Natural Frequencies of Oscillations of Oceans Frequencies of Tsunamis

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SUMMARY:
The vertical and horizontal circular frequencies of oscillations of oceans increase with bulk modulus of the solid-air-water mixture, and with the decrease in density of the ocean water, and depth of the ocean. The ratio of the vertical circular frequency and the horizontal circular frequency depends on the Poisson's ratio of the ocean water. Comparisons have been carried with the new expressions of natural frequencies and those available in the literature. New expressions of the dynamic water-amplification factors based on the dynamic water masses have been proposed for two cases: rock and soil surrounding conditions, and compared with dynamic soil-amplification factors which are based on the dynamic soil masses.

Keywords: Frequency, tsunami, amplification, ocean, depth.

1. INTRODUCTON

Resonant problems are the main engineering concerns for many structures under vibrations or in dynamically-loaded environments, especially for many buildings in earthquake-prone areas. In dealing with any structures on lands or in open seas for resonant conditions, the natural frequencies of oscillations of the structures, foundations, foundation mediums must be determined in the engineering analyses. The foundation mediums could generally be soil layers, rock layers or water layers. Recently, there are too much destructions and enormous damages in terms of properties and human lives due to the two biggest tsunamis, i.e. 2004 Sumatra and 2011 Tohoku tsunamis, so there is certainly a need to study the natural frequencies of oscillations of oceans.

Expressions of the dynamic stiffness, dynamic damping, dynamic soil mass, dynamic water masses and dynamic water heights, which have been recently developed by Truong [1991, 1995, 2009, 2010, 2011a, b, c, d, e], have been used to design shallow and deep foundations, to determine the tsunami heights and to reduce the effect of damages due to tsunamis by especially using air bubbles, to derive dynamic stress distributions in soils and natural frequencies of soil and rock layers. This paper presents the vertical and horizontal natural frequencies of oceans based on the vertical and horizontal dynamic water masses or the dynamic water heights, and proposes the dynamic water-amplification factors.

2. NATURAL CIRCULAR FREQUENCIES OF OSCILLATIONS OF OCEANS BY DYNAMIC WATER MASSES

For the solid-air-water (**SAW**) mixtures, the natural circular frequencies of the oceans in the vertical and horizontal directions could be expressed based on the vertical and horizontal dynamic water masses or dynamic water heights by Truong [2011c, d, and e], respectively, as follows:

$$\omega_z = \frac{\sqrt{B_{saw}}}{h_z s_{saw} \sqrt{\rho_{saw}}} = \frac{V_{saw}}{h_z s_{saw}} \tag{2.1}$$

$$\omega_x = \frac{\sqrt{B_{saw}}}{h_z \sqrt{\rho_{saw}}} = \frac{V_{saw}}{h_z} \tag{2.2}$$

Where ω = circular frequency, subscripts z and x are for vertical and horizontal directions, respectively; h_z = ocean depth, ρ_{saw} = mass density of the solid-air-water (**SAW**) mixture, which can be determined by

$$\rho_{saw} = \frac{\gamma_w}{g}\left(\frac{Se + G_s}{1+e}\right) \tag{2.3}$$

Where γ_w = Unit Weight of Water (or sea water), S = Degree of Saturation, G_s= Specific Gravity of solid particle which varies from 2.65 to 2.80 for seabed sands (Jian et al., 1991), g = Gravitational acceleration, e = void ratio, B_{saw} = Bulk Modulus of elasticity of solid-air-water (**SAW**) mixture, which can be determined by the Wood equation (Wood, 1930).

$$\frac{1}{B_{saw}} = \frac{e}{1+e}\frac{1}{B_{aw}} + \frac{1}{1+e}\frac{1}{B_s} \tag{2.4}$$

Where B_{aw} = Bulk Modulus of elasticity of air-water (**AW**) mixture (Richart et al., 1970), B_s = Bulk Modulus of elasticity of solid particles, and

$$s_{saw} = \frac{\sqrt{(1-2\mu_{saw})}}{\sqrt{2(1-\mu_{saw})}} \tag{2.5}$$

Where μ_{saw} = Poisson' ratio of solid-air-water (SAW) mixture. For the solid-air-water (SAW) mixture, the wave velocity, V_{saw}, is

$$V_{saw} = \frac{\sqrt{B_{saw}}}{\sqrt{\rho_{saw}}} \tag{2.6}$$

The ratio of the vertical circular frequency and the horizontal circular frequency is

$$R_{zx} = \frac{1}{s_{saw}} \tag{2.7}$$

The vertical and horizontal circular frequencies depend on the vertical and horizontal components of an earthquake, respectively. If there is no vertical component of earthquake, i.e. horizontal earthquakes, the vertical circular frequency of the earthquake is equal to zero.

3. VERTICAL AND HORIZONTAL NATURAL CIRCULAR FREQUENCIES OF OCEANS

The vertical and horizontal natural frequencies of oceans, respectively, are

$$f_z = \frac{V_{saw}}{2\pi h_z s_{saw}} \tag{3.1}$$

$$f_x = \frac{V_{saw}}{2\pi h_z} \tag{3.2}$$

The vertical and horizontal natural frequencies increase with the increase in the wave velocity of the solid-air-water (SAW) mixture and with the decrease in the water depth, as shown in Eqns. (3.1) and (3.2). The variation of the vertical and horizontal natural frequencies of the SAW mixtures with 1% solid particles with the range of the water depths from 5 m to 15000 m and the range of percentages of air bubbles from 1% to 20%, respectively, are shown in Table 3.1 and Fig. 3.1.The values in the first four columns after the first column of water depth are those of the vertical natural frequencies.

The vertical and horizontal natural frequencies of the Pacific, Indian and Atlantic Oceans, which have the same average depth of 4000 m, respectively, are 0.01529 Hz and 0.0015 Hz for cases of the SAW mixtures with 1% solid particles and 1% of air bubbles. If the average depth of Pacific Ocean is 4637 as shown in the paper by Chris (2006), the vertical and horizontal natural frequencies of the Pacific Ocean, respectively, are 0.0133 Hz and 0.0013 Hz. So, the ratio of the vertical natural frequency is about ten times the horizontal natural frequency.

The vertical and horizontal natural frequencies of the Southern Ocean (also known as the Great Southern Ocean, the Antarctic Ocean, and the South Polar Ocean), which has the average depth of 4500 m, respectively, are 0.007 Hz and 0.001 Hz for cases of the SAW mixtures with 1% of solid particles and 2% of air bubbles. The vertical and horizontal natural frequencies of the Arctic Ocean, which has the average depth of 1200 m, respectively, are 0.028 Hz and 0.0039 Hz for cases of the SAW mixtures with 1% of solid particles and 2% of air bubbles.

Table 3.1. Variation of Vertical and Horizontal Natural Frequencies of the SAW mixtures with 1% solids particles with Water Depths and Percentage of Air Bubbles

Depth, m	1 % Air V	2% V	5% V	20% V	1% Air H	2%	5%	20% H
5	12.2325	6.1872	2.552	0.7198	1.2172	0.866	0.5568	0.29387
10	6.11625	3.0936	1.276	0.3599	0.6086	0.433	0.2784	0.14693
15	4.0775	2.0624	0.851	0.2399	0.4057	0.289	0.1856	0.09796
50	1.22325	0.6187	0.255	0.072	0.1217	0.087	0.0557	0.02939
100	0.61163	0.3094	0.128	0.036	0.0609	0.043	0.0278	0.01469
200	0.30581	0.1547	0.064	0.018	0.0304	0.022	0.0139	0.00735
500	0.12233	0.0619	0.026	0.0072	0.0122	0.009	0.0056	0.00294
1000	0.06116	0.0309	0.013	0.0036	0.0061	0.004	0.0028	0.00147
2000	0.03058	0.0155	0.006	0.0018	0.003	0.002	0.0014	0.00073
3000	0.02039	0.0103	0.004	0.0012	0.002	0.001	0.0009	0.00049
4000	0.01529	0.0077	0.003	0.0009	0.0015	0.001	0.0007	0.00037
5000	0.01223	0.0062	0.003	0.0007	0.0012	9E-04	0.0006	0.00029
7000	0.00874	0.0044	0.002	0.0005	0.0009	6E-04	0.0004	0.00021
8000	0.00765	0.0039	0.002	0.0004	0.0008	5E-04	0.0003	0.00018
10000	0.00612	0.0031	0.001	0.0004	0.0006	4E-04	0.0003	0.00015
12000	0.0051	0.0026	0.001	0.0003	0.0005	4E-04	0.0002	0.00012
15000	0.00408	0.0021	9E-04	0.0002	0.0004	3E-04	0.0002	9.8E-05

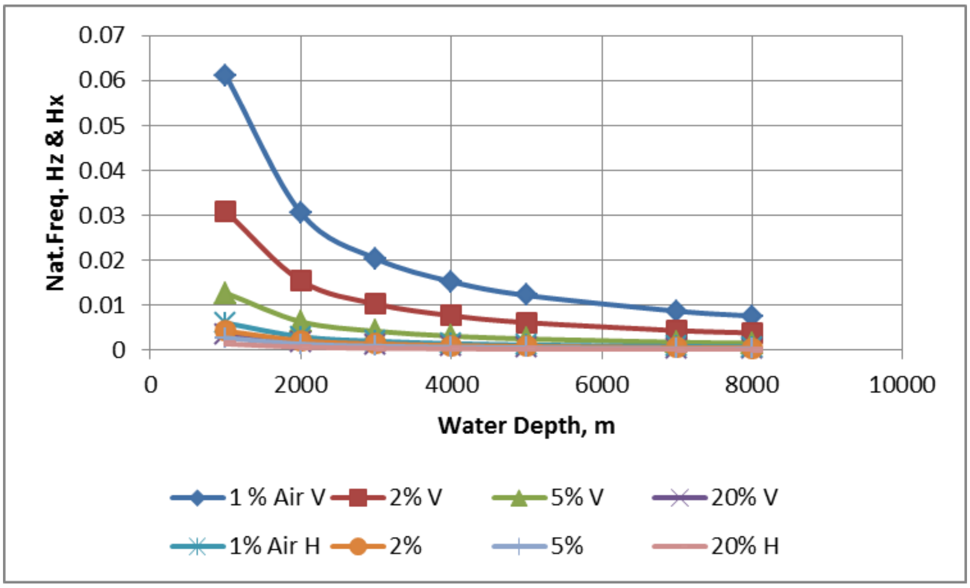

Figure 3.1. Variation of Vertical and Horizontal Natural Frequencies of the SAW mixtures with Water Depths and Percentages of Air Bubbles.

4. THE NATURAL FREQUENCIES PROPOSED BY OTHER RESEARCHERS

The acoustic signal, induced in the compressible water layer by the seafloor motion, vibrates at frequencies (Nosov, 1999).

$$f_n = \frac{C(2n+1)}{4h_z} \tag{4.1}$$

Where n= 0, 1, 2, 3 …, h_z = ocean depth, and C= sound speed (1500 m/s). When n = 0, Eqn. (4.1) is

$$f_o = \frac{C}{4h_z} \tag{4.2}$$

The linear fundamental natural frequency for a liquid water depth h_z in a rectangular tank of length L defined by Lamb (1932) as

$$f_\omega = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h_z}{L}\right)} \tag{4.3}$$

The natural frequency increases with the increase in water depth, as shown in Eqn. (4.3), as also found by Yu et al. (1999) based on the experimental results of horizontally shaking some small water tanks for their study of a non-linear model of the tuned liquid damper. The biggest tank used by Yu et al. (1999) has the lengths in three dimensions: length of 900 mm, width of 335 mm and the maximum water depth of 71 mm.

The tuned liquid damper is modelled numerically as an equivalent tuned mass damper with non-linear stiffness and damping, which are derived from extensive experimental results (Yu et al. 1999). The natural frequencies of a water tank have been considered as constants with the increase in the water depth, especially water depth in the range of from 1 to 50 m (Table 4.1 and Fig. 4.1). Note that the first three tank lengths in Table 4.1 are the tank lengths used by Yu et al. (1999).

Table 4.1. Variation of Natural Frequency of a Water Tank with Water Depth and Tank Length

Depth,m	L=0.335	L=0.59	L=0.9	L=2	L=5	L=100	L=1000
0.015	0.571	0.325	0.213	0.177	0.038	0.0019	0.00019
0.15	1.438	0.937	0.646	0.553	0.121	0.0061	0.00061
0.3	1.521	1.104	0.823	0.762	0.171	0.0086	0.00086
0.4	1.526	1.134	0.876	0.858	0.196	0.0099	0.00099
0.5	1.526	1.145	0.903	0.932	0.218	0.0111	0.00111
1	1.527	1.150	0.930	1.102	0.295	0.0157	0.00157
2	1.527	1.150	0.931	1.148	0.364	0.0221	0.00221
5	1.527	1.150	0.931	1.150	0.394	0.0349	0.00350
10	1.527	1.150	0.931	1.150	0.395	0.0487	0.00495
15	1.527	1.150	0.931	1.150	0.395	0.0586	0.00606
50	1.527	1.150	0.931	1.150	0.395	0.0846	0.01103

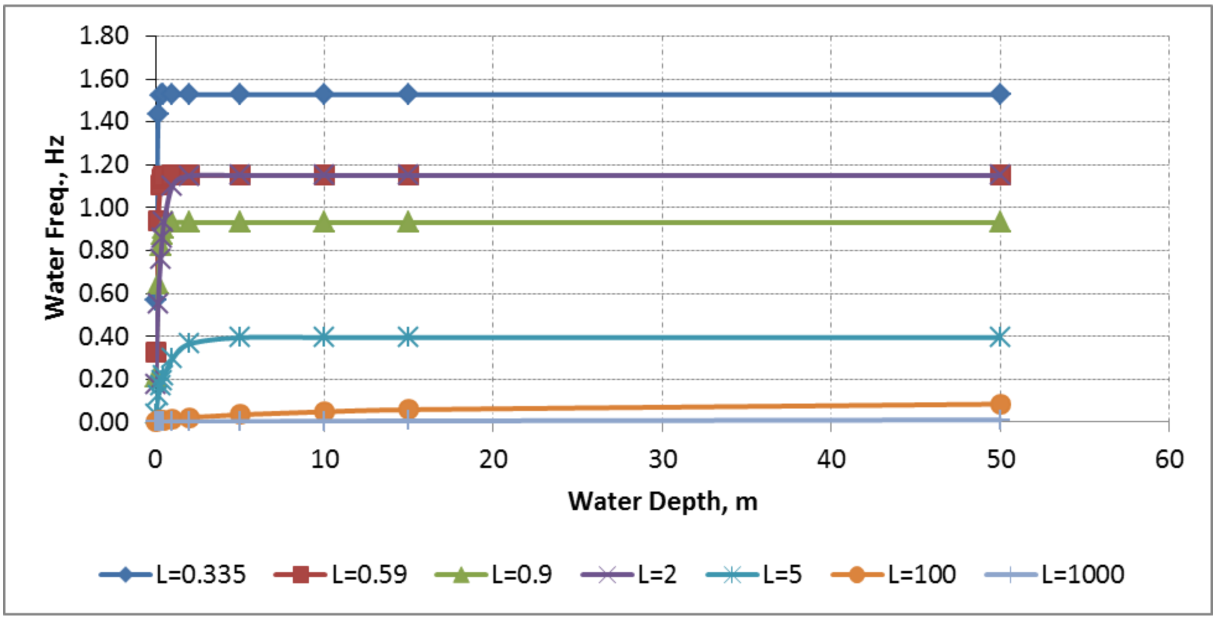

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Figure 4.1. Variation of Natural Frequency of Water Tank with Water Depth and Tank Length

A simulation study on a simple two-dimensional rectangular tank with rigid walls subjected to horizontal and vertical accelerations using an inviscid and incompressible fluid to examine the nonlinear behaviour of fluid motion. The study revealed that the fundamental frequency of the flow is strictly dependent on tank width and depth (Chen et al., 1999). With the exception of frequencies near to the natural frequency of the fluid in the tank, the potential theory of Frank (1967) predicts the exciting roll moments fairly good for all filling levels in the tank (Journée, 2000). The vertical and horizontal natural frequencies of the soil or rock layer (Truong, 2011f), respectively, are

$$f_{nz} = \frac{V_s}{2\pi sh} = \sqrt{\frac{G}{\rho}}\frac{1}{2\pi sh} \tag{4.4}$$

$$f_{nx} = \frac{V_s}{2\pi h} \tag{4.5}$$

Where V_s = Shear velocity of soil or rock, h= Thickness of the soil or rock layer, ρ = Mass Density of the medium (soil or rock); m_f = the mass of the footing; G = Shear Modulus of the medium (soil or rock); and

$$s = \sqrt{\frac{(1-2\mu)}{2(1-\mu)}} \tag{4.6}$$

Where μ = Poisson' ratio of soil or rock layer.

The ratio R_{fa} of the natural frequency Eqn. (4.4) and that of Saita et al. (2004) in the vertical direction is

$$R_{fb} = \frac{2}{\pi\, s} A_f \tag{4.7}$$

Where A_f is the amplification factor (Saita et al., 2004). If the amplification factor A_f is equal to 1.0, the Poisson's ratio is 0.17 for cases of rock medium, then the value of Eqn. (4.7) is also equal to 1 (Truong 2011f). The amplification factors due to the lithology unit for hard rock, soft rock, hard soil, medium soil, soft soil, and very soft soil are 1, 1.1, 1.7, 2, 2.2, and 2.8, respectively (Garcia-Rodriguez et al. 2008).

5. DYNAMIC WATER-AMPLIFICATION FACTORS FOR ROCK AND SOIL ENVIRONMENTS

5.1. Rock Environments

In general, the vertical and horizontal dynamic water-amplification factors for cases water surrounded by rock layers could be defined as the ratio of the dynamic rock mass (DRM) and the dynamic water mass (DWM) in vertical and horizontal directions, respectively, as

$$A_{Fz} = \frac{A_r\sqrt{\rho_r G_r}}{\omega_r s_r}\,\frac{\omega_{saw} s_{saw}}{A_w\sqrt{\rho_{saw} B_{saw}}} \tag{5.1}$$

$$A_{Fx} = \frac{A_r\sqrt{\rho_r G_r}}{\omega_r}\,\frac{\omega_{saw}}{A_w\sqrt{\rho_{saw} B_{saw}}} \tag{5.2}$$

Where A_r = rock area under vibration, A_w = Water area under vibration, and subscript r is for rock.

If the rock area is equal to water area, and the circular frequency of rock medium is also equal to the water area, then Eqns. (5.1) and (5.2), respectively, simply become

$$A_{Fz} = \frac{\sqrt{\rho_r G_r}}{\sqrt{\rho_{saw} B_{saw}}}\,\frac{s_{saw}}{s_r} \tag{5.3}$$

$$A_{Fx} = \frac{\sqrt{\rho_r G_r}}{\sqrt{\rho_{saw} B_{saw}}} \tag{5.4}$$

5.2. Soil Environments

Similarly, the vertical and horizontal dynamic water-amplification factors for cases water surrounded by soil layers could be defined as the ratio of the dynamic soil mass (DSM) and the dynamic water mass (DWM) in vertical and horizontal directions, respectively, as

$$A_{Fz} = \frac{A_s\sqrt{\rho_s G_s}}{\omega_s s_s}\frac{\omega_{saw}s_{saw}}{A_w\sqrt{\rho_{saw}B_{saw}}} \tag{5.5}$$

$$A_{Fx} = \frac{A_s\sqrt{\rho_s G_s}}{\omega_s}\frac{\omega_{saw}}{A_w\sqrt{\rho_{saw}B_{saw}}} \tag{5.6}$$

Where A_s = soil area under vibration, G = shear modulus, and subscript s is for soil.

If the soil area is equal to water area, and the circular frequency of soil medium is also equal to the water area, then Eqns. (5.5) and (5.6), respectively, simply become

$$A_{Fz} = \frac{\sqrt{\rho_s G_s}}{\sqrt{\rho_{saw}B_{saw}}}\frac{s_{saw}}{s_s} \tag{5.7}$$

$$A_{Fx} = \frac{\sqrt{\rho_s G_s}}{\sqrt{\rho_{saw}B_{saw}}} \tag{5.8}$$

6. DYNAMIC SOIL-AMPLIFICATION FACTORS

The vertical and horizontal dynamic soil-amplification factors have been defined as the ratio of the dynamic rock mass (**DRM**) and the dynamic soil mass (**DSM**) (Truong, 2011b), as follows:

$$A_{Fz} = \frac{A_r\sqrt{\rho_r G_r}}{\omega_r s_r}\frac{\omega_s s_s}{A_s\sqrt{\rho_s G_s}} \tag{6.1}$$

$$A_{Fx} = \frac{A_r\sqrt{\rho_r G_r}}{\omega_r}\frac{\omega_s}{A_s\sqrt{\rho_s G_s}} \tag{6.2}$$

Eqn. (6.1) has been rearranged by Truong (2011b) as

$$A_{Fz} = \frac{A_r\sqrt{\rho_r G_r}}{A_s\sqrt{\rho_s G_s}}\frac{\omega_s s_s}{\omega_r s_r} = R_A R_\rho R_G R_\omega R_\mu \tag{6.3}$$

Where R_A = Ratio of the area of the rock surface and the area of the soil surface.
R_ρ = Ratio of the square root of the rock density and the square root of the soil density.
R_G = Ratio of the square root of the shear modulus of rock and the square root of shear modulus of soil.
R_ω = Ratio of the circular frequency of the soils and the circular frequency of the rock, and

$$R_{\mu} = \frac{s_s}{s_r} \tag{6.4}$$

Boore and Joyner (1997) has suggested the amplification factor

$$A_F = \frac{\sqrt{\rho_r G_r}}{\sqrt{\rho_s G_s}} = R_{\rho} R_G \tag{6.5}$$

The ratios of Eqns. (6.1) and (6.2) and Eqns. (5.1) and (5.2), which are the ratios of the vertical and horizontal dynamic soil amplifications factors and those for water, respectively, are already presented as Eqns. (5.5) and (5.6).

7. FREQUENCIES OF TSUNAMIS

When a tsunami moves into shallower water, the height and the orbital velocity increase and the wavelength decreases, while the wave period remains invariant. In general, tsunami periods typically range from five minutes to two hours (UNESCO, 2006), so the frequencies of tsunamis vary from 0.0033 Hz to 0.00014 Hz in the open ocean. The period of the "Tsunami window" has been defined by Ward (2002) from 100-1000 seconds. Typical wavelengths of a wave with a period of 30 minutes range between 400 km in the deep sea and 20 km in shallow water (Bork et al. 2007).

The period of a tsunami depends on the characteristics of the tsunamigenic earthquakes, such as the corner frequency, the moment magnitude, the width and length of the earthquake faults, the sliding length, dip angle, earthquake velocity, properties of the rock layers and sedimentations, and duration. Actually, there are many periods or frequencies in a tsunami. The tsunami wavelengths depend on the area of the earthquake and the ocean sediments. The corner period has been used in other codes of practices for earthquake loading in their response spectrum provisions. In Eurocode 8-2001, the corner period is used as 2 seconds to "cap" the predicted displacement demand. It can be shown that the value of the corner period is very sensitive to crustal conditions and moment magnitude, with the corner period increasing with increasing value of the moment magnitude (Lam et al., 2004).

Especially, the impulse-type excursion of the water surface following an earthquake does not constitute a solution in analytical wave velocity. If it is interpreted as a linear superposition of simple waves, the individual waves propagate in all directions with their specific phase velocities. In deep oceans, part of the spectrum will be short waves. Short waves, the ratio of the ocean depth to the wavelength is greater than 0.25, have a period-dependent phase velocity $gT_{short}/2\pi$. Short partial waves with small periods thus lag behind waves with greater periods. This process is called frequency dispersion. It weakens the primary signal of a tsunami. According to this theory, the dominant long-wave signal, that is the ratio of the ocean depth and wavelength is smaller than 0.05, propagates in a dispersion-free way, i.e. with a velocity of the square root of the product of the gravitational acceleration and the ocean depth, that is only depth dependent (Bork at al., 2007).

Tsunami modelling has always been traditionally undertaken using the shallow water wave equations which are non-frequency dispersive long wave equations. However, recently observed data from the Indian Ocean Tsunami of Dec 26, 2004 using satellite altimetry data that were subject to wavelet analysis by Kulikov (2005) found that the tsunami waves were highly dispersive (Rivera, 2006).

The expressions of the vertical and horizontal dynamic water masses of the SAW mixtures based on the wave propagation in ocean water, which are related to the vertical and horizontal components of earthquakes, respectively; both increase with the decrease in the appropriate vertical and horizontal frequencies of tsunamis (Truong, 2011b, c, d, e), respectively, as

$$m_z = \frac{A\sqrt{\rho_{saw}B_{saw}}}{2\pi\, f_z s_{saw}} \tag{7.1}$$

$$m_x = \frac{A\sqrt{\rho_{saw}B_{saw}}}{2\pi\, f_x} \tag{7.2}$$

Where A = fault area of earthquakes and f = frequency of earthquake.

If there is no vertical component of earthquake, the value of the vertical dynamic water mass (Eqn. (7.1)) is equal to zero.

The investigations (Houston, 1999; Bilek and Lay, 1999) suggested that some earthquakes rupture slowly because of the presence of shallow, unconsolidated sediments. The process of gravity wave excitation by a slow rupture on a shallow fault may be relevant, as slow rupture can generate low-frequency gravity waves which take the form of tsunami waves at the ocean surface (Novikova et al. 2000).

8. RESULTS AND DISCUSSIONS

The vertical and horizontal natural frequencies of oceans based on the vertical and horizontal dynamic water masses or dynamic water heights increase with the increase in wave velocity of the SAW mixture and with decrease in the depth of the oceans. The natural frequencies proposed by Lamb (1932), which are applicable for water tanks and have been found to be constants for very deep water depths, could not be used to determine the natural frequencies for big oceans.

The vertical and horizontal natural frequencies of oceans greatly decrease with the increase of 1% of air bubbles for the low range of air bubbles from 0% to 2%. The vertical and horizontal natural frequencies of the Pacific, Indian and Atlantic Oceans, which have the same average depth of 4000 m, respectively, are 0.01529 Hz and 0.0015 Hz for cases of the SAW mixtures with 1% solid particles and 1% of air bubbles.

The dynamic water-amplification factors depend on the ratio of the square root of the products of the appropriate mass density and bulk modulus of the ocean water and those for soil or rock environments. Note that the vertical and horizontal water attenuations of the wave propagation with distance have not been taken into account in the determining the above dynamic water-amplification factors. Further research work and/or experimental studies are necessarily required to find out (i) the actual vertical and horizontal periods of tsunamis in the open seas, (ii) the relationship between the earthquake frequencies and the frequencies of tsunamis, and (iii) the relationship between lengths of earthquake faults and the wavelength of tsunamis.

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