

Liquefaction and lateral spreading by dynamic soil mass for earthquakes

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Abstract—Dynamic soil mass for earthquakes can be used to evaluate the liquefaction and lateral spreading in earthquakes. Dynamic soil mass increases with the increase in the contact area of disturbance between bedrock and the soil, the square root of both soil density and shear modulus of soil, and decreases with the increase in the circular frequency of the earthquake. The ratio of the dynamic soil masses for vertical and horizontal directions is linearly proportional to the horizontal circular frequency, inversely proportional to the vertical circular frequency, and increases with the increase of the Poisson's ratio. Effects of different soil and rock layers on the response to earthquakes are also investigated in detail.

Keywords—Dynamic soil mass, earthquake, lateral spreading, liquefaction.

I. INTRODUCTION

LIQUEFACTION and lateral spreading are the main concerns in strong earthquakes. Liquefaction potential and lateral spreading have been extensively investigated by many researchers, e.g. Martin et al. [1] and Ishihara et al. [2], respectively. But, no one has been able to propose any method to theoretically quantify the amount of disturbed soil to be liquefied or moved laterally in urban areas, as also mentioned by Baziar et al [3].

The purpose of this paper is to propose the expressions of the dynamic soil masses for evaluating liquefaction potential and lateral spreading based on the work by Truong [4, 5, 6, 7 and 8] for earthquakes, respectively.

II. DYNAMIC SOIL MASS FOR EARTHQUAKES

Dynamic soil mass for earthquakes could be defined as the vibrating soil mass is normally moving diagonally upward and completely dependent on the nature of the earthquake, especially with the circular frequencies in horizontal and vertical directions, Poisson's ratio, type of earthquake, shear modulus of soil, and length and width of the earthquake fault.

Truong [4, 5, 6, 7 and 8] showed that dynamic soil masses for shallow foundations have increased with the area of the footing, the square root of both shear modulus and density, and decreased with the circular frequency for both vertical and horizontal vibrations. The ratio of the dynamic soil masses for

the two modes is equal to the ratio of velocity of Push wave (P-waves), V_p , to that of Shear wave (S-waves), V_s . So, the dynamic soil mass for earthquakes and for a uniform soil profile can be expressed as follows:

$$m_{SEU} = \frac{A\sqrt{\rho G}}{\omega_x} + \frac{A\sqrt{\rho G}}{\omega_z s} \quad (1)$$

Where A = Contact area between bedrock and the soil is caused by the shaking area which is the product of the length of the earthquake fault and the moving width of the earthquake fault, ρ = Mass Density of the soil, G = Shear Modulus of soil, ω_x = Circular frequency of the earthquake in horizontal direction, ω_z = Circular frequency of the earthquake in vertical direction, and

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

Where μ = Poisson' ratio of soil.

The first and second terms of the right hand side of (1) are the horizontal and vertical dynamic soil masses due to a normal earthquake, respectively. If the earthquake has no vertical acceleration, the second term on the right hand side is zero.

The vertical component of earthquake ground motion has generally been neglected in the earthquake-resistant design of structures. This is gradually changing due to the increase in near-source records obtain recently, coupled with field observations confirming the possible destructive effect of high vertical vibrations. Normally, the vertical component of ground motion has a lower energy content than the horizontal component over the frequency range. However, it tends to have all its energy concentrated in a narrow, high frequency band, which can prove damaging to engineering structures with vertical periods within this range. The vertical component of ground motion was shown to be significant and should be considered in analysis when the proposed structure is sited within approximately 25 km of an earthquake [9].

Note that (1) was derived by Truong [4, 5, 6, 7 and 8] based on the wave propagation in ideal solids. However, real soils have special characteristics which cause their response to wave energy to differ from those developed by ideal solids. The voids in soil masses are filled with water, air, or mixtures of

Manuscript received April 11, 2012; Revised version received June 4, 2012.

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fluids, and these pore fluids may significantly influence the dynamic behavior of soils [10].

The ratio of the dynamic soil mass in vertical direction to that in horizontal direction can be determined by

$$R_{zx} = \frac{\omega_x}{\omega_z s} \tag{3}$$

If the circular frequency in the horizontal direction is equal to that in the vertical direction, the ratio becomes

$$R_{zx} = \frac{1}{s} = \frac{V_P}{V_S} \tag{4}$$

The variation of the ratio R_{zx} (4) with Poisson's ratio has been presented in detail by Truong [5] or Richart et al. [10].

The angle of the direction of the total dynamic soil mass forming with the horizontal direction is expressed by

$$\alpha(\text{deg.}) = \frac{90\omega_x}{\omega_z s + \omega_x} \tag{5}$$

If the circular frequency in the horizontal direction is equal to that in the vertical direction, the angle becomes

$$\alpha(\text{deg.}) = \frac{90}{s + 1} \tag{6}$$

The variation of the angle of earth movement increases from 54 degrees to 75.2 degrees with the increase in Poisson's ratio from 0.10 to 0.48 based on (6) (Fig.1). If the value of the horizontal circular frequency is twice that of the vertical circular frequency, the angle of earth movement increases from 67.5 degrees to 82.0 degrees with the increase in Poisson's Ratio from 0.10 to 0.48.

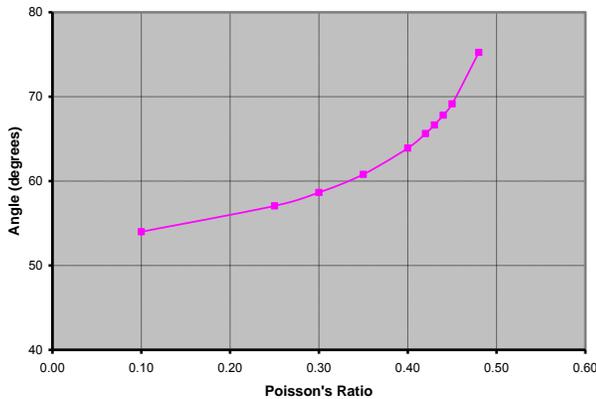


Fig. 1 Variation of the direction of earth movement with the Poisson's ratio

Note that the presence of the water table in the soil mass changed the wave-propagation characteristics of the soil

structure. Possibly even more important is the fact that the presence of the water table converts the soil mass into a layered system. The upper layer transmits wave energy through the soil structure, while the saturated layer transmits wave energy through both the soil structure and the fluid.

For a non-uniform soil profile with n different soil layers, the dynamic soil mass becomes

$$m_{SEN} = \sum_{i=1}^{i=n} \frac{A\sqrt{\rho_i G_i}}{\omega_{xi}} + \sum_{i=1}^{i=n} \frac{A\sqrt{\rho_i G_i}}{\omega_{zi} s_i} \tag{7}$$

Where n = Number of soil layers

III. RELATIONSHIP BETWEEN CORNER FREQUENCY AND DYNAMIC SOIL MASS

The dynamic soil masses caused by the vertical and horizontal components of an earthquake could be used to determine the ratio of the P-wave corner frequency and S-wave corner frequency. The ratio of P-wave dynamic soil mass and S-wave dynamic soil mass is

$$R_m = \frac{m_z}{m_x} = \frac{\omega_x}{\omega_z s} = \frac{\omega_x V_P}{\omega_z V_S} \tag{8}$$

If the P-wave dynamic soil mass is equal to the S-wave dynamic soil mass, Eq. (8) becomes

$$\omega_z = \frac{\omega_x}{s} = \frac{\omega_x V_P}{V_S} \tag{9}$$

The ratio of the circular frequency due to the vertical direction of an earthquake and that due to the horizontal direction of the earthquake is

$$R_f = \frac{\omega_z}{\omega_x} = \frac{f_z}{f_x} = \frac{1}{s} = \frac{V_P}{V_S} \tag{10}$$

The ratio R_f , which can be approximately considered as the ratio of P-wave corner frequency and S-wave frequencies in geotechnical earthquake engineering areas for some cases, e.g. for thrust earthquakes with very small dip angles, varies from 1.41 to 1.87 for Poisson's ratio of the source rock from 0.05 to 0.3 (Table 1 and Fig.2). The maximum range of dry V_p/V_s is for simple cubic packing of sandstones, varies only from 1.414 to 1.732 when Poisson's ratio of the spheres varies from 0 to 0.5. For practical purposes, dry V_p/V_s for packings of common rock-forming minerals is from 1.4 to 1.5 [11].

Table 1 Variation of the ratio of P-wave corner frequency and S-wave corner frequency with Poisson's Ratio

Mu	0.00	0.05	0.10	0.15	0.20	0.25	0.30
s	0.71	0.69	0.67	0.64	0.61	0.58	0.53
1/s	1.41	1.45	1.50	1.56	1.63	1.73	1.87

The corner frequencies of P waves are 1.4 times higher than on the average than those of S waves for small earthquake at focal depths of 30 km to 50 km in the northern part of Honshu, Japan [12]. P wave corner frequencies are 1.7 higher than S wave corner frequencies for Oroville, California aftershocks [13]. The ratio of P-wave corner frequency and S-wave corner frequency is also mentioned as 1.5 by other researchers [14]-[15]-[16].

Many of observations have shown longer pulse width, or lower corner frequencies, of S waves than of P waves for small to larger earthquakes. P wave corner frequency is higher than S wave frequency for the majority of earthquakes despite the region, size and depth of earthquakes [17]. Therefore, the variation in the ratio of the P-waves corner frequency and S-wave corner frequency of the findings of many researchers could be explained due to the variation in Poisson's ratio of the source rock.

The ratio of the P-waves corner frequency and S-wave corner frequency, which is the ratio of the P-wave velocity and S-wave velocity, increases with the increase in the Poisson's ratio of the source rock of the earthquake fault, or increase in value of $1/s$, mainly for Poisson's ratio source rock varying from 0.10 to 0.20 (Fig. 2). Because the P-wave velocity is higher than the S-wave velocity, the corner frequency due to interference effects is higher for P-waves than for S waves [18]. In this case, the dynamic soil mass due to the vertical component of the earthquake is equal to that due to the horizontal component of the earthquake.

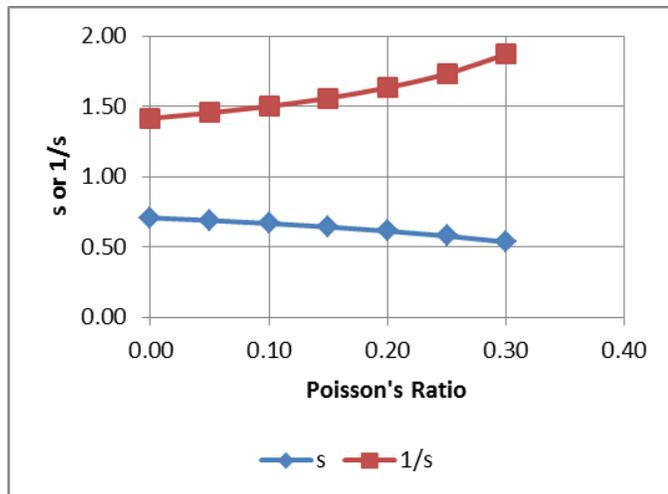


Fig. 2 Variation of the ratio of P-wave corner frequency and S-wave corner frequency, $1/s$, with Poisson's Ratio.

Near the source of an earthquake, ground motion is characterized mainly by source spectra, only modified by rupture dynamics. The P-wave spectrum has a higher corner frequency than that of S-wave. P and S corner frequencies gradually shift to lower frequencies as waves propagate away from the source due to differentially stronger attenuation of higher frequencies. Consequently, the vertical motion will be modified at a faster rate [9].

IV. LIQUEFACTION POTENTIAL AND LATERAL SPREADING

The total masses of the structure and the foundation system are normally supported directly or indirectly by the dynamic soil mass in earthquake through the foundation system which can be shallow or deep foundations. The total mass of the structure-foundation-soil system for earthquake cases in vibration analyses based on the work by Truong [6, 7 and 8] could be represented by

$$m_T = m_{St} + m_f - \frac{A_f \sqrt{\rho G}}{\omega_x} - \frac{A_f \sqrt{\rho G}}{\omega_z s} \quad (11)$$

Where m_T = total mass, m_{St} = mass of the structure, m_f = footing mass, and A_f = Area of the foundation in contact with soil.

The third and fourth terms on the right hand of the equal side are the dynamic soil masses for horizontal and vertical directions, respectively.

For many different soil layers, the dynamic soil mass of the first soil layer normally could be added to the total mass of the structure-foundation-soil if the first soil layer settled the same time with the foundation whether horizontal vibration or vertical vibration due to earthquakes occurs. In this case, the dynamic soil mass of the first soil layer could be called as an added soil mass. The total thickness of the different soil layers influenced by vibration increases with the decrease in the circular frequency of the vibration (Eqs. 1, 7 and 8).

For earthquakes with horizontal vibrations and no vertical vibrations, if the top 2 soil layers settled with the foundations, so the top two dynamic soil masses becomes two added soil masses, then (11) becomes:

$$m_T = m_{St} + m_f + \sum_1^2 \frac{A_f \sqrt{\rho_i G_i}}{\omega_{xi}} - \sum_2^n \frac{A_f \sqrt{\rho_i G_i}}{\omega_{xi}} \quad (12)$$

Similarly, for earthquakes with vertical vibrations and no horizontal vibrations, if the top 2 soil layers settled with the foundations, then (11) becomes:

$$m_T = m_{St} + m_f + \sum_1^2 \frac{A_f \sqrt{\rho_i G_i}}{\omega_{zi}} - \sum_2^n \frac{A_f \sqrt{\rho_i G_i}}{\omega_{zi}} \quad (13)$$

The dynamic soil mass increases with the increase in the density of the soil, especially for partially or fully saturated soils. So, the fully or nearly saturated soils can cause noticeably damage to the structures than the dry soils. Water can be considered as the soil lubrication for the lateral spreading or liquefaction, and seismic methods which measure the travel times of the compression waves in the soil will often identify the velocity of the compression wave in water than in the soil structure.

According to Special Publication 117A [19], 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. Note that project development, changes in local or regional water management patterns, or both, can significantly raise the water table or create zones of perched water.

The movement of the horizontal dynamic soil mass is also considerably facilitated by the presence of an initial locked-in static shear stress (Seed et al. [20], and Normandeau et al. [21], especially for locations near slopes, rivers, and oceans, and could break even reinforce concrete piles during strong earthquakes as well shown in the literature, e.g. Yasuda et al. [22].

Note that (i) the maximum lateral acceleration causing horizontal dynamic soil mass is generally almost twice the maximum vertical acceleration; for example, in 1987, Whittier fault with Richter magnitude of 6.1, the maximum lateral and vertical accelerations are 0.45g and 0.20g, respectively; (ii) the largest horizontal acceleration of 1.24g was experienced at Pacoima dam due to the San Fernando Earthquake with the Richter magnitude of 6.4 to 6.6 in 1971, and (iii) the largest ground acceleration of the offshore quake has been recorded about 1.85g for the Cape Mendocino fault with the Richter magnitude of 7.0 in 1992.

Two cases that could cause a structure to collapse by the failure of its foundation when (i) the large amount of dynamic soil mass underneath the foundation system is horizontally moving away from the structure causing excessive settlement to structure even when the field conditions indicate there was only partial saturation of a dense soil, and therefore liquefaction alone is a very unlikely explanation, as called as "seismic fluidization" by Richards et al. [23]-[24], or lateral spreading by Ishihara et al. [2] for saturated sand cases, and (ii) liquefaction for cases with and without lateral spreading when the mean effective stress in a saturated soil reduces to zero, when the frequency of the structure-foundation-soil system has reached a certain value, and the structure also collapses when the structure-foundation-soil system has its frequency over the value of the frequency that causes the total mass is equal to zero or negative. The latter can be called the resonant failure case for any particular structure in consideration.

One method which has been suggested for preventing liquefaction is to blow compressed air into the ground for lowering the degree of saturation of ground water in the protection zone where tiny air bubbles are to be mixed in down to such a level as liquefaction of the zone of ground does not occur at the time of violent earthquake. But, the vertical

dynamic soil mass could (i) increase the degree of saturation by strong vertically shaking the air bubbles out of the soil at the time of the earthquake, especially for cases with cohesionless soils, and (ii) damage the air compressors. Note also that there is also some excessive settlement taking place due to the horizontal movement of the horizontal dynamic soil mass. Truong [7] has showed that the increase in percent of air bubbles could also reduce the height of the tsunamis, save human lives and properties.

V. DYNAMIC AMPLIFICATION FACTORS AND DYNAMIC ATTENUATION FACTORS

Effects of different soil and rock layers on the response to earthquakes have been investigated by determining ground amplifications with the expressions of the dynamic soil masses and dynamic rock masses. The circular frequency of the corner frequency of earthquakes is used in the expressions of the dynamic soil masses and dynamic rock masses.

In general, the harder the materials the higher the response due to earthquakes is. For the same thicknesses of rock and soil, the response of the rock is normally greater than the response of the soil by using the same corner frequency. For instance, for the same Poisson's ratio of 0.3 and the same corner frequency of 0.015 HZ, the amplification factor is 4.84, for the shear wave velocities of soil and rock of 310 m/s and 1500 m/s, respectively.

The vertical and horizontal the combined dynamic site-amplification-attenuation factors have been defined as "submitted for publication" [25]; and with no dynamic attenuation factor γ in [8]; respectively.

$$F_{Acz} = \frac{A_r \sqrt{G_r \rho_r}}{A_s \sqrt{G_s \rho_s}} \frac{f_s s_s}{f_r s_r} e^{-\left(\frac{2\pi f s}{V_s}\right)} \quad (14)$$

$$F_{Acx} = \frac{A_r \sqrt{G_r \rho_r}}{A_s \sqrt{G_s \rho_s}} \frac{f_s}{f_r} e^{-\left(\frac{2\pi f}{V_s}\right)} \quad (15)$$

Or

$$F_{Acz} = R_{Ars} R_{Grs} R_{\rho rs} R_{fsr} R_{ssr} e^{-\left(\frac{2\pi f s}{V_s}\right)} \quad (16)$$

$$F_{Acx} = R_{Ars} R_{Grs} R_{\rho rs} R_{fsr} e^{-\left(\frac{2\pi f}{V_s}\right)} \quad (17)$$

Where f = frequency of the medium, i.e. for soil or for rock layer. R = ratio of the same appropriate parameters for rock and soil, e.g. R_A = ratio of fault area and soil area; subscripts rs and sr are for rock and soil and soil and rock. The expression of site-amplification factor from Quarter-Wavelength Method, which is a similar form with (15), has been also presented by Hashash et al. [26].

The product of R_{Grs} and $R_{\rho rs}$, which has been defined as the amplification factor by [27], is independent with the frequency

of the earthquake. The site amplification factor increases with the increase in the fault area; shear modulus, density and Poisson's ratio of rock layer; and Poisson's ratio and frequency of soil layer.

Site amplification factors at frequencies of 1.5, 3, 6, and 12 Hz were determined for 132 stations of the USGS seismic network in central California from coda waves of 185 local earthquakes in this area using a recursive stochastic inversion method. The site amplification at a station is systematically related to the geology underlying that station. The site amplification is high for young, Quaternary sediments and decreases with increasing geologic age at all frequencies between 1.2 and 12 Hz. The rate of decrease varies with frequency where site amplification at low frequencies shows a faster rate of decrease with age than at higher frequencies [28].

The combined dynamic amplification-attenuation factor could substantially increase if the frequency of the earthquake is equal to the frequency of the soil or rock layers. The expressions of vertical and natural frequencies of the soil or rock layers based on the dynamic soil masses have been presented and compared with those of other researchers [29].

VI. DYNAMIC SOIL HEIGHTS AND DYNAMIC EXCESS PORE WATER PRESSURES

The dynamic soil or rock heights based on the vertical and horizontal dynamic soil masses, which are the thicknesses of the soil or rock layer under the influence of the earthquakes from the focal depth, are determined for the vertical and horizontal vibrations [6]-[8], respectively.

$$h_z = \frac{V_s}{\omega_z s} \quad (18)$$

$$h_x = \frac{V_s}{\omega_x} \quad (19)$$

If the ground water table is very high, e.g. near or at the ground level, the dynamic soil heights become the dynamic excess pore water pressures. The vertical and horizontal dynamic liquefaction factors (DLFs) have been proposed by "unpublished" [29] as follows:

$$L_z = \frac{h_{ez} \gamma_w}{z \gamma_t} = \frac{V_{saw} \gamma_w}{s \omega_z z \gamma_t} \quad (20)$$

$$L_x = \frac{h_{ex} \gamma_w}{z \gamma_t} = \frac{V_{saw} \gamma_w}{\omega_x z \gamma_t} \quad (21)$$

Where h_e = dynamic excess pore water pressure, subscripts z and x are for vertical and horizontal components of an earthquake, γ_t = total unit weight of soil above the ground water table, and V_{saw} = the shear wave velocity of the solid-air-water (SAW) mixtures.

The vertical effective stress of the soil is equal to zero when the vertical or horizontal dynamic liquefaction factor (DLF) is equal to 1. The dynamic liquefaction factor decreases with the decrease in the shear wave velocity of the solid-air-water (SAW) mixtures. The shear wave velocity substantially decreases of the solid-air-water (SAW) mixtures with the small increase in the percentage of air bubbles in the solid-air-water (SAW) mixtures, especially in the low range of percentage of air bubbles from 0.0 to 5% [7]-[9]-"submitted for publication" [30]-[31]-[32]. Therefore, the effective stress greatly increases with the small increase in the percentage of air bubbles in the solid-air-water mixtures. Note that tests were conducted for specimens with different initial soil suctions or initial saturation and the same dry density under undrained conditions for both air and water; unsaturated sand specimens lost their effective stress under cyclic loading even if the degree of saturation is about 80% [33]. The maximum excess pore water pressure ratio reaches 97% in some layer at a site where the deformation of soil increases rapidly, the site is recognized as complete liquefaction no matter what the depth and the thickness of the liquefiable layer will be [34].

The vertical and horizontal dynamic excess pore water pressure for soil profiles with three layers of soil or rock, e.g. hard rock, weathered rock and soil layers, can be defined as

$$h_e = \frac{H_s h_{s2z}}{(H_r / I_{rs2}) + (H_{wr} / I_{rwr}) + (H_{s3} / I_{s3s2}) + H_{s2}} \quad (22)$$

Where H = thickness of soil or rock; subscripts r, wr, s1, s2, s3 and F are for rock, weathered rock, soil No.1, soil No.2, soil No.3 and earthquake fault, respectively; I = dynamic impedance factor which is the ratio of dynamic rock height to weathered rock height or dynamic soil height; subscripts rwr, rs2 and s are for rock to weathered rock, rock to soil No.2, and soil No.3 to soil No.2, respectively.

The relationship between the dynamic liquefaction factors and the moment magnitudes can be determined based on the following relationships between the corner frequency and the moment magnitude proposed by [35] or [36], respectively.

$$M = \frac{\Delta \sigma V_s^3}{8.47 f_c^3} \quad (23)$$

$$f_c = 4.9(10^6) V_s \left(\frac{\Delta \sigma}{M} \right) \quad (24)$$

Where $\Delta \sigma$ = Drop Stress, e.g. 100 bar; M = moment magnitude, V_s = Shear wave velocity of source rock in km/sec, and f_c = corner frequency.

VII. RELATIONSHIP BETWEEN DYNAMIC LIQUEFACTION FACTOR AND MOMENT MAGNITUDE

For a five-layer soil profile, source rock, weathered rock and 3 soil layers; the properties of five layers of soil or rock are shown in Table 2. Soil No.1 is the soil above the ground

water level, e.g. 15m; soil No.2 is the liquefiable soil; and the focal depth and the moment magnitude of the Loma Prieta earthquake in 1989 caused by a slip along the San Andreas Fault are 18 km and 7.0, respectively. The vertical and horizontal dynamic liquefaction factors and moment magnitude due to vertical or horizontal components of an earthquake decrease from 3.75 to 0.75, from 2.77 to 0.55, from 7.5 to 6.1 with the increase in vertical corner frequency and horizontal corner frequency, from 0.1 to 0.5 Hz, and from 0.06 to 0.32Hz, respectively (Table 3, and Figs.3 and 4).

The horizontal corner frequency is equal to the product of the vertical corner frequency and s. Note that the signals in the range from 0.01 Hz to 0.5 Hz rose exceptionally three hours before the Loma Prieta earthquake (Wikipedia- The Free Encyclopedia); the vertical and horizontal corner frequencies of the moment magnitude of 7.04 are 0.17 Hz and 0.11 Hz, respectively.

Table 2 Properties of five soil or rock layers

Layer	Soil 1	Soil 2	Soil 3	w.Rock	Rock
Density	1.9	1.992	2	2.7	2.8
P. Ratio	0.333	0.495	0.45	0.15	0.15
Velocity	360	133.8	600	800	3600
H, m	15	285	600	1100	16000

Table 3 Variations of dynamic liquefaction factors and moment magnitudes with corner frequencies

fcz	0.1	0.13	0.17	0.2	0.3	0.4	0.5
fcx	0.06	0.08	0.11	0.13	0.19	0.26	0.32
Lf _z	3.75	2.88	2.2	1.87	1.25	0.94	0.75
Lf _x	2.77	2.13	1.63	1.39	0.92	0.69	0.55
Mz	7.5	7.27	7.04	6.9	6.55	6.3	6.1
Mx	7.5	7.27	7.04	6.9	6.55	6.3	6.1

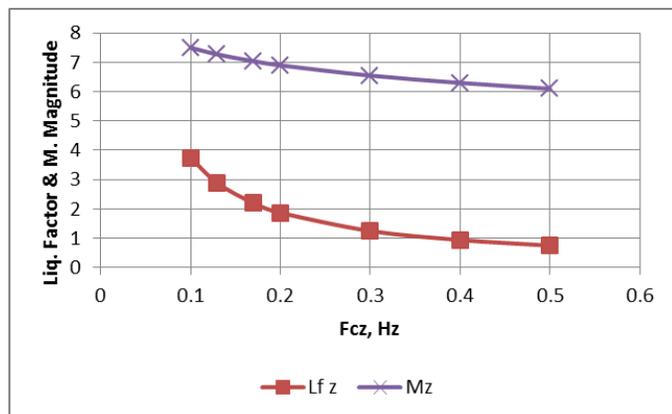


Fig. 3 Variations of the vertical dynamic liquefaction factor and moment magnitude with the corner frequency.

The relationship between the horizontal dynamic liquefaction factor and the moment is in the exponential form (Fig. 5), as

$$L_x = 0.0005 e^{1.158M} \tag{25}$$

The square of the correlation coefficient is equal to 1.0.

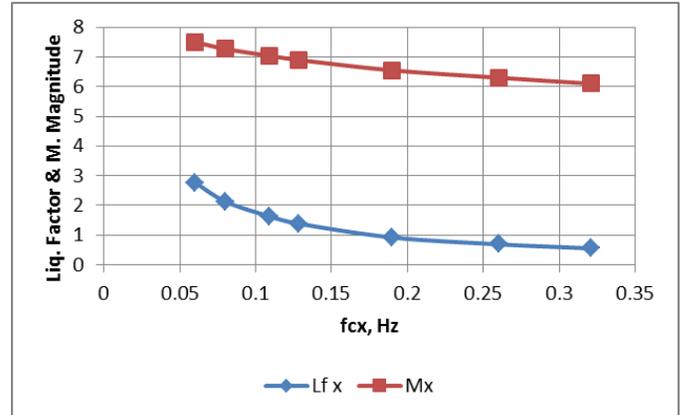


Fig. 4 Variations of the horizontal dynamic liquefaction factor and moment magnitude with horizontal corner frequency

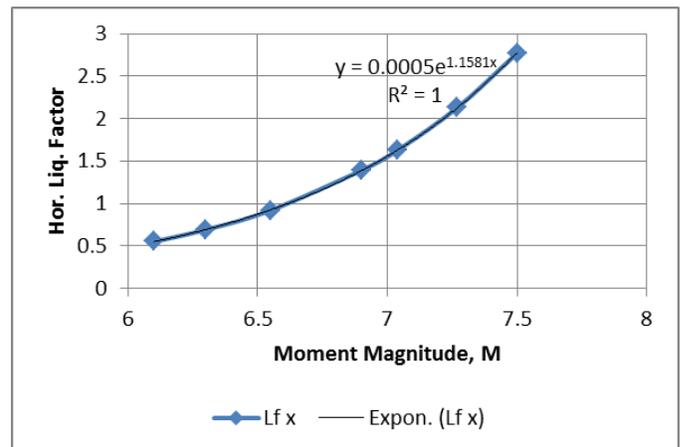


Fig. 5 Relationship between the horizontal dynamic liquefaction factor and moment magnitude

VIII. RELATIONSHIP BETWEEN DYNAMIC LIQUEFACTION FACTOR AND DEPTH OF GROUND WATER TABLE

The vertical and horizontal dynamic liquefaction factors decrease from 6.8 to 1.05, from 5 to 0.78 with the increase in the depth of soil No.1 from 5 m to 30 m, which is also the depth of the ground water table, respectively (Table 4 and Fig. 6). The vertical and horizontal liquefaction factors become less than 1 when the depth of the ground water table is greater than 32 and 25 m, respectively. Note that the increase in thickness of soil No.1 decreases the thickness of soil No.2 or the thickness of liquefiable soil.

The liquefaction due to the horizontal vibration did not take at the depths of 25 m and 30 m, which are the depth of

the ground water table, because the liquefaction factors are 0.95 and 0.78, respectively. In other words, the effective stress at the depth 25 m or 30 m is not equal to zero or greater than zero.

The relationship between the horizontal dynamic liquefaction factor and the depth of the ground water table is in power form, as follows:

$$L_x = 26.829 D^{-1.038} \tag{26}$$

The square of the correlation coefficient is equal to 0.9998.

Table 4 Variations of vertical and horizontal dynamic liquefaction factors with the depth of ground water table

hs1	5	10	15	20	25	30
Lfz	6.8	3.4	2.2	1.6	1.28	1.05
Lfx	5	2.5	1.6	1.2	0.95	0.78

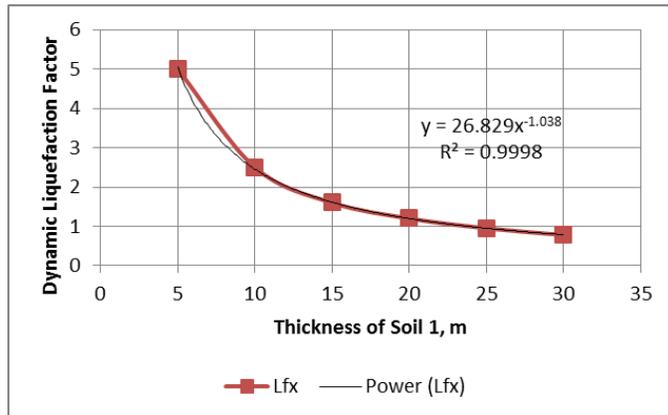


Fig. 6 Relationship between the horizontal dynamic liquefaction factor and depth of the ground water table.

IX. RELATIONSHIP BETWEEN DYNAMIC LIQUEFACTION FACTOR AND THICKNESS OF LIQUEFIABLE SOIL

The vertical and horizontal dynamic liquefaction factors decrease from 1.35 to 0.66, from 1.08 to 0.57 with the decrease in the thickness of the liquefiable soil from 175 m to 85 m, which is also the depth of the ground water table, respectively (Table 5 and Fig. 7). The vertical and horizontal liquefaction factors become less than 1 when the depth of the ground water table is greater than 125 and 155 m, respectively.

Table 5 Variations of vertical and horizontal dynamic liquefaction factors with the thickness of liquefiable soil

hs2	175	165	155	145	135	125	85
Lfz	1.35	1.27	1.2	1.12	1.04	0.97	0.66
Lfx	1.08	1.03	0.98	0.92	0.86	0.81	0.57

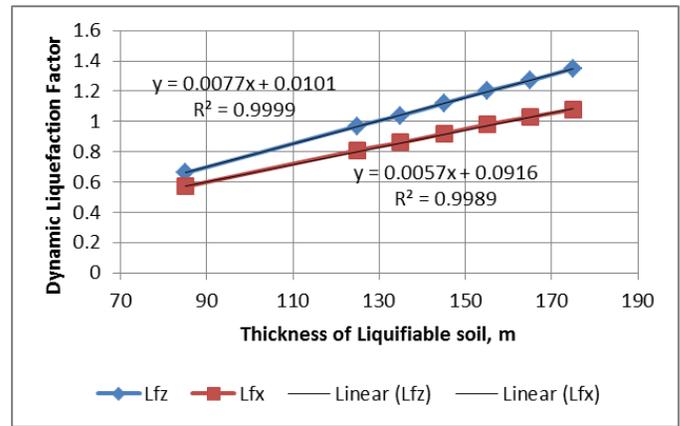


Fig. 6 Relationships between the vertical and horizontal dynamic liquefaction factors and thickness of liquefiable soil.

The relationships between the vertical and horizontal dynamic liquefaction factors with the thickness of the liquefiable soil, respectively, are

$$L_z = 0.0077h + 0.0101 \tag{27}$$

$$L_x = 0.0057h + 0.0916 \tag{28}$$

The vertical and horizontal squares of the relation coefficients are 0.9999 and 0.9989, respectively.

The soil becomes liquefiable if the thickness of the liquefiable soil is less than 125 m for and 155 m for vertical and horizontal components of earthquakes, respectively. The vertical moment magnitude or the horizontal moment magnitude is equal to 7.04, as for the Loma Prieta earthquake.

X. CONCLUSIONS

The dynamic soil masses for horizontal and vertical directions due to earthquakes could cause the failure of the structure and foundation system by excessive vertical settlement, liquefaction with and without lateral spreading, and resonant condition.

In some top soil layers in multiple soil layers, the dynamic soil masses could become the added soil masses if the soils in the top soil layers settled down with the foundations due to earthquakes.

The angle of the earth movement from the horizontal direction increases from 67.5 degrees to 82.0 degrees with the increase in Poisson's Ratio from 0.10 to 0.48 when the earthquake has the value of horizontal circular frequency is twice that of the vertical circular frequency,

The introduction of the air bubbles into the soil at the time of violent earthquake could substantially reduce the damages by earthquakes by preventing the liquefaction to occur.

For the same thickness, Poisson' ratio and corner frequency, the response of the rock layer is about 3 or 4 times that of the

soil layer, especially due to higher value of the wave velocity of the rock layer compared to that of the soil layer.

The ratio of the P-wave corner frequency and S-wave corner frequency could be equal to the ratio of the P-wave velocity and S-wave velocity.

The dynamic liquefaction factor increases with the increase in the moment magnitude and thickness of the liquefiable soil; with decrease in the corner frequency and the depth of the ground water table. The higher dynamic liquefaction factor, the higher the risk of the liquefaction is; and the dynamic liquefaction factor is equal to 1 when the effective stress is equal to zero.

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