Wave-Propagation Velocity, Tsunami Speed, Amplitudes, Dynamic Water-Attenuation Factors

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SUMMARY:
Wave-propagation velocity increases with the increase in bulk modulus, and the decrease in mass density of sea water, while tsunami speed increases with the increase in the ocean depth. Comparisons between wave-propagation velocity and tsunami speed have been carried out in details. The vertical and horizontal dynamic water-attenuation factors increase with the increase in the frequencies of the wave, the square root of water density and with the decrease in the square root of the bulk modulus of sea water. Initially, dynamic water heights are calculated with different values of air percentages, soils and frequencies, and finally, the tsunami amplitudes at the coast lines are also estimated. Shoaling amplification factor depends on many factors, such as the refraction rays, bulk modulus, density of water, and water depths.

Keywords: Velocities, tsunami, amplitudes, Dynamic water height, Dynamic water-attenuation factors.

1. GENERAL INSTRUCTIONS

Tsunamis are long gravity waves that are generated in the ocean by abrupt geophysical events such as undersea earthquakes, submarine landslides, or volcanic eruptions. Among them, those caused by undersea earthquakes are most frequent. Sometimes these processes work in conjunction with each other to enhance the amplitudes of the tsunamis. The largest seismic sea wake known from geologic history is the one created by the impact of the K-T meteor 65 million years ago. The 10-mile-wide asteroid hit Earth at 72,000 kms (45,000 miles) per hour and created a wave estimated to be 914 meters (3,000 feet) high that travelled throughout Earth's oceans. Tsunamis are called long waves or shallow water waves because their wave-lengths which are the distances between successive wave crests are much longer than the water depth. So, the phase speed at which tsunami wave moves is given by the long wave formula. The tsunami speed, which is dependent on the water depth, does not depend on the properties of the ocean water, while the wave-propagation velocity largely depends on the properties of water, such as the bulk modulus and density. Earthquake waves travel significantly faster than tsunami waves, and frequently trip the tsunameter into "Event Mode" before tsunami arrives. The vertical shifting of the seafloor from the earthquake acts to lift or compress the water column above, showing an in pressure as the seafloor rises, or decrease in pressure as the seafloor falls (Meinig et al. 2005).

For many years, there was no mathematical expression to estimate the tsunami amplitude based on the earthquake data, until recently, Truong (2011a, b, and c) has developed the expressions of the dynamic water masses and dynamic water heights in the vertical and horizontal directions based on the expression of the dynamic soil mass (Truong, 1993, 2009, 2010, 2011d, e). Even thought, some attempts have been made to find the relationship between the moment magnitude and the tsunami height, but it is applicable only to local conditions because it is totally dependent on the properties of the oceanic sediments and sea water (Abe, 1979).

For the 2004 Indian Ocean earthquake, the maximum height of 50 cm of the first two wave fronts produced by the main quake spaced 500 km to 800 km apart, was recorded by the US-French

satellites, called TOPEX/Poseidon and Jason-1, two hours after the massive earthquake struck just off the coast of Indonesia. The average depth of the Indian Ocean is 3890m. Legeais et al. (2010) found that the amplitudes, which were recorded on Jason-1, TOPEX, Envisat and Geosat altimeters, are 60cm, 35cm, 20 cm and 15 cm for the time of 2 hours, 3.15 hours, 7 hours and 9 hours after the earthquake, respectively. So, the initial amplitude of the tsunami of the 2004 Indian Ocean earthquake must be greater than 60 cm. Not that the accuracy of the Topex/Poseidon altimeter satellite is nearly 1 cm.

For the 2011 Tohoku earthquake, the maximum tsunami height of 85 cm was recorded by observing the HF radars on both Asian and American continents (Lipa et al., 2011). The typical period of tsunami waves is more than 1000 seconds and the amplitude in deep sea is never above 100 cm hence, the vertical accelerations is of the order of 0.00001g (Sahviv, 2005). The tsunami amplitude is normally defined as the water level at the time of tsunami occurrence measured relative to the reference water level which is the mean sea level. This paper presents (i) various velocities and speeds caused by earthquakes, in deep and shallow depths, and in the air, (ii) dynamic water heights and tsunami amplitudes, and (iii) shoaling amplification factors and dynamic attenuation factors in sea water.

2. WAVE PROPAGATION VELOCITIES

The expressions for dilatational and distortional wave velocities in solid-air-water (**SAW**) mixture (Richart et al., 1970; Truong, 2011a, b, c) can be defined, respectively, as

$$V_{Psaw} = \frac{1}{s_{saw}} \sqrt{\frac{B_{saw}}{\rho_{saw}}} \qquad (2.1)$$

$$V_{Ssaw} = \sqrt{\frac{B_{saw}}{\rho_{saw}}} \qquad (2.2)$$

Where ρ_{saw} = Mass Density of the solid-air-water (**SAW**) mixture (Richart et al., 1970 and Truong, 2011a, b, c), which can determined by

$$\rho_{saw} = \frac{\gamma_{saw}}{g} \left(\frac{S_{saw}e + G_s}{1+e} \right) \qquad (2.3)$$

where γ_{saw} = Unit Weight of solid-air-water, S = Degree of Saturation, G_s= Specific Gravity of solid particles (soil particles) which varies from 2.65 to 2.80 for seabed sands (Jian et al., 1991), g = Gravitational acceleration varies from 978.0 cm/sec^2 at the equator to 983.2 cm/sec^2 at the poles, e = void ratio, B_{saw} = Bulk Modulus of elasticity of solid-air-water (**SAW**) mixture (Wood, 1930), and

$$s_{saw} = \frac{\sqrt{(1-2\mu_{saw})}}{\sqrt{2(1-\mu_{saw})}} \qquad (2.4)$$

Where μ_{saw} = Poisson' ratio of solid-air-water mixture.

The solid-air-water (**SAW**) mixtures having no solid particles become the air-water (**AW**) mixtures, and become the pure water mixtures if the **SAW** mixtures do not have solid particles and air bubbles (Truong, 2011a, b, c). Poisson's ratio of the air-water (**AW**) mixtures also depends on the percentage of air bubbles and has been proposed by Truong (2011a) as

$$\mu_{aw} = 0.5 \left(1 - \frac{V_a}{V_{aw}} \right) \qquad (2.5)$$

Where V_a = Volume of air bubbles, and V_{aw} = total volume of air-water mixture.

If there are no air bubbles in air-water (**AW**) mixture, then Poisson's ratio becomes 0.5 for air-free water or the incompressible fluid. Air bubbles in water increase the compressibility several orders of magnitudes above that in bubble-free water, thereby greatly reducing the velocity and increasing attenuation of acoustic waves (Dominenco, 1982). In the surf zone, the percent of air bubbles in ocean water is normally in the range of 0 to 10% in average and dependent on the location and time, but its instantaneous maximum is 30-50% (Mori et al. 2007, 2008; and Mori, 2010). The wave velocity in air which is normally varies with the pressure and temperature, is 1127 ft/sec (343.5 m/s) at standard conditions. The standard conditions are (i) the standard temperature of 20^0 C, and (ii) standard pressure of 760mm Hg.

3. DYNAMIC WATER HEIGHTS

The vertical and horizontal dynamic water heights of H_z and H_x of the tsunami wave for the solid-air-water (**SAW**) mixture have been presented (Truong, 2010 b, c), respectively, as follows:

$$H_z = \frac{\sqrt{B_{saw}}}{\omega_z s_{saw} \sqrt{\rho_{saw}}} = \frac{V_{Psaw}}{\omega_z} \qquad (3.1)$$

$$H_x = \frac{\sqrt{B_{saw}}}{\omega_x \sqrt{\rho_{saw}}} = \frac{V_{Ssaw}}{\omega_x} \qquad (3.2)$$

Where ω_x = Circular frequency of the earthquake in horizontal direction, and ω_z = Circular frequency of the earthquake in vertical direction.

4. TSUNAMI SPEEDS AND HORIZONTAL ORBITAL VELOCITIES

Based on the gravity wave theory, in its simplest form, an incompressible oceanic layer has been normally considered (Okal, 1988). The phase velocity or tsunami speed (or celerity) of the shallow-water gravity wave is independent of the wave period and its dispersion relation is given in terms of the acceleration of gravity g by:

$$V_{ph} = \sqrt{g(D + A)} \qquad (4.1)$$

Where   D = water depth, and A = wave amplitude.

For a water depth of 4 km and a gravitational acceleration field of 9.8 m/s2, the wave celerity is about 200 m/s (720 km/h). This phase velocity is the velocity of energy propagation, not the velocity of the water itself. The particles of water move and interact in such a manner as to transfer the energy radially outward along the travel path of the tsunami. Both the theory and observations indicate that this particle is much lower, being about 2 cm/s (72 km/h). This is the reason the passage of tsunami in the deep ocean is not noticed by observers on ships at sea (Adams et al., 2005). For the 2004 Sumatra tsunami, the arrival time in Sri Lanka and India indicates that a large westward velocity should be in the order of 1000 km/h (Annunziato et al., 2005). The horizontal water particle (orbital) velocity at the shallow water depth, which has been observed by radar systems, has been defined by Lipa et al. (2011) as:

$$V_o = h_d \frac{g^{1/2} D_d^{1/4}}{D_s^{3/4}}$$

(4.2)

Where h = tsunami height at deep water level, D_d = deep water depth, and D_s = shallow water depth

For deep water, the orbits are circles with radii equal water heath. For shallow water the orbits becomes flattened ellipse that collapse into horizontal back/forth trajectories in the very-shallow limits. The vertical and horizontal orbital velocities for deep oceans (depth of 4000 m), continental edge (depth of 200 m) and coast (depth of 10 m) are 0.002, 0.02, and 0.05 m/s; and 0.02, 0.2 and 0.5 m/s, respectively. The ratio of the horizontal orbital velocities and the vertical orbital velocity is 10. The ratio of the phase speed and orbital velocity at shallow water depth is

$$R_{po} = h_d \frac{D_d^{1/4}}{D_s^{1/4}}$$

(4.3)

The phase speed at shallow water depth can be determined from the orbital velocity as

$$V_{ph} = h_d \frac{D_d^{1/4}}{D_s^{1/4}} V_o$$

(4.4)

Kowalik et al. (2010) have studied the tsunami-tide interactions and proposed the phase speed at high tide as follows:

$$V_{pht} = \sqrt{g(D + A + h_t)}$$

(4.5)

Where h_t = the sea level change relative to mean sea level at high tide. It is normally that if the tsunami waves arrive at high tide, or if there are concurrent storm waves in the area, the effects will be cumulative and the inundation and destruction even greater.

The phase velocity also depends on the bulk modulus and mass density of the solid-air-water (**SAW**) mixtures, so the phase velocity at the same depth and amplitude of sea wave should be

$$V_{ph1} = \sqrt{g(D + A + h_t)} \left(\frac{\rho_0 B_1}{\rho_1 B_0} \right)^{1/4}$$

(4.6)

Where subscripts 0 and 1 are for the initial and last conditions, respectively. The incompressible ocean layer, which has no air bubbles, is used for the initial condition (Okal, 1988).

Groups of waves with similar wavelengths and periods will travel together across the ocean as wave trains. Wave trains move at a speed called the group speed, V_g that is one-half the speed of the individual waves in the wave train for the deep water waves. The group speed is the speed at which the energy in the train is propagating.

Tsunami waves normally oscillate very slowly and are considered as the shallow water waves. For the shallow waves and transitional waves, the group velocity is normally equal to the phase velocity. Their period, i.e. the time interval between consecutive crests, varies between several minutes to around two hours, depending on the water depth, the type, size and spatial orientation of the initiation process in the area of origin. When waves enter shallow water, the wave speed and wavelength of the tsunami decrease and the wave height increases, and the wave period does not change. As a result, the front of the leading wave becomes significantly steeper because of the pile-up effect of the succeeding waves, an important factor that controls the ensuing wave run-up at the coast. It is normally the velocity of shallow-water wave is independent of wave length (Eqn. (4.1)). In water depths between 1/2 wave length and 1/25 wave length, which are the transitional depths between deep water and shallow water waves, it is necessary to use a more precise expression (UNESCO, 2006).

$$V_{ph} = \sqrt{\left(\left(\frac{g\lambda}{2\pi}\right)\left[\tanh\left(\frac{2\pi D}{\lambda}\right)\right]\right)} \tag{4.7}$$

For tsunamis generated by earthquakes, the typical wave length ranges from 20 to 300 km. For tsunamis generated by landslides, the wave length is much shorter, ranging from hundreds of meters to tens of kilometers.

5. TSUNAMI AMPLITUDES AND SHOALING AMPLIFICATION FACTOR

About 50% of the tsunami energy is reflected from the edge back into ocean. However, as the tsunami enters the shoaling water, the wavelength shortens and the amplitude increases, the period remains constant, except at barrier reefs where amplitude may decrease and wave frequencies may double (Adams, et. al, 2005). The change of wave amplitude with shoaling water depth and with the effect of wave refraction (Adams et al., 2005) is given by

$$A_s = \left[\frac{D_d}{D_s}\right]^{1/4} \left(\frac{B_d}{B_s}\right)^{1/2} A_d \tag{5.1}$$

where A is the amplitude of the tsunami wave measured from mean still-water level to a peak or trough, B is the refracted wave ray spacing, subscripts s and d refer to shallow (coastal) and deep water, respectively.

The increase in height of a wave as it approaches almost to a coast is expressed by Green's law, which is valid for slow varying water depth.

$$H_s = \left[\frac{D_d}{D_s}\right]^{1/4} H_d \tag{5.2}$$

Green's law is applicable in the ocean where depths are constant over distances comparable to the wavelengths of tsunamis. The increase in the height of a wave as it moves towards shallower waters can also be explained by the principle of the conservation of energy. The tsunami should slow down as it approaches shallower waters. The resulting loss in kinetic energy due to the decrease in speed is compensated by an increase in amplitude. Approximation of the tsunami as a shallow-water wave is permissible only as long as the water depth is at least 10 times the amplitude of the tsunami. For shallower depths, one must restore the disproportionate terms to the theoretical equation and begin to consider the run-up of the tsunami onto the land (Adams et al., 2005). The change of wave amplitude with shoaling water depth due to the horizontal components of earthquakes, properties of the solid-air-water (SAW) mixture; and based on the horizontal dynamic water mass (Truong, 2011a, b, c), the law of conservation of linear momentum, and the theory of wave gravity; is given by

$$A_s(D_s + A_s) = \left[\frac{B_{ssaw}\rho_{dsaw}}{B_{dsaw}\rho_{ssaw}}\right]^{1/2} \left[A_d(D_d + A_d)\right]\frac{\omega_d}{\omega_s} \tag{5.3}$$

If the amplitude, A_d, is very small compared to the ocean depth, D_d; e.g. 0.5 m to 4000m, Eqn. (5.3) becomes

$$A_s(D_s + A_s) = \left[\frac{B_{ssaw}\rho_{dsaw}}{B_{dsaw}\rho_{ssaw}}\right]^{1/2} \left[A_d(D_d)\right]\frac{\omega_d}{\omega_s} \tag{5.4}$$

Similary, the dynamic water height due to the vertical components of earthquakes

$$A_s\left(D_s+A_s\right)=\left[\frac{B_{ssaw}\rho_{dsaw}}{B_{dsaw}\rho_{ssaw}}\right]^{1/2}\left[A_d\left(D_d+A_d\right)\right]\frac{\omega_d}{\omega_s}\frac{s_d}{s_s} \tag{5.5}$$

Or

$$A_s\left(D_s+A_s\right)=\left[\frac{V_{ssaw}}{V_{dsaw}}\right]\left[A_d\left(D_d+A_d\right)\right]\frac{\omega_d}{\omega_s}\frac{s_d}{s_s} \tag{5.6}$$

Ward et al. (2008) mentioned that the thorniest issue in tsunami calculation is not deep water propagation, but rather be "first mile" where the waves generate and the "last mile" where the waves run into shallow water and then onto land. The dynamic shoaling amplification factor can be defined as:

$$F_A=\frac{A_s}{A_d} \tag{5.7}$$

The most simplified shoaling amplification factor has been presented by Ward (2001) and Geist (2002) as

$$F_A=\left[\frac{D_d}{D_s}\right]^{1/4} \tag{5.8}$$

For the average depth of Pacific Ocean of 4000m, vertical and horizontal frequencies of 1 Hz, and the initial amplitude of 0.5m; the variations of the amplitudes and tsunami speeds at the shallow depth of 10m, amplification factors, and the vertical and horizontal dynamic water heights of the solid-air-water (SAW) mixtures with the percentage of air bubbles are presented in Table 5.1 and Figures 5.1 and 5.2. The last column of Table 5.1 is for cases with the initial amplitude of 0.6m and the percentage of 0.05% of air bubbles. Note that (i) the tsunami speed of 35.6 km/h based on the theory of wave of the incompressible fluid, which is constant with the variation of the percentages of air bubbles, is denoted as Sp. Ds in Table 5.1 and Fig. 5.1; (ii) the constant tsunami amplitude of 2.23 at the depth of 10m based on the Green's law is denoted as A Ds G in Table 5.1 and Fig. 5.2; and (iii) the bulk modulus of 2142225 kPa of the SAW mixtures with free air bubbles has been used in calculating the values in Table 5.1.

There are two assumed cases of the initial solid-air-water (SAW) mixtures in Table 5.1, the percentages of air bubbles are 0 and 0.005% for the first and second conditions, respectively. The first condition is for free air of the SAW mixture, as cases of the compressible fluids, as mentioned by Okal, 1988 and other researchers with the assumptions of the theory of wave gravity. The bulk modulus, shear wave velocity, and the vertical and horizontal dynamic heights of the SAW mixtures enormously decrease with the increase in the percentage of air bubbles from 0.005% to 1%. The speed at 10m depth, the amplitude of the tsunami wave and the amplification factor based on the Green theory without effects of refraction and ocean tide are 35.66 km/h, 2.23 m and 4.47, respectively; and independent with the percentages of air bubbles (Table 5.1). The calculated amplitude of tsunami greatly underestimated the actual amplitude of tsunami. The tsunami amplitudes due to the horizontal and vertical components of earthquake with the initial percentage of air bubbles of 0.005% decrease from 40 m to 1.05 m, and from 40 m to 0.11 m with the increase in the percentage of air bubbles from 0.005% to 2%, respectively. For cases with the percentage of air bubbles of 0.005%, the speeds and amplitudes at 10 m depth for the two cases of the SAW mixtures are 11.8 and 24.1 km/h, 2.0 and 15.9 m, respectively. Note that the tsunami speed and the height of the SAW mixtures at the coastlines of the 2004 Sumatra tsunami have been recorded about 15 km/h and 30m, respectively. For cases with the percentage of air bubbles of 0.005%, the amplification factors based on the Green's law and the new proposed expression (Eqn. (5.3)) are 4.47 and 31.8, respectively. The ratio between the values of the two methods is about 7.1(=31.8/4.47) as compared with that of 0.87(=3.9/4.47) for cases with the percentage of air bubbles of 1% of the SAW mixtures.

Table 5.1. Variations of tsunami speeds, amplitudes, amplification factors, bulk moduli, vertical and horizontal dynamic water heights with the percentage of air bubbles.

Air %	0.005	0.01	**0.05**	0.1	1	2	**0.05-0.6**
Sp. Ds	35.66	35.66	35.66	35.66	35.66	35.66	35.66
Ds 0	17.46	16	11.8	10	5.73	4.82	11.8
Ds 0.005	35.66	32.64	24.1	20.5	11.7	9.9	24.1
A Ds 0 x	6.8	5.2	**2**	1.1	0.13	0.07	**2.3**
A 0.005	40	32.8	15.9	10.5	1.9	1.05	17.8
A Ds G	2.23	2.23	2.23	2.23	2.23	2.23	2.68
Fa G	4.47	4.47	4.47	4.47	4.47	4.47	4.47
Fa PT x 0	13.6	10.4	4	2.2	0.3	0.14	3.8
Fa pt x.005	80	65.6	31.8	21	3.9	2.1	29.7
A 0	1.52	0.37	0.28	0.08	0.004	0	0.33
A 0.005	40	10.4	10.058	3.32	0.028	0.11	11.26
Fa pt X0	3.04	0.74	0.56	0.16	0.008	0.003	0.54
Fa pt z.005	80	20.76	20.1	6.65	0.55	0.21	18.8
Poisson R	0.49995	0.4999	0.4995	0.499	0.495	0.49	0.4995
Bsaw	1227818	860510	253595	134775	14287	7167	253595
Vsaw,	3986.1	3337.1	1811.9	1321.3	432	307.6	1811.9
Hz saw	3944.8	3302.2	1793.0	1847.9	191.9	97.1	1793.0
Hx saw	176.2	147.5	80.1	58.4	19.1	13.6	80.1
s saw	0.00707	0.01	0.0226	0.03161	0.0995	0.14	0.0226
Freq z x	1	1	1	1	1	1	1

For the initial amplitude of 0.6 at depth of 4000m and for cases of the percentage of air bubbles of 0.005%, the amplitudes at the depth of 10m for the two cases of the SAW mixtures are 2.3 and 17.8 m, respectively; as shown in the last column of Table 5.1. So, the increase in amplitude of 0.1m at the depth of 4000m, the increase in amplitude at the depth of 10m is 0.3 m for the cases with no initial air bubbles in the SAW mixtures. If the initial amplitude of 0.4 m, the amplitudes at the depth of 10m for the two cases of the SAW mixtures are 1.6 m and 13.0 m, respectively.
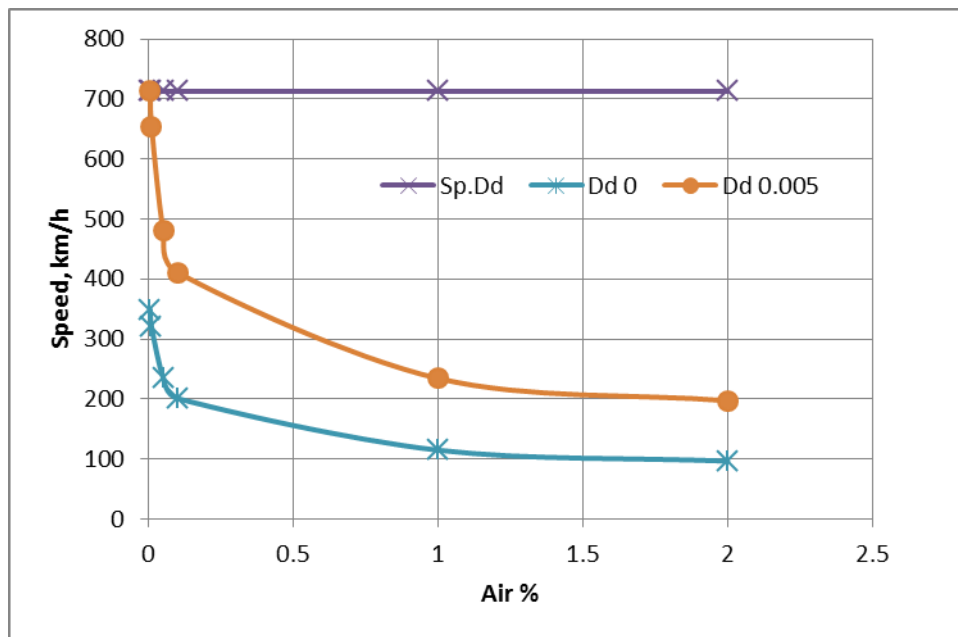

Figure 5.1. Variation of tsunami speeds with the percentage of air bubbles for two initial conditions of the SAW mixtures
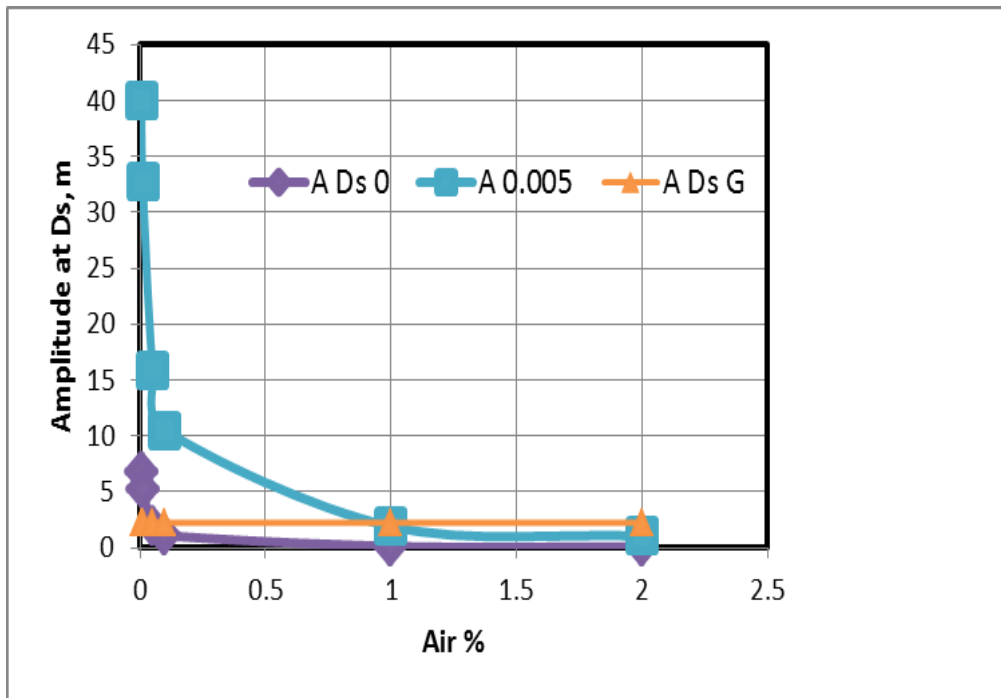
Figure 5.2. Variation of amplitudes with the percentage of air bubbles for two initial conditions of the SAW mixtures

The shear wave velocities of the SAW mixtures of 3986.1 km/h, 3337.1 km/h, 1812km/h and 1321 km/h for the four cases of the percentages of air bubbles of 0.005%, 0.01%, 0.05% and 0.1%, respectively, are much greater than the phase velocity of 713 km/h based on the theory of wave gravity for the average Pacific Ocean depth of 4000m. The average depth of the Indian Ocean is also 4000m, the arrival time in Sri Lanka and India indicates that a large westward velocity should be in the order of 1000 km/h for the 2004 Sumatra tsunami (Annunziato et al., 2005).

6. AMPLITUDE, WAVELENGTH AND DEPTH RELATIONSHIP

The "Ursell parameter" (Murty, 1977; Weissert, 1990) is defined as

$$U \equiv \frac{A\lambda^2}{D^3} \tag{6.1}$$

Where A = Amplitude of the wave, D = Depth, and λ = Wavelength. U<1, it means the linear theory of long waves is valid (Murty. 1977); U=1, it means that the Boussinesq's equations are valid; U>1, it means that the theory of finite amplitude long waves must be used. The breakdown point occurs at U=1, the depth D can be determined by:

$$D = \sqrt[3]{\frac{A\lambda^2}{U}} \tag{6.2}$$

The linear wave theory begins to break down and the wave speed will be slower than the observed values when the depth is less than that determined by Eqn. (6.2).

7. DYNAMIC WATER-ATTENUATION FACTORS

The vertical and horizontal dynamic water-attenuation factors can be defined based on the dynamic water heights (Truong, 2011a, b, c), respectively, as:

$$A_{tz} = \frac{2\pi f_z s_{saw}\sqrt{\rho_{saw}}}{\sqrt{B_{saw}}} = \frac{2\pi f_z}{V_{Psaw}} \tag{7.1}$$

$$A_{tx} = \frac{2\pi f_x \sqrt{\rho_{saw}}}{\sqrt{B_{saw}}} = \frac{2\pi f_x}{V_{Ssaw}} \tag{7.2}$$

If geometrical spreading is only considered in a constant depth basin, then to an upper limit approximation the wave height as a function of distance from the source (Mader, 2001) would be

$$H = H_0 \frac{R_o}{R} \tag{7.3}$$

Where R_o = the initial source radius, R = the distance the wave has traveled from the source, and H_o = the initial height of the source.

8. CONCLUSSIONS

The tsunami amplitudes and the shoaling amplification factors based on the theory of wave gravity and the Green's law are much smaller than those in real situations, especially for 2004 Sumatra tsunami. While the tsunami speed from the theory of wave gravity are overestimated, e.g. about 2 times than that recorded in the literature.

The tsunami amplitudes, speeds, and the dynamic shoaling amplification factors of the solid-air-water (SAW) mixtures, which are based on the dynamic water masses, decrease with the increase in the percentages of air bubbles. The shear-wave velocities and the vertical and horizontal dynamic water heights substantially decrease with the increase in the percentages of air bubbles. Air bubbles could firstly save human lives and secondly greatly reduce damages to many properties and infrastructures.

The shear wave velocity of the SAW mixtures are much higher than the tsunami speeds based on the theory of wave gravity for the low range, from 0.005% to 0.1%, of the percentage of air bubbles. The effects of air bubbles on tsunami heights, speeds and amplitudes are very important and should be taken into account in the analyses of tsunami waves in the very strong earthquakes, e.g. 2004 Sumatra and 2011 Tohoku earthquakes.

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