Principles and Equipment to Reduce Earthquake Effects on Liquefaction and Tsunamis

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SUMMARY:
Soil liquefaction and the great height of the tsunami waves are the main concerns in highly-populated areas with the strong earthquakes due to heavy loss of human lives and great damages to properties. Principles to reduce the effects of strong earthquakes on liquefaction and the height of tsunamis are (i) to reduce the degree of saturation of soil, and (ii) to increase the percentage of air bubbles in sea water, respectively. The vertical and horizontal dynamic liquefaction factors (**DLF**s) due to the vertical and horizontal components of an earthquake have been introduced to evaluate the liquefaction potential of the solid-air-water (**SAW**) mixtures. Equipment to generate air into soil and sea water is comprised of perforated pipes, geo-fabric materials, air compressors and power generators.

Keywords: Liquefaction, Tsunami, gas/air bubbles, density, Principles, Equipment

1. INSTRODUCTION

For many decades, intensive efforts have been devoted by many research institutions, private and public organisations to reduce or eliminate liquefaction potential, e.g. by improving the site conditions through different methods, which are normally considered as expensive to many builders and developers, such as: (i) densification, especially by vibro-compaction, (ii) enhanced drainage, (iii) increased effective stress or strength, (iv) sand compaction pile method, and (v) change of soil fabric by chemical grouting method. But little work has been conducted to directly reduce the tsunami heights, even though there have been currently established the very complicated and costly warning systems in in Asian countries in the last decade, especially due to the enormous damages of properties and heavy loss of human lives of the recent two gigantic tsunamis of 2004 Sumatra and 2011 Tohoku tsunamis. Cost-effective mitigation techniques are necessarily and urgently required by many countries around the world to reduce the damages and loss of human lives due to soil liquefaction and the enormous tsunami heights.

This paper presents the principles and equipment of using air bubbles in soil and ocean water, and the expressions of the vertical and horizontal dynamic liquefaction factors (**DLF**s) due to the vertical and horizontal components of an earthquake to evaluate the earthquake potential of the solid-air-water (**SAW**) mixture. The use of air/gas or micro air bubbles in the voids of the fully saturated sand to prevent the liquefaction in soils has been investigated by many researchers, especially by Martin et al. (1975), Yoshimi et al. (1989), Yang et al. (2003), Ishihara et al. (2003), Yegian et al. (2007) with experimental investigation, Kobayashi et al. (2010) and Raghunandan et al. (2011). The effects of air bubbles, solids and frequencies on tsunami heights by dynamic water masses and dynamic water heights have been recently studied by Truong (2011a, b and c), even though the use of air bubble at sea had been utilized by ship captains to save lives at sea in 1936.

2. PRINCIPLES OF LIQUEFACTION AND TSUNAMI MITIGATION

2.1. Soil Liquefaction Mitigation

When the fully saturated sand below the water table is subjected to an extended period of severe ground shaking, the excess pore water pressure tends to increase. This generation of excess pore water pressure leads to temporary reduction in effective stress and shear strength, and eventually causes the ground to liquefy and fail. So, liquefaction can only occur for the fully saturated soils, normally for the uniform clean sands or clay-free deposits of sands and silts. The actions in the soil which produce liquefaction are: seismic waves, primarily shear waves, passing through saturated granular layers, distort the granular structure, and cause loosely packed group of particle to collapse.

Muhanthan and Schofield (2000) noted that the 100% pore pressure rise is a necessary condition but not a sufficient condition. The formation of openings and the presence of high hydraulic gradient, which leads to the disintegration of the continuum into classic blocks of soil, is another important requirement. While, soil liquefaction has been referred to (i) significant loss of strength and stiffness due to cyclic pore pressure generation, (ii) Saturation (or at least near-saturation), and (iii) rapid (largely undrained) loading (Seed et al., 2001). Liquefaction was also observed even in unsaturated zone (Sheng, 1999). The soils frequently encountered in geotechnical engineering are unsaturated. The liquefiable soil layer under the phreatic surface is not, as usual assumed fully saturated, but in a partially saturated states (Tsukamoto and Ishihara, 2002 and 2007). In-situ test results, including compression wave velocity measurements indicate that partial saturation conditions may exit below ground water level for a few meters due to presence of air bubbles (Ishihara et al., 2001; and Nakazawa et al., 2004) or gas bubbles in marine sediments and oil sands (Mathiroban et al, 2004).

According to Special Publication 117A (2008), Guidelines for Evaluating and Mitigating of Seismic Hazards in California, in order to be susceptible to liquefaction, potentially liquefiable soils must be saturated or nearly saturated. In general, the liquefaction hazards are most severe in the upper 15.24m (50 ft) of the surface, but on a slope near a free face or where deep foundations go beyond that depth, liquefaction potential should be considered at greater depths. If it can be demonstrated that any potentially liquefiable materials present at the site: (a) are currently unsaturated e.g. are above the water table), (b) have not previously been saturated (e.g. are above the historic-high water table), and (c) are highly unlikely to become saturated (given foreseeable changes in the hydrologic regime), then such soils generally do not constitute a liquefaction hazard that would require mitigation.

The effective vertical overburden shear stresses at the depth of interest based on the vertical and horizontal dynamic water heights (Truong, 2011a, b and c), and the P-wave and S-wave velocities of an earthquake, respectively, are

$$\sigma'_{voz} = \sigma_{vo} - u = \sigma_{vo} - \frac{\sqrt{B_{saw}}}{\omega_z s_{saw}\sqrt{\rho_{saw}}}\gamma_w = \sigma_{vo} - \frac{V_{saw}}{\omega_z s_{saw}}\gamma_w \qquad (2.1)$$

$$\sigma'_{vox} = \sigma_{vo} - \frac{\sqrt{B_{saw}}}{\omega_x\sqrt{\rho_{saw}}}\gamma_w = \sigma_{vo} - \frac{V_{saw}}{\omega_x}\gamma_w \qquad (2.2)$$

Where σ_{vo} = the total vertical overburden stress, u = excess pore water pressure, γ_w = unit weight of water, ω_x = circular frequency of the earthquake in horizontal direction, ω_z = circular frequency of the earthquake in vertical direction, ρ_{saw} = mass density of the solid-air-water (**SAW**) mixture (Truong 2011a, b and c; and Richart et al, 1970), which can determined by

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

Where S = Degree of Saturation, G_s= Specific Gravity of solid particle, g = Gravitational acceleration, e = void ratio, B_{saw} = Bulk Modulus of elasticity of the solid-air-water (**SAW**) mixture, which can be determined by the Wood equation (Wood, 1930), and

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

Where μ_{saw} = Poisson's ratio of the SAW mixture. The expression for wave-propagation velocity in the solid-air-water (**SAW**) mixture (Richart et al. (1970), has been defined as

$$V_{saw} = \sqrt{\frac{B_{saw}}{\rho_{saw}}} \tag{2.5}$$

Vertical component of strong ground motion is mainly associated with body-waves: vertically propagating compressional (P-wave) and horizontally dilatational (S-wave) waves. Compared to horizontal component, vertical motion may be richer in high frequency content in the near-field of an earthquake fault. As the distance from the source increases, difference in frequency content between horizontal and vertical components becomes much smaller as a result of faster attenuation of high frequencies with distance, and mixing of horizontal and vertical motions by non-homogeneities along the wave path (Kalkan et al, 2007).

The vertical excess pore water pressure increases with the increase in bulk modulus, and with the decrease in mass density of the solid-air-water (**SAW**) mixture and the circular frequency of the earthquake (Eqns. (2.1) and (2.2)). The vertical excess pore water pressure from the P-wave velocity becomes infinite when the Poisson's ratio of the SAW mixture is equal to 0.5 as for the incompressible fluid, as expected. So, the principle to reduce the effects of strong earthquakes on soil liquefaction is to reduce the S-wave velocities of the SAW mixtures: (i) by reducing the bulk modulus, and (ii) by increasing the mass density of the SAW mixture. Because free water does not transmit shear stress, standing water above ground surface is not included in the calculation of the total vertical overburden stress (Tokimasu and Yoshimi, 1983).

The degree of saturation is controlled during a triaxial compression test by the coefficient B of Skempton which can be related to the degree of saturation by the following relation (Lade and Hernandez, 1977).

$$B = \frac{1}{1 + nB_s\left(\frac{Sr}{B_w} + \frac{(1-S_r)}{U_w}\right)} \tag{2.6}$$

Where B_s = bulk modulus of soil skeleton, B_w = bulk modulus of water, n = porosity, S_r = degree of saturation, and U_a = water pore pressure. B is equal to zero 1 if there is no void in the soils, and equal to 0 if the soil is fully saturated. If the sandy soil with the porosity of 0.4, the degree of saturation of 0.99 and the pore water pressure of 300 kPa, the value of B is equal to 0.0024.

The vertical and horizontal dynamic liquefaction factors (**DLF**s) at a depth z of the ground water table due to the vertical and horizontal components of an earthquake could be defined, respectively, as follows:

$$L_z = \frac{V_{saw}\gamma_w}{s\omega_z z\gamma_t} \tag{2.7}$$

$$L_x = \frac{V_{saw}\gamma_w}{\omega_x z \gamma_t} \tag{2.8}$$

Where γ_t = total unit weight of soil above the ground water table.

The vertical effective stress of the soil is equal to zero when the vertical or horizontal dynamic liquefaction factor (**DLF**) is equal to 1. For the depth of 15m of the ground water table with the mass density of 1.9 T/m^3 of the soil above the ground water level, the vertical and horizontal circular frequencies of the earthquake must be 7.5 Hz and 0.74 Hz, respectively, in order to have the zero effective stress at the depth of the ground water level, with the shear wave velocity of 133.8 m/s, the porosity of 0.4, and Poisson's ratio of 0.495 of the SAW mixture. If the vertical or horizontal dynamic liquefaction factor (**DLF**) is much greater than 1, then soil is in boiling state or quick sand condition because of the very high excess pore water pressure. So, the lower the dynamic liquefaction factor (DLF), the higher resistance of the soil due to an earthquake will be expected. In general, the resistance of the soil to the earthquake increases with the increase in the depth of the soil above the ground water table, total unit weight of the soils, and the circular frequency of the earthquake and with the decrease in the shear wave velocity of the solid-air-water (**SAW**) mixture.

2.2. Tsunami Mitigation

The vertical and horizontal dynamic water heights generated by the vertical and horizontal components of an earthquake have been presented by Truong (2011a, b, and c), respectively, as follows:

$$H_z = \frac{\sqrt{B_{saw}}}{\omega_z s_{saw}\sqrt{\rho_{saw}}} = \frac{V_{saw}}{\omega_z s_{saw}} \tag{2.9}$$

$$H_x = \frac{\sqrt{B_{saw}}}{\omega_x \sqrt{\rho_{saw}}} = \frac{V_{saw}}{\omega_x} \tag{2.10}$$

The vertical and horizontal dynamic water heights are actually the vertical dynamic hydraulic heights generated by the vertical and horizontal components of an earthquake, respectively, which cause the upward flow of water and should be used to calculate the vertical excess pore water pressures for cases of the vertical and horizontal vibrations, respectively, as in the cases of soil liquefaction. The height of the excess pore water pressure is a metre of water in a laboratory or several kilometres of water in an ocean abyss (Schofield and Wroth, 1968). The amount of solid particles in ocean water from 0.001% to 10% is very small in the SAW mixtures compared with the great amount of solid particles from 57% to 64% of the total volume of the SAW mixture based on the normal porosity of sandy soil typically from 0.43 to 0.36.

The percentages of air bubbles and solids of the SAW mixtures, ocean sediments and the frequencies of earthquakes could greatly affect the dynamic water heights, e.g. the study by Truong (2011a, b and c). For the offshore environment, bubbles of methane, nitrogen and carbon dioxide are formed within the seabed by the decomposition of organic matter. The presence of these gas bubbles can have a major influence on the engineering properties of the soil. As gas bubbles in marine sediments are typically much larger than normal void spaces, the bubbles cannot be considered as simply changing the compressibility of the pore fluid (Wheeler, 1986). In the ocean, the major of natural bubble entrainment is the break-up of large volume of air by breaking waves. Air bubbles could also be produced by the deep sea volcanoes. Bubble concentration as well as the penetration depth of bubbles increase with increasing wind speed (Kolovayev, 1976 and Wu, 1988). Kolovayev (1976) found that the most numerous bubbles in the depth range from 1.5 m to 8.0m are those with radii of about 70 µm and very few bubbles have radii greater than 300 µm.

2.3. Principles to Soil Liquefaction and Tsunami Mitigation

The bulk modulus of the SAW mixture, S-wave velocity, the vertical and horizontal dynamic water heights substantially decrease from 6256613kPa to 70790kPa, from 560 m/s to 188.4 m/s, from 1245.7 m to 133 m, and from 27.85 to 9.4, with the increase in the percentage of air bubbles from 0.05% to 0.5%, respectively (Table. 2.1, Figures 2.1 and 2.2). The porosity of 0.4, the percentage of solids of 60%, and the vertical and horizontal circular frequencies of 20.1 rads/sec (3.2 Hz) have been used in estimating the S-wave velocity and the vertical and horizontal dynamic water heights in Table 2.1, Figures 2.1 and 2.2. The vertical dynamic water heights due to the horizontal components of the earthquakes or horizontal vibrations would be 72.73m and 76.97m if the initial percentages of air bubbles are 0.001% and 0.0001%, respectively. So, the reduction in the excess pore water pressure is about 91% if the SAW mixture has 1% of air bubbles. The decrease in the initial water saturation can mitigate the liquefaction. Martin et al. (1975) explained that a 1% reduction in the degree of saturation can lead to 28% reduction. According to Yang et al. (2003), a reduction in saturation by 1% led to a reduction in the excess pore pressure ratio from 0.60 to 0.15 under pure horizontal excitation; that is a reduction of 75%. Note that the porosity of 0.4, which has been used to calculate shear wave velocities and the dynamic water heights in Table 2.1 and Figure 2.2, was used by Martin et al. (1975).

Table 2.1. Variation of S-wave Velocity and Dynamic Water Heights with Percentages of Air Bubbles

Air %	0.05	0.1	0.2	0.5	1	2	5	10	15
Bsaw	625613	334401	173178	70790	35656	17894	7173.3	3589.3	2393.5
Rho saw	1.9958	1.9956	1.9952	1.994	1.992	1.9886	1.976	1.956	1.936
Vsaw	559.91	409.38	294.63	188.43	133.8	94.88	60.26	42.84	35.16
Mu	0.49975	0.4995	0.499	0.4975	0.495	0.49	0.475	0.45	0.425
Hz	1245.7	644.2	328	132.87	66.88	33.7	13.73	7.07	4.84
Hx	27.85	20.36	14.65	9.37	6.65	4.72	3	2.13	1.75

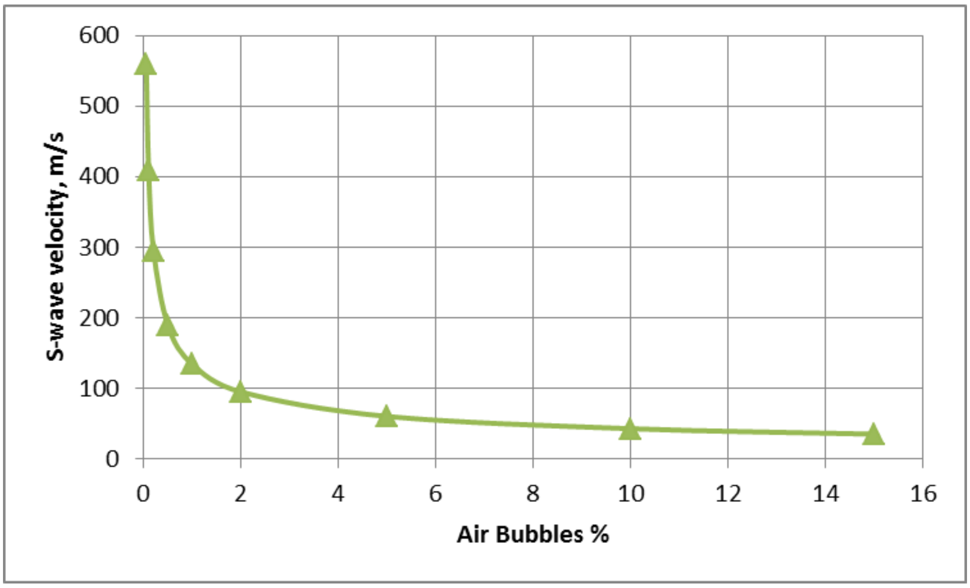

Figure 2.1. Variation of Shear wave velocity with the percentage of air bubbles

Analysis of the free-field response of liquefiable sandy soil layer under dynamic loading shows that the initial water saturation has a significant influence on the layer liquefaction resistance. The decrease in the initial water saturation can mitigate the liquefaction. With the decrease in water saturation, the initial liquefaction will be delayed and the liquefaction zone will be reduced. When the water saturation is lower than certain value, the liquefaction cannot occur (Bian, 2007).

A small reduction in the degree of water saturation of sand could result in a significant increase in strength against liquefaction (Martin et al. (1975), Yoshimi et al, (1989) and Yang et al. (2003)). It has been known that unsaturated sands have a significantly higher resistance to liquefaction than saturated sands. Liquefaction potential of saturated sand can be reduced if the degree of saturation of the sand is effectively lowered (Ishihara et al, 2003). 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). Wheeler (1986) studied the stress-strain behaviour of unsaturared soil containing discrete bubbles of gas in a program of experimental and theoretical research and also found that even small volume of gas bubbles reduces the undrained bulk modulus dramatically. So, the principles to liquefaction and tsunami mitigations are simply to introduce some appropriate amount of air bubbles in the fully saturated soils or in ocean waters depending on the site conditions and initial degree of saturation of soils.

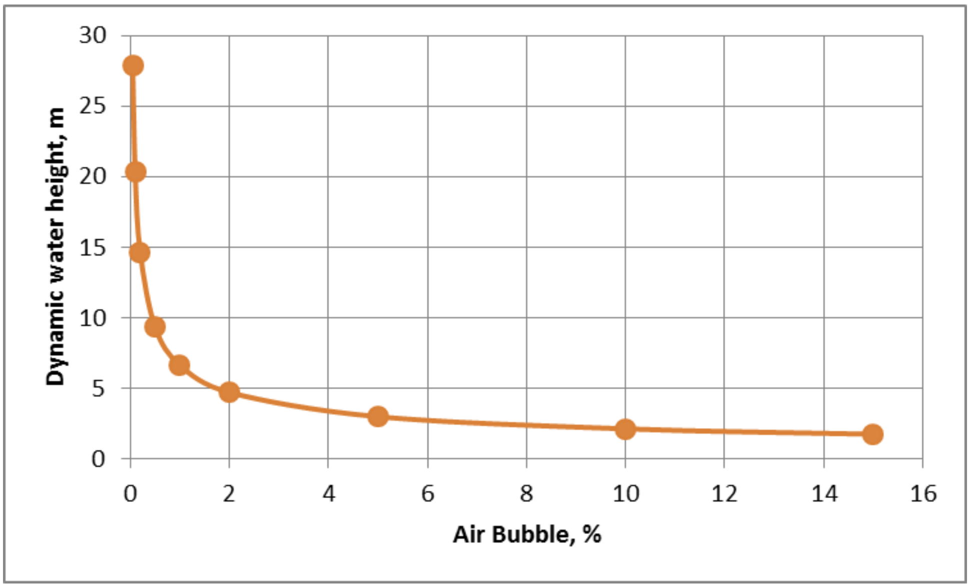

Figure 2.2. Variation of dynamic water height with the percentage of air bubbles

Table 2.2. Variation of bulk density, velocity and dynamic water heights with porosity

Solid %	70	60	50	40	30	20	10	1	0.1
n	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.99	0.999
Bsaw	47522	35655	28531	23780	20385	17838	15857	14416	14286
Rho saw	2.16	1.99	1.83	1.66	1.49	1.32	1.16	1	0.99
Vsaw	148.4	133.8	125	119.8	116.9	116	117	119.7	120
e	0.429	0.667	1	1.5	2.33	4	9	99	999
Hz	74.2	66.9	62.5	59.9	58.5	58	58.52	59.82	60
Hx	7.38	6.65	6.32	5.96	5.82	5.77	5.82	5.95	5.97

The bulk modulus, density and shear wave velocity of the SAW and the vertical dynamic water heights of the vertical and horizontal components of an earthquake decrease from 47522 kPa to 14286 kPa, from 2.16 T/m3 to 0.99 T/m3, from 148.4 m/s to 120 m/s, from 74.2 m to 60 m, and from 7.38m to 5.97m, with the increase in the porosity from 0.3 and 0.999, and the void ratio from 0.429 to 999, respectively, with the percentage of 1 % of air bubbles of the SAW mixture, and the vertical and horizontal frequencies of 20 Hz (Table 2.2). The vertical dynamic water height due to horizontal vibration decreases with the increase in porosity, as shown in Figure 2.3. The increase in density by densification or by reducing the porosity could increase the bulk modulus and the excess pore water pressures of the SAW mixture because of the increase in the shear wave velocity based on the expressions of the dynamic water heights. The vertical dynamic water height due to the horizontal vibration firstly decreases from 7.38m to 5.77m with the decrease in percentage of solid particles from 0.7 to 0.2%, and finally increases with the decrease of the percentage of solid particles from 0.2 to 0.001% (Table 2.2 and Figure 2.4). The ocean water might have the percentage of solids from 0.1% to 10% depending on the site conditions.

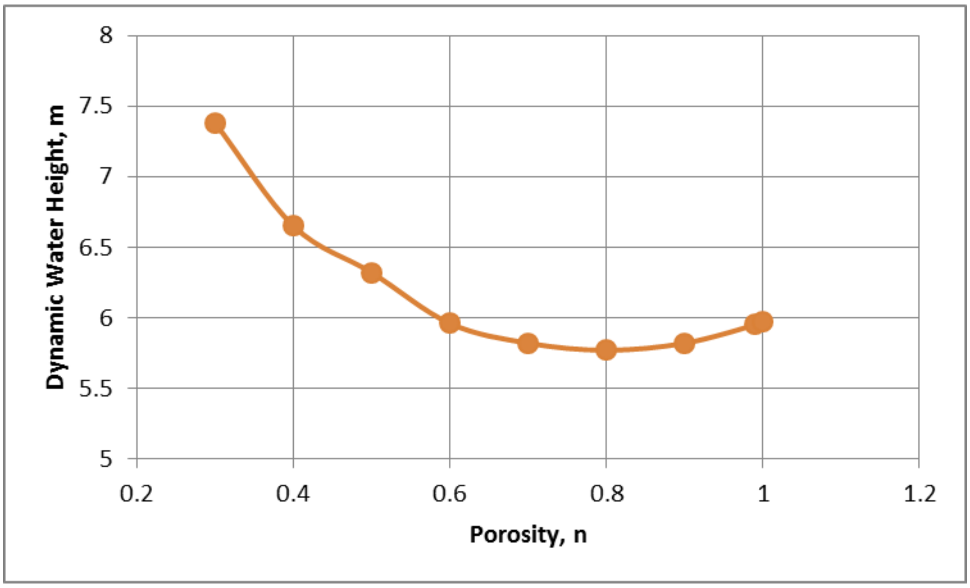

Figure 2.3. Variation of the dynamic water height due to horizontal vibration with porosity

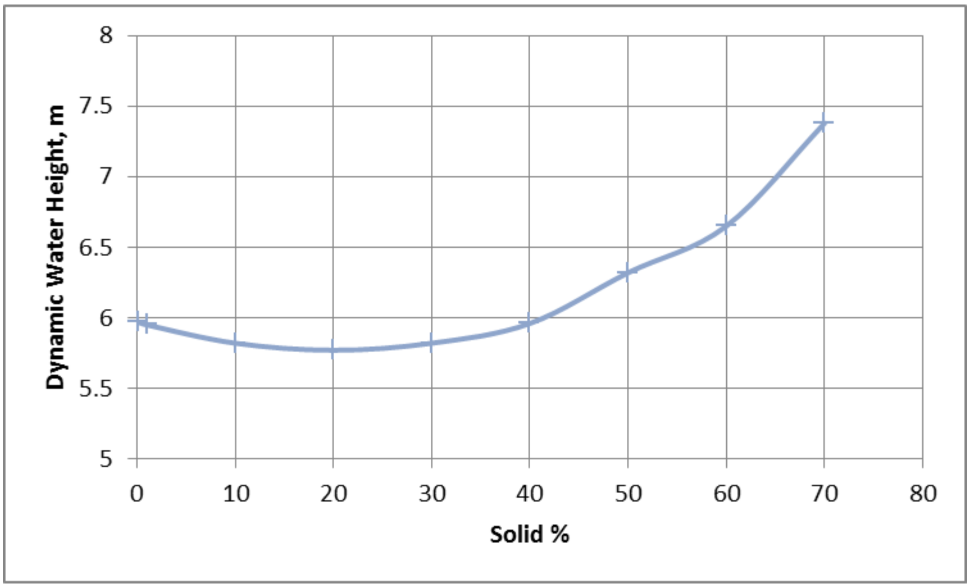

Figure 2.4 Variation of the dynamic water height with the percentage of solid particles

The vertical dynamic liquefaction factor (**DLF**) at the depth of the ground water table of 15 m will be 1.00, 21.31, and 46.30, and the horizontal dynamic liquefaction factor (DLF) will be 1.01, 1.50, and 3.27; if the degree of saturation of the SAW mixture is 0.990, 0.995 and 0.999, respectively; for the mass density of the soil above the ground water table of 1.9 T/m^3, the vertical and horizontal circular frequencies of an earthquake of 7.5 Hz and 0.74 Hz, respectively; the shear wave velocity of 133.8 m/s and Poisson's ratio of 0.495 of the SAW mixture.

3. EQUIPMENT OF LIQUEFACTION AND TSUNAMI MITIGATION

Even though, there are many ways to produce the air bubbles in soils and in ocean water, but the main equipment are power generators, water pumps, air compressors and perforated pipes. The proper geotextiles are also need to protect the perforated pipes from clogging or contamination of soils into perforated pipes. As for drainage purposes, geotextiles should be woven monofilament or non-woven needed fabrics. Woven slit film and non-woven heat bonded fabrics should not be used as they are prone to clogging. Primary considerations for geotextiles are (i) suitable apparent opening size for non-woven fabrics, or percent open area for woven fabrics, to maintain air and water flow even with sediment and microbial film build-up, and (ii) maximum forces that will be exerted on the fabric, etc.

Power generators should be used because there are many cases of no main electricity due to the strong earthquakes cutting off the main power supply. The power generators, water pumps, air compressors and perforated pipes should be operational any time, especially in the emergency cases, e.g. just before and during earthquakes; and should be completely protected from any damages due to strong earthquakes, if possible.

3.1. Soil Liquefaction Mitigation

For the existing structures, there are many different ways to have partially unsaturated soil below phreatic lines. For example, the ground water could be pumped out and mixed with air bubbles by the use of air compressors and recharge the air-water (AW) mixtures back to ground water. Nagao et al. (2007) and Kobayashi et al. (2010) have used the micro bubble injection methods with micro bubbles of 10 to 100 micro-meters diameter, because the micro bubbles can retain submerged for several tens of minutes. Perforated pipes also could be vertically or horizontally, temporarily or permanently installed into the ground and they could be used to directly inject air-water (AW) mixtures, compressed air or non-hazardous chemicals to create gas bubbles into ground water depending on the site conditions. Induced Partial Saturation (IPS) will be a cost-effective and practical solution for new as well as existing structures. The mitigation measure that is being explored improves earthquake resistance of loose sands by introducing some amount of air/gas in the voids of the sand. Two different methods to introduce air/gas in the fully saturated sands are: (i) generation of hydrogen and oxygen gases in the liquefaction susceptible soils through electrolysis and (ii) drainage and recharge method, or air entrapment in the voids by draining and reintroducing water in the fully saturated sand (Yegian et al. 2007; and Bayat et al. 2009).

3.2. Tsunami Mitigation

Perforated pipes are wrapped with the appropriate geotextile to prevent clogging with soil or other materials, especially small fish, etc. are laid along the coast lines at the depth of about 10m or 15m where properties and human lives are needed to be protected, especially the high density populated areas. Secured remote controls to operate the power generators, air compressors are necessary and should be protected from any damages caused by tsunamis. The perforated pipes should not cause any harm or danger to environments, e.g. small fish; and are protected against any human destruction, e.g. fisherman; the numbers of perforated pipes, air compressors and power generators depends on the percentages of air bubbles to be introduced in the SAW mixtures and the initial percentages of the SAW mixtures at the sites. A wall of bubbles was formed by compressed air escaping from a pipe laid on the sea bottom across the mouth of harbor. It was expected that the presence of the air bubbles would decrease the compressibility of the sea water in this location and thereby decrease the propagation of wave energy into the harbor (Evans (1956), "A Wall of Bubbles Controls the Waves" (1959), and Kurihara (1958)). Another application of bubbles in water to reduce the dynamic forces has been described by Graves (1968), in which a curtain of air bubbles has effectively reduced hydraulic-blast forces on submerged structures (Richart et al, 1970). In April 1936, many ship captains had used the perforated pipes and air compressors to produce air bubbles to substantially reduce the high amplitudes of ocean waves, or calm down the turbulences at sea, to save human lives.

There are many current tsunami mitigation strategies which have been proposed such as: (i) land use management to minimize the development in areas of potential tsunami inundation, (ii) preservation of natural barriers or dunes along coastlines, (iii) establishment of design standards, building codes, or guidelines for construction of buildings within coastal areas, (iv) increased public awareness and education about tsunami risks, warning signs and preparedness action, and (v) development of a warning systems to alert people to evacuate to higher ground or to upper stories of sturdily built structures (Pacific Disaster Center, 2005).

4. CONCLUSIONS

The bulk modulus, shear-wave velocity and vertical dynamic water heights due to vertical and horizontal vibrations and excess pore water pressure substantially decreases with the increase in the percentage of air bubbles or with the decrease in the degree of saturation of the solid-air-water mixtures, especially in the low range of percentages of air bubbles from 0% to 1%.

The vertical height of the excess pore water pressure in fully saturated soils increases with the shear-wave velocity of the SAW mixture and decreases with the increase in the circular frequency of the earthquake. The vertical and horizontal dynamic liquefaction factors (**DLF**s) due to the vertical and horizontal components of an earthquake decrease with the increase in the depth of the ground water table, mass density of the soil above the ground water table, and the increase in the circular frequencies of earthquakes; with the decrease in the shear velocity of the solid-air-water (**SAW**) mixture. The lower the dynamic liquefaction factors (DLFs), the higher the resistance of soil to the earthquakes will be. The dynamic liquefaction factor (DLF) is equal to 1 when the effective stress at the depth of the ground water level is zero.

Equipment to soil liquefaction and tsunami mitigations are mainly power generators, air compressors, water pump, geotextiles and perforated pipes. The air-water mixture, non-hazardous chemicals to create air bubbles and compressed air could be injected into fully saturated soils to reduce the degree of saturation in soils. Proper geotextiles should be used to prevent the perforated pipes from clogging.

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