to be controlled by the global stiffness which is generated from any combination D(d1, d2, ..., dm) of damaged and undamaged dolphins. The failure of each dolphin can be defined in such a way that the maximum response at the top of the dophin w_D (the maximum displacement or acceleration) may exceed the critical value w_{cr}:

$$\text{event } E \equiv \langle w_D \geq w_{cr};\ w_D = \max(u_{Di} \text{ or } v_{Dj}) \rangle \cdots (15)$$

When the site S is surrounded in the seismic environment where the i-th fault can initiate the earthquake EQ_i of the maximum magnitude $M^i_{max}(T)$ during the service life T, the conditional probability of the VLFS can be formulated by

$$\begin{aligned} \mathrm{Re}[E\,|\,S, T] &= 1 - \sum_i P_{EQ}[E_i\,|\,S]P[EQ_i, T] \\ &= 1 - \sum_i \{1 - \exp(-\nu_{0i}T)\}\int P[E_i\,|\,a]f_A\{a\,|\,G(S), \\ &\quad M^i_{max}(T)\}da \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (16) \end{aligned}$$

where a, $G(S)$, $M^i_{max}(T)$, EQ_i and ν_{0i} are the acceleration at the baserock, the ground characteristics, the maximum magnitude, the i-th earthquake and its annual occurrence rate, respectively, while P[ ], f(|), Re [ ] are probability distribution, density and reliability functions, respectively.

4 Numerical Results

The numerical model is assumed to be as large as an international airport, so that the length, width and height are 5 000 m, 1 000 m and 10 m, respectively. The dolphins are located at 50 m intervals, so that 116 units of dolphins are arranged along the longer side, while 17 units are set along the shorter side. The standard type of dolphin is assumed to have the following parameters:

Term	Amount
Typical period, $2\pi/\omega_{1j}$	0.5 s
Damping factor, h_{1j}	5%
Traveling wave velocity, c_s	3 000 m/s
Incident angle, ψ	45°
Spring constant, k_j	10 000 tf/m
Mass of the dolphin, m_j	741 t
Damping coefficient, h_{2j}	10%
Floating damper, C	2%
Spatial parameter, α	1

The strong motion accelerogram measured at the hard ground are selected from the historical database of severe earthquales in Japan. The profiles of these data are shown in **Fig. 4** and the spectral contents are com-

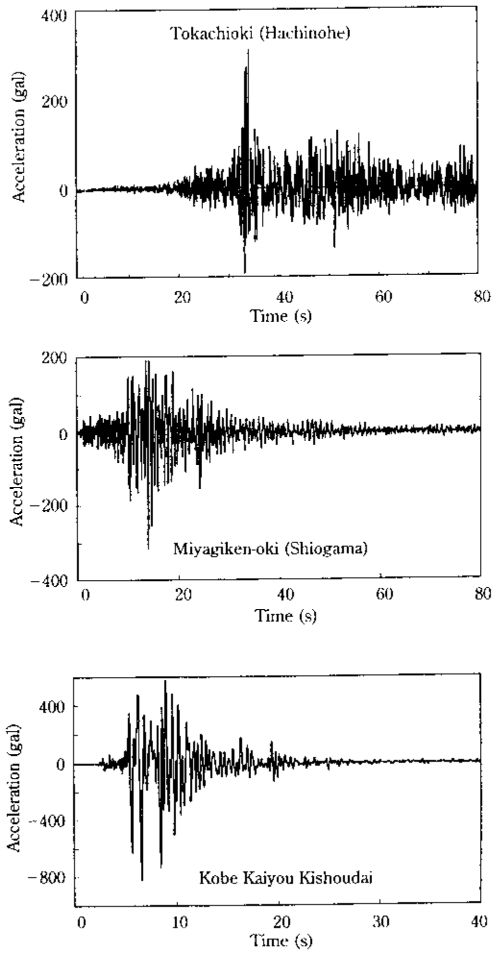

Fig. 4 Strong motion earthquake data[4)]

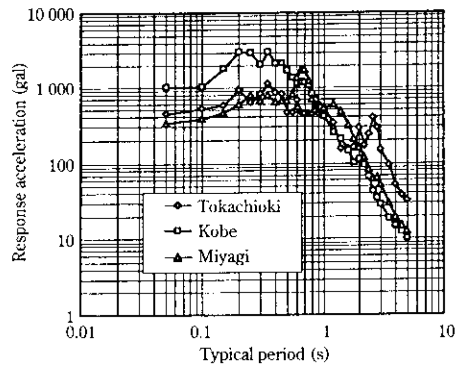

Fig. 5 Response spectra of the earthquakes[4)]

pared with each other in **Fig. 5**. The first two earthquakes were tectonic, while the last one was an active fault type. Since the VLFS has long typical periods, the seismic record having many spectral contents in the longer periods is the most preferable. So the record of Tokachi-oki (Hachinohe) is used as the standard data in this analysis.

Figure 6 shows the typical period of the floating

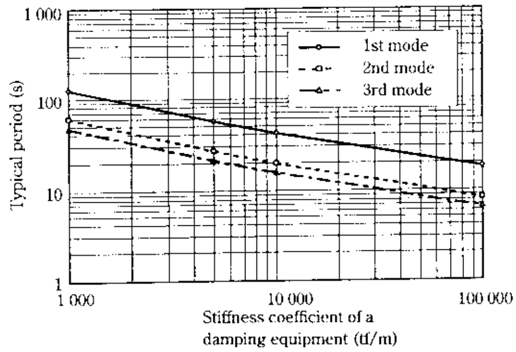

Fig. 6 Typical period of floating structure for several stiffness coefficients of the connecting device of dolphin[4)]

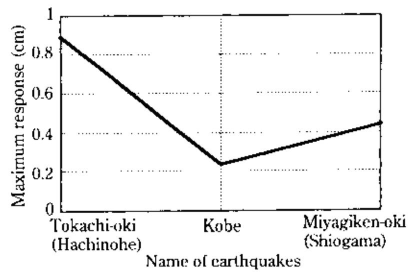

Fig. 7 Earthquake response of floating structure[4)]

structure and dolphin system for several stiffness coefficients (k_j) in the connecting device of the dolphin in Fig. 2. A longer typical period is obtained for the smaller stiffness coefficient in this model. This trend is the same for each mode. The typical period (1st mode) of the VLFS is 20 to 120 s for the stiffness coefficients of 1 000 to 100 000 tf/m. This suggests that the VLFS having a long typical period is insensitive in the earthquake response analyses, because the current strong motion accelerogram does not include such spectral contents of extremely long periods.

Figure 7 is the maximum response of the VLFS at the farthest dolphin from its gravity center for those three earthquakes. This figure shows that the response of VLFS expressed with the displacement (cm) is less than 1 cm for these earthquakes. The response by the record of Kobe Kaiyou Kishoudai is the smallest among them, while the response by the record of Tokachi-oki is the largest. These differences depend upon the spectral contents of the input earthquakes. The spectrum of the Tokachi-oki's record has the largest, especially in the longer period which is appropriate with the amplification of the response of the VLFS.

According to the Kobe record, the response of the VLFS to an earthquake of the active fault type does not always cause a large amplification of the response, although its maximum amplitude is the largest. This phenomenon is also due to the spectral content which

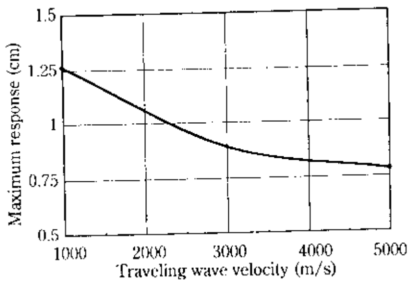

Fig. 8 Earthquake response for several traveling wave velocities[4]

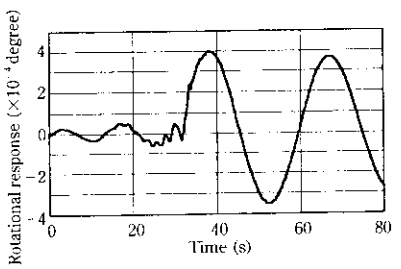

Fig. 9 The rotaional response under progressive failure process[4]

does not include comparatively longer periods.

The effect of traveling wave velocity is shown in **Fig. 8**, in which smaller velocity greatly amplifies the response of the VLFS, while the response for large velocity is decreased because of its small phase delay effect.

The numerical simulation for the progressive failure of the VLFS is carried out with the integrand P $[E_i \mid a]$ of Eq. (16) for the actual earthquake motion. The rigorous estimation, on the other hand, of structural safety using Eq. (16) is not applied because the major concern is placed on the point that a progressive failure of dolphins may or may not have been caused by the severe earthquake ground motion.

In the case study, when the response of a dolphin exceeds the critical level (equal to 60% of the maximum response of all the dolphins), the stiffness of the dolphin is assumed to be completely lost.

Figure 9 shows the rotational response of the VLFS under progressive failure process, in which the response abruptly increased after 32s, which corresponds to the time when the first failure of dolphins occured. The typical periods (1st, 2nd and 3rd modes in second) of the VLFS are also increased from (41.3, 19.7, 15.5) to (115.5, 41.3, 29.6), respectively, as shown in **Fig. 10**.

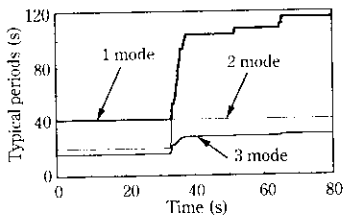

Fig. 10 Typical periods under progressive failure process

5 Conclusion

Seismic response analysis is conducted for a numerical model of a very large floating structure (VLFS).

Two types of earthquakes, one initiated from tectonic plate boundary in the Pacific Ocean and the other from a near-field fault rupture, are applied to assess the instability of the structural system.

Numerical results indicate that

(1) The methodology of the seismic response analysis for a very large floating structure can be formulated on an analytical basis, in which the floating structure itself is assumed as the rigid body.

(2) The typical floating structure has a long period of 40 to 120 s (1st mode) ; thus, the maximum responses of the structural system at the dolphin farthest from the gravity center for those three earthquakes were limited to less than 1 cm.

(3) A slow propagating seismic wave velocity increased the rotational response of the VLFS.

(4) The progressive failure of the dolphins can generate a large response of the VLFS, and the typical periods under the deteriorating process also increase to two or three times their original values.

6 Acknowledgment

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