SEISMIC ANALYSIS OF VERTICAL CYLINDRICAL TOWERS IN ICE-COVERED SEAS

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SUMMARY

An analytical approach is presented for the seismic response of vertical cylindrical towers totally or partially covered with ice sheet on the sea surface. The vertical cylindrical tower is idealized as an elastic circular cylindrical shell. The surrounding ice sheet is treated as an annular rigid boundary attached to the tower. The hydrodynamic pressure is obtained in closed form by a domain division method based on the linear potential flow theory. The seismic response is formulated by the Rayleigh-Ritz method and wet mode superposition approach. Based on the numerical results concerning wet mode free vibration and seismic response against horizontal ground motion, the change in response behavior due to the extent of ice sheet is discussed.

INTRODUCTION

A vertical cylindrical tower has been used as one of typical fixed offshore structures. When the structure is located in the first year ice area and in the seismically active region, the seismic response with and without covered ice is a critical design consideration to assure structural safety and serviceability [Croteau, 1983].

In the first year ice area, the sea surface is covered by ice sheet in winter, while it becomes free surface in summer. When subjected to earthquake ground motion, hydrodynamic pressure is generated on the exterior surface of structure. The hydrodynamic pressure may be divided into two components: one is the pressure component due to rigid body motion of structure, the other is the pressure component due to elastic deformation of structure. The first component is dominant if the structure is rigid, while the second component becomes significant if the structure is flexible. The distribution pattern of the hydrodynamic pressure may be, therefore, considerably different depending on structural flexibility. When the sea surface is totally or partially covered with ice, the hydrodynamic pressure generally increases because of the confined effect due to ice sheet against horizontal ground motion [Kiyokawa *et al.*, 1998]. The increase in hydrodynamic pressure may change wet mode frequencies and shapes and, consequently, the dynamic behavior during earthquakes in winter may be considerably different from that in summer.

Seismic analyses of vertical cylindrical towers submerged in water have been extensively carried out [Tanaka *et al.*, 1980]. However, there are very few studies on the seismic behavior of such structures in the ice field. This study is concerned with an analytical approach for the seismic response of vertical cylindrical towers that are totally or partially covered with ice sheet on the sea surface. In the mathematical formulation, the vertical cylindrical tower is idealized as an elastic circular cylindrical shell. Based on the linear potential flow theory, the hydrodynamic pressure is obtained in closed form against horizontal ground motion at sea bottom. Using the Rayleigh-Ritz method, the equation of motion of the structure in the ice field is derived, taking into account structural deformation. First of all, the wet mode free vibration analysis is carried out to investigate the change in wet mode frequencies and shapes due to the extent of surrounding ice. Then, the seismic response analysis is performed to predict the dynamic behavior of vertical cylindrical towers with and without ice sheet against horizontal ground motion. Based on the numerical results, the difference between the dynamic behavior during earthquakes in winter and that in summer is presented. Moreover, the change in dynamic behavior due to the extent of ice sheet is discussed.

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ANALYTICAL MODEL AND ASSUMPTIONS

The analytical model of a vertical cylindrical tower subjected to horizontal ground motion is shown in Fig.1. The tower is surrounded by an annular ice sheet of constant thickness at sea surface. In the figure, a, h, and l are the radius, thickness and height of the vertical cylindrical tower, b and c are the radius and thickness of the annular ice sheet, d is the water depth, U_g is the horizontal ground displacement and w is the elastic deformation of tower. A cylindrical coordinate system (r, θ, z) is used. The origin is located at the center of the vertical cylindrical tower on the sea bottom. The following assumptions are introduced in this study:

1. The stationary part of horizontal ground accelerations at sea bottom is ergodic and zero-mean Gaussian process.
2. The sea water is irrotational, inviscid and incompressible.
3. The water depth is constant and sea water extends to infinity.
4. The motion of vertical cylindrical tower is not constrained by ice sheet.
5. The ice sheet is treated as rigid boundary at sea surface.

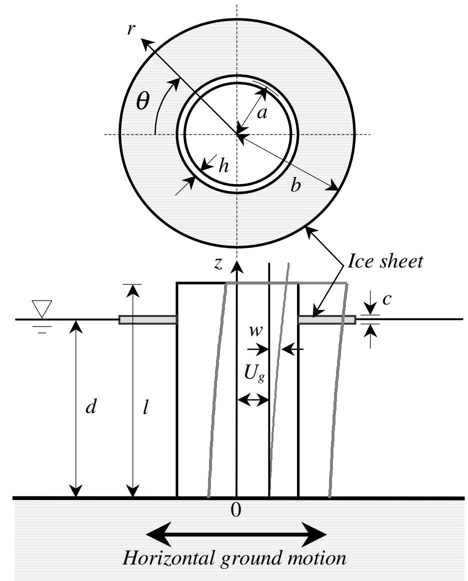


Fig.1 Geometric parameters of a cylindrical tower

WET MODE FREE VIBRATION IN ICE FIELD

Wet mode shape

The dynamic behavior of vertical cylindrical towers may be evaluated by wet mode superposition approach. Wet mode shapes may be expressed in terms of the superposition of orthogonal functions that satisfy geometrical boundary conditions. The displacement components in axial, circumferential and radial directions may be expressed as

$$u_{mn} = \sum_{j=1}^{N} U_{mnj} g_j(z) \cos n\theta \exp(i\omega_{mn} t)\ , \quad v_{mn} = \sum_{j=1}^{N} V_{mnj} f_j(z) \cos n\theta \exp(i\omega_{mn} t)\ , \tag{1a,b}$$

$$w_{mn} = \sum_{j=1}^{N} W_{mnj} f_j(z) \cos n\theta \exp(i\omega_{mn} t)\ , \tag{1c}$$

in which N is the number of superposition of orthogonal function, U_{mnj}, V_{mnj} and W_{mnj} are mode amplitude coefficients, $i = \sqrt{-1}$, ω_{mn} is the mn-th wet mode circular frequency, t is time, and $g_j(z)$ and $f_j(z)$ are orthogonal functions that are assumed by the j-th longitudinal and transverse vibration mode shapes of a cantilever beam, respectively, given by

$$g_j(z) = \sin \frac{(2j-1)\pi}{2l} z\ , \quad f_j(z) = \cosh \mu_j z - \cos \mu_j z - c_j (\sinh \mu_j z - \sin \mu_j z)\ , \tag{2a,b}$$

in which

$$c_j = (\sinh \mu_j l - \sin \mu_j l)/(\cosh \mu_j l + \cos \mu_j l)\ , \tag{3}$$

in which $\mu_j l$ is the j–th root which satisfies the following transcendental equation,

$$\cosh \mu_j l \cos \mu_j l + 1 = 0\ . \tag{4}$$

Hydrodynamic pressure

The hydrodynamic pressure acting on vertical cylindrical towers in free vibration may be obtained on the basis of linear potential flow theory. The fluid domain is divided into ice-covered and free surface regions as shown in Fig.2.

The governing equation in the ice-covered region is given by

$$\nabla^2 \phi^{(i)} = 0 , \qquad a \le r \le b ,\ 0 \le z \le \bar{d} , \tag{5a}$$

The boundary conditions are as follows:
Sea bottom condition,

$$\frac{\partial \phi^{(i)}}{\partial z} = 0 , \qquad a \le r \le b ,\ z = 0 , \tag{5b}$$

Ice surface condition,

$$\frac{\partial \phi^{(i)}}{\partial z} = 0 , \qquad a \le r \le b ,\ z = \bar{d} , \tag{5c}$$

Structure-water interface condition,

$$\frac{\partial \phi^{(i)}}{\partial r} = \dot{w} , \qquad r = a ,\ 0 \le z \le \bar{d} . \tag{5d}$$

The velocity potential, $\phi^{(i)}$, in the ice-covered region may be obtained in closed form with unknown coefficients as :

$$\phi^{(i)} = \sum_{n=0}^{\infty} \left[D_{n0} \left(\frac{b}{r} \right)^n + E_{n0} \left(\frac{r}{b} \right)^n + \sum_{s=1}^{\infty} \left\{ D_{ns} \frac{K_n(l_s r)}{K_n(l_s b)} + E_{ns} \frac{I_n(l_s r)}{I_n(l_s b)} \right\} \cos l_s z \right] \cos n\theta \exp(i\sigma t) , \tag{6}$$

in which $K_n(l_s r)$ and $I_n(l_s r)$ are the modified Bessel functions of order n of the first kind and second kind, D_{n0}, D_{ns}, E_{n0} and E_{ns} are unknown coefficients, and $l_s = s\pi / \bar{d}$.
On the other hand, the governing equation in the free surface region is given by

$$\nabla^2 \phi^{(f)} = 0 , \qquad 0 \le z \le d ,\ r \ge b , \tag{7a}$$

The boundary conditions are as follows:
Sea bottom condition,

$$\frac{\partial \phi^{(f)}}{\partial z} = 0 , \qquad r \ge b ,\ z = 0 , \tag{7b}$$

Free surface condition,

$$\frac{\partial \phi^{(f)}}{\partial z} + \frac{1}{g} \frac{\partial^2 \phi^{(f)}}{\partial t^2} = 0 , \qquad r \ge b ,\ z = d , \tag{7c}$$

Radiation condition,

$$\lim_{r \to \infty} \sqrt{r} \left(\frac{\partial \phi^{(f)}}{\partial r} + ik\phi^{(f)} \right) = 0 , \qquad r \to \infty . \tag{7d}$$

The velocity potential, $\phi^{(f)}$, in the free surface region may be obtained in closed form with unknown coefficients as

$$\phi^{(f)} = \sum_{n=0}^{\infty} \left\{ B_{n0} \frac{H_n^{(2)}(kr)}{H_n^{(2)}(kb)} \cosh kz + \sum_{l=1}^{\infty} C_{nl} \frac{K_n(k_l r)}{K_n(k_l b)} \cos k_l z \right\} \cos n\theta \exp(i\sigma t) , \tag{8}$$

in which $H_n^{(2)}(kr)$ is the Hankel function of order n of the second kind, B_{n0} and C_{nl} are unknown coefficients, and k and k_l are wave numbers that satisfy the following transcendental equation,

$$\sigma^2 = kg \tanh kd = -k_l g \tan k_l d . \tag{9}$$

The unknown coefficients may be determined by imposing the continuity conditions between iced-covered and free surface regions:

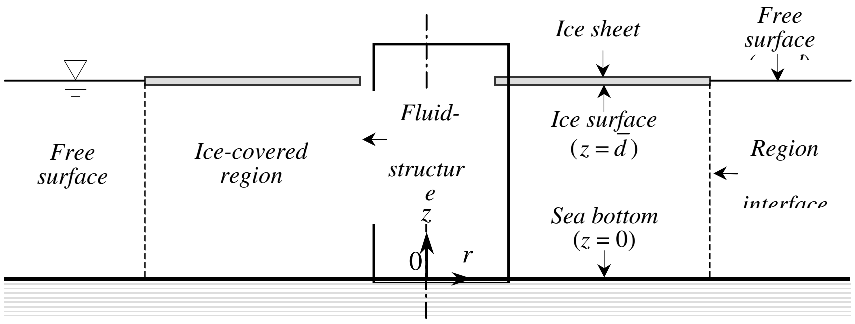


Fig.2 Fluid domain divided into two regions

Kinematic continuity conditions,

$$\frac{\partial \phi^{(i)}}{\partial r} = \frac{\partial \phi^{(f)}}{\partial r} \;, \qquad r = b \,,\; 0 \le z \le \bar{d} \,, \tag{10a}$$

$$\frac{\partial \phi^{(f)}}{\partial r} = 0 \;, \qquad r = b \,,\; \bar{d} \le z \le d \,, \tag{10b}$$

Pressure continuity condition,

$$\phi^{(i)} = \phi^{(f)} \;, \qquad r = b \,,\; 0 \le z \le \bar{d} \,. \tag{10c}$$

The hydrodynamic pressure acting on vertical cylindrical towers may be evaluated from the Bernoulli equation:

$$p = -\rho_w \frac{\partial \phi^{(i)}}{\partial t} \;, \qquad r = a \,, \tag{11}$$

in which ρ_w is the mass density of water.

Eigenvalue problem

Using $U_{mnj}(t) = U_{mnj} \exp(i\omega_{mn} t)$, $V_{mnj}(t) = V_{mnj} \exp(i\omega_{mn} t)$ and $W_{mnj}(t) = W_{mnj} \exp(i\omega_{mn} t)$ as generalized coordinates, the motion of freely vibrating vertical cylindrical towers coupled with water is governed by the Lagrange's equations:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{U}_{mnj}}\right) - \frac{\partial T}{\partial U_{mnj}} + \frac{\partial S}{\partial U_{mnj}} = 0 \,,\; \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{V}_{mnj}}\right) - \frac{\partial T}{\partial V_{mnj}} + \frac{\partial S}{\partial V_{mnj}} = 0 \,,\; \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{W}_{mnj}}\right) - \frac{\partial T}{\partial W_{mnj}} + \frac{\partial S}{\partial W_{mnj}} = Q_{mnj} \,, \tag{12a,b,c}$$

in which $\cdot = \partial / \partial t$, T and S are the kinetic and strain energy of circular cylindrical shells [Novozhilov, 1970], respectively, and Q_{mni} is the generalized force given by

$$Q_{mnj} = \int_0^l \int_0^{2\pi} p \cdot f_j(z) \cos n\theta a d\theta dz \,. \tag{13}$$

Solving eqs. (12a-c) yields the modal equations of motion in matrix form,

$$\{[K] - \Delta([M] + [M_W])\}\{\delta\} = 0 \,, \tag{14}$$

in which $[K]$, $[M]$ and $[M_W]$ are structural stiffness, structural mass and added mass matrices $(3N \times 3N)$, respectively, $\{\delta\} = \{U \mid V \mid W\}^T$, $\{U\}$, $\{V\}$ and $\{W\}$ are mode shape amplitude coefficient vectors $(3N \times 1)$, $\Delta = \rho_s \omega_{mn}^2 (1 - \nu^2) \cdot a^2 / E$, and ρ_s , ν and E are the mass density, Poisson's ratio and Young's modulus of structure. Wet mode frequencies and shapes may be obtained by solving the frequency equation,

$$|\,[K] - \Delta([M] + [M_W])| = 0 \,. \tag{15}$$

SEISMIC RESPONSE IN ICE FIELD

Wet mode superposition

Making use of a wet mode superposition approach, the displacement responses in axial, circumferential and radial directions may be expressed as

$$u = \sum_{m=1}^{\infty} u_{m1}(z) \cos\theta \, q_{m1}(t) \,,\; v = \sum_{m=1}^{\infty} v_{m1}(z) \sin\theta \, q_{m1}(t) \,,\; w = \sum_{m=1}^{\infty} w_{m1}(z) \cos\theta \, q_{m1}(t) \,, \tag{16a,b,c}$$

in which $q_{m1}(t)$ is the $m1$-th generalized coordinate. Other response quantities, such as accelerations and internal forces, may be obtained in the similar way. Only the first Fourier wave number is considered for horizontal ground motion under the assumption of rigid sea bottom.

Hydrodynamic pressure

The hydrodynamic pressure acting on vertical cylindrical towers subjected to earthquake ground motion may be obtained on the basis of linear potential flow theory. The fluid domain is divided into ice-covered and free surface regions.

The governing equation in the ice-covered region is given by

$$\nabla^2 \phi^{(i)} = 0 \ , \qquad a \le r \le b \ , \ 0 \le z \le \bar{d} \ , \qquad (17a)$$

The boundary conditions are as follows:
Sea bottom condition,

$$\frac{\partial \phi^{(i)}}{\partial z} = 0 \ , \qquad a \le r \le b \ , \ z = 0 \ , \qquad (17b)$$

Ice surface condition,

$$\frac{\partial \phi^{(i)}}{\partial z} = 0 \ , \qquad a \le r \le b \ , \ z = \bar{d} \ , \qquad (17c)$$

Structure-water interface condition,

$$\frac{\partial \phi^{(i)}}{\partial r} = \dot{U}_g + \dot{w} \ , \qquad r = a \ , \ 0 \le z \le \bar{d} \ . \qquad (17d)$$

The velocity potential, $\phi^{(i)}$, in the ice-covered region may be obtained in closed form with unknown coefficients. The unknown coefficients may be determined by imposing the continuity conditions between iced-covered and free surface regions. Using the Bernoulli equation, the hydrodynamic pressure may be evaluated as

$$P = P_R + \sum_{m=1}^{\infty} P_{Em1} \ , \qquad (18)$$

in which P_R and P_{Em1} are the hydrodynamic pressure components due to rigid body motion and elastic deformation of vertical cylindrical towers, respectively, given by

$$P_R = -m_0^*(z)\cos\theta \cdot \ddot{U}_g(t) - C_0^*(z)\cos\theta \cdot \dot{U}_g(t) \ , \qquad (19a)$$

$$P_{E_{m1}} = -m_{m1}^*(z)\cos\theta \cdot \ddot{q}_{m1}(t) - C_{m1}^*(z)\cos\theta \cdot \dot{q}_{m1}(t) \ , \qquad (19b)$$

in which $m_0^*(z)$, $C_0^*(z)$, $m_{m1}^*(z)$ and $C_{m1}^*(z)$ represent the axial distribution functions.

Modal equation of motion

The equivalent external forces in axial, circumferential and radial directions may be expressed as the combination of the inertia forces of vertical cylindrical tower and the hydrodynamic pressure components, respectively, given by

$$P_z = 0 \ , \ P_\theta = -\rho_s h \sin\theta \cdot \ddot{U}_g(t) \ , \ P_r = \rho_s h \cos\theta \cdot \ddot{U}_g(t) + P_R + \sum_{m=1}^{\infty} P_{Em1} \ , \qquad (20a,b,c)$$

The dynamic behavior of vertical cylindrical tower is governed by the Lagrange's equation:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_{m1}}\right) - \frac{\partial T}{\partial q_{m1}} + \frac{\partial S}{\partial q_{m1}} = Q_{Dm1} + Q_{Am1} \ , \qquad (21)$$

in which Q_{Dm1} is the $m1$-th generalized damping force and Q_{Am1} is the $m1$-th generalized force given by

$$Q_{Am1} = \int_0^l \int_0^{2\pi} \{P_z u_{m1}(z)\cos\theta + P_\theta v_{m1}(z)\sin\theta + P_r w_{m1}(z)\cos\theta\} a\, d\theta\, dz \ . \qquad (22)$$

Making use of the orthogonal properties of wet mode shapes of vertical cylindrical tower, the $m1$-th uncoupled modal equation of motion may be obtained as

$$(M_{m1} + M_{m1}^*)\ddot{q}_{m1}(t) + (C_{m1} + C_{m1}^*)\dot{q}_{m1}(t) + (K_{m1} + K_{m1}^*)q_{m1}(t) = Q_{m1}(t) \ , \qquad (23)$$

in which M_{m1}, C_{m1} and K_{m1} are the $m1$-th generalized mass, generalized damping and generalized stiffness, respectively, M_{m1}^*, C_{m1}^* and K_{m1}^* are the $m1$-th generalized added mass, generalized added damping and generalized added stiffness, respectively, and $Q_{m1}(t)$ is the $m1$-th generalized force given by

$$Q_{m1}(t) = \rho_s h \pi a \int_0^l \{-v_{m1}(z) + w_{m1}(z)\} dz \cdot \ddot{U}_g(t) + \int_0^d \int_0^{2\pi} P_R w_{m1}(z)\cos\theta\, a\, d\theta\, dz \ . \qquad (24)$$

Stochastic response

The horizontal ground acceleration at sea bottom is characterized by the modified Kanai-Tajimi power spectral density function given by

$$S_{\ddot{U}g\ddot{U}g}(\sigma)=S_0\left[\frac{1+4\xi_g^2(\sigma/\omega_g)^2}{\left\{1-(\sigma/\omega_g)^2\right\}^2+4\xi_g^2(\sigma/\omega_g)^2}\right]\left[\frac{(\sigma/\omega_k)^4}{\left\{1-(\sigma/\omega_k)^2\right\}^2+4\xi_k^2(\sigma/\omega_k)^2}\right],\ -\infty<\sigma<+\infty, \quad (25)$$

in which the first and second brackets represent the Kanai-Tajimi low pass filter [Tajimi, 1960] and the Clough-Penzien high pass filter [Clough and Penzien, 1975], respectively, S_0 is the spectral intensity, ξ_g and ω_g are parameters of the low pass filter, and ξ_k and ω_k are parameters of the high pass filter.

On the basis of a linear random vibration theory, the variances of displacement responses in axial, circumferential and radial directions can be obtained by

$$\bar{u}^2=\sum_{m=1}^{\infty}u_{m1}^2(z)\cos^2\theta q_{m1}^2(t),\ \bar{v}^2=\sum_{m=1}^{\infty}v_{m1}^2(z)\sin^2\theta q_{m1}^2(t),\ \bar{w}^2=\sum_{m=1}^{\infty}w_{m1}^2(z)\cos^2\theta q_{m1}^2(t), \quad (26a,b,c)$$

in which $\bar{q}_{m1}^2$ is the variance of the $m1$-th generalized coordinate given by

$$\bar{q}_{m1}^2=\int_{-\infty}^{+\infty}(M_{m1}+M_{m1}^*)^2\left(\alpha_{m1}^2+\frac{\beta_{m1}^2}{\sigma^2}\right)|H_{m1}(\sigma)|^2 S_{Q_{m1}Q_{m1}}(\sigma)d\sigma, \quad (27)$$

in which $S_{Q_{m1}Q_{m1}}(\sigma)$ is the power spectral density function of the generalized force, $Q_{m1}(t)$, and $|H_{m1}(\sigma)|^2$ is the $m1$-th transfer function given by

$$|H_{m1}(\sigma)|^2=\frac{1}{(M_{m1}+M_{m1}^*)^2\left\{(\omega_{m1}^2-\sigma^2)^2+4(\xi_{m1}+\xi_{m1}^*)^2\omega_{m1}^2\sigma^2\right\}}, \quad (28)$$

and α_{m1} and β_{m1} are coefficients given by

$$\alpha_{m1}=\left\{\rho_s h\pi a\int_0^l(-v_{m1}(z)+w_{m1}(z))dz+\pi a\int_0^d m_0^*(z)w_{m1}(z)dz\right\}/(M_{m1}+M_{m1}^*), \quad (29a)$$

$$\beta_{m1}=\pi a\int_0^d C_0^*(z)w_{m1}(z)dz/(M_{m1}+M_{m1}^*). \quad (29b)$$

NUMERICAL RESULTS AND DISCUSSTION

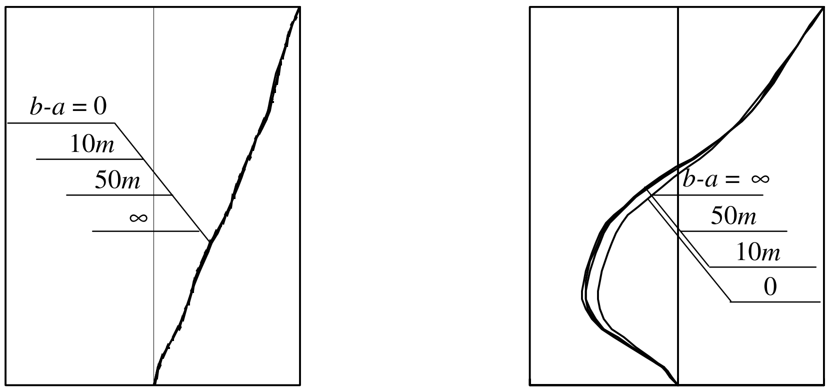
For numerical computations, dimensions and material constants are assumed as follows: radius of tower = 20*m*, thickness of tower = 0.2*m*, height of tower = 80*m*, Young's modulus of tower =2.0×10^{11} N/m^2, Poisson's ratio of tower = 0.3, mass density of tower =8.0×10^3 kg/m^3, material damping ratio in air = 0.02, mass density of sea water =1.02×10^3 kg/m^3. Four different widths of annular ice sheet attached to the tower are considered: *b-a* = 0, 10*m*, 50*m* and ∞. *b-a* = 0 and ∞ correspond to no ice sheet and full ice sheet, respectively. In eq. (25), the spectral intensity S_0= 4.3×10^{-3} m^2/sec^3rad, parameters of the low pass and high pass filters are ω_g =15.6 *rad/sec*, ξ_g =0.6, ω_k =1.0 *rad/sec* and ξ_k =0.6.

Figure 3 shows the variation in wet mode shapes due to the width of annular ice sheet for (*n,m*)=(1,1) and (1,2) modes. The water depth is 64*m*. Each wet mode shape is almost the same in spite of the width of annular ice sheet.

Figure 4 shows the variation in wet mode frequencies due to water depth for (1,1) and (1,2) modes. The water depth is normalized by the height of vertical cylindrical tower as d/ℓ. Wet mode frequencies decrease with the increase in water depth as well as the increases in the width of annular ice sheet. Higher wet mode frequencies decrease rapidly for shallow water.

Figure 5 shows the power spectral density function of horizontal ground acceleration and the location of wet mode frequencies when the widths of annular ice sheet are 0 and ∞. Lower wet mode frequencies are located in the central region of the power spectrum of horizontal ground acceleration.

Figure 6 shows the axial distributions of hydrodynamic pressure components due to rigid body motion and elastic deformation of vertical cylindrical tower at $\theta=0$. The hydrodynamic pressure components due to rigid body motion and elastic deformation vanishes at sea surface for no ice sheet. However, they becomes large with the increase in the width of annular ice sheet. The total hydrodynamic pressure is dominated by the hydrodynamic pressure component due to elastic deformation. With the increase in the width of annular ice sheet, the hydrodynamic pressure becomes large along the vertical cylindrical tower.



(1,1) mode (1,2) mode

Fig.3 Variation in wet mode shapes due to the extent of ice

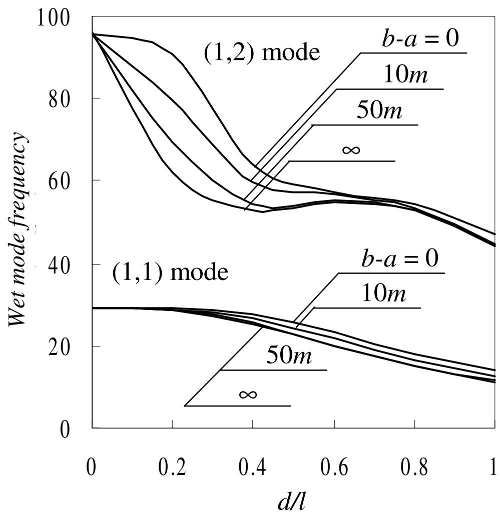


Fig4. Variation in wet mode frequencies due to water depth

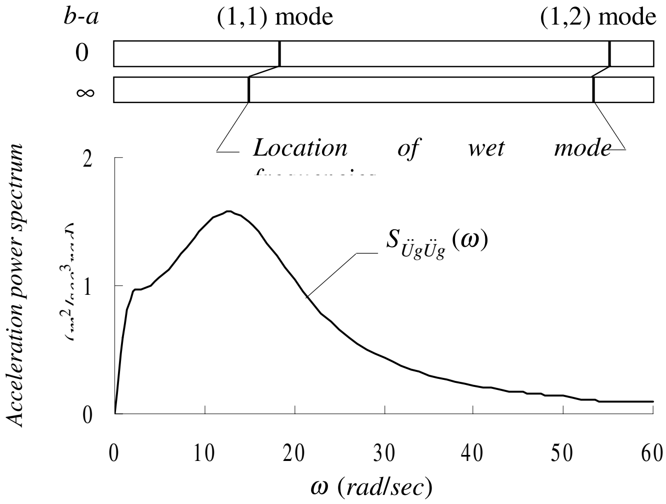
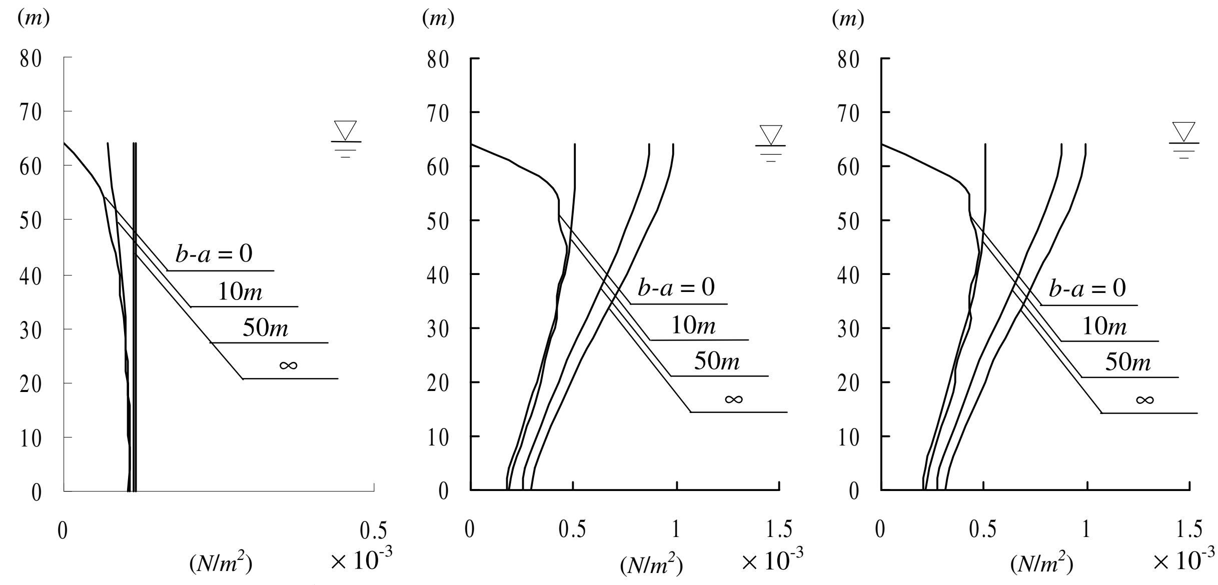


Fig.5 Power spectral density function of horizontal ground motion and wet mode frequencies for *b-a* = 0 and ∞



(a) Pressure component due to rigid body motion

(b) Pressure component due to elastic deformation

(c) Total hydrodynamic pressure

Fig.6 Hydrodynamic pressures due to rigid body motion and elastic deformation at $\theta = 0$

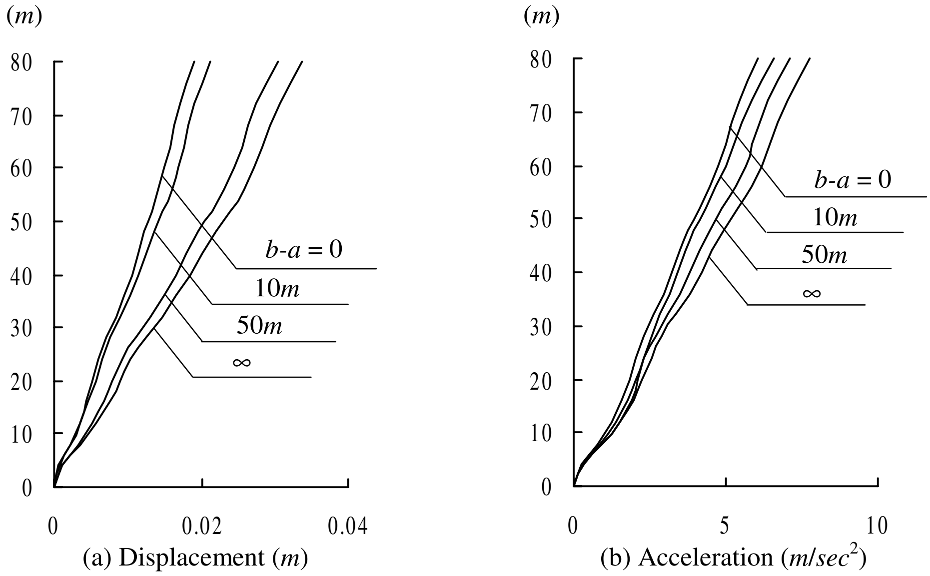


Fig.7 Radial displacement and acceleration responses due to the extent of ice sheet

Figure 7 shows the axial distributions of radial displacement and acceleration responses at $\theta = 0$. The water depth is 64*m*. The displacement response increases with the increase in the width of annular ice sheet. The acceleration response also increases with the increase in the width of annular ice sheet.

CONCLUSIONS

Based on the linear potential flow theory, the hydrodynamic pressure acting on vertical cylindrical towers subjected to horizontal ground motion is obtained in closed form. Using the Rayleigh-Ritz method, the seismic response of vertical cylindrical towers in the ice field is formulated, taking into account structural deformation. Based on the numerical results, the following conclusions can be obtained.

1. Wet mode shapes are almost the same in spite of the width of annular ice sheet. On the other hand, wet mode frequencies decrease with the increase in water depth as well as the increase in the width of annular ice sheet. Higher wet mode frequencies decrease rapidly for shallow water.
2. The hydrodynamic pressure components due to rigid body motion and elastic deformation become small in the vicinity of sea surface for no ice sheet. However, they become large with the increase in the width of annular ice sheet. The total hydrodynamic pressure is dominated by the hydrodynamic pressure component due to elastic deformation. With the increase in the width of annular ice sheet, the hydrodynamic pressure becomes large along the vertical cylindrical tower.
3. The displacement response becomes large with the increase in the width of annular ice sheet. The acceleration response becomes also large with the increase in the width of annular ice sheet.

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