13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2661

SOIL LIQUEFACTION INDUCED BY RAYLEIGH WAVE

Jie CUI [1], Fu-Lu MEN [2] and Xiangjian WANG[3]

SUMMARY

In this paper, after a brief introduction on the research results obtained by the authors on wave propagation in water saturated soils, the discussion is made on the effect of seismic wave type on sand liquefaction potential. Based on some macroscopic evidences gained in actual earthquake field investigation and a preliminary theoretical analysis, it is pointed out by authors that Rayleigh waves should be an essential cause of liquefaction for the fields beyond the epicentral region with saturated sand deposits at shallow depths. By using single and two phase medium model, authors analyzed the characteristics of Rayleigh wave propagation and its effects on the sand liquefaction, and suggested some further works to be done aiming at the development of a new comprehensive method of evaluating liquefaction potential. Finally, a preliminary guideline for microzonation of liquefaction on the basis of Rayleigh wave field survey and analysis is presented.

INTRODUCTION

In the last decade or so we have made a series of studies [1-3] on wave propagation in water saturated soil layer and obtained some useful qualitative and quantitative results which are of benefit to the further understanding of several interesting phenomena of saturated soil layers on seismic wave propagation and ground motion. We have also touched soil liquefaction problems.

Theoretically speaking, sand liquefaction in actural fields during earthquakes must be caused by the seismic waves transmitted from the hypocenter movement. In the last decades, it has been customarily attributed to the densification tendency of loose sand under a vertically upward transmitted shear wave from the baserock, inducing the accumulation of residual pore water pressure. Up to the present, a great number of publications on evaluation methods of liquefaction have been available. They, as is well known, may be divided into four categories including (1) Seed simplified method; (2) effective stress response analysis method; (3) probabilistic method; and (4) empirical method.

We have made some studies (4) on the mechanism of sand liquefaction and the analysis of its dynamic process of development, based on a theory of two phased media, taking account of their nonlinear constitutive relations, dilatancy, rigidity degradation, etc. For one-dimensional problems, a set of 6 differential equations with 6 variables is concluded and the entire process of the 6 variables, as a function of time, may be obtained simultaneously by solving this set of equations, which gives a clear picture of the mechanism of liquefaction. The analysis has, however, made also for a horizontal shear wave input.

A question we may naturally arise: what type of waves is prone to cause liquefaction? Is it right enough to attribute liquefaction to the action caused by shear body waves only, as usually dominated in the previous publications in this field? In what follows a tentative answer will be made, based on a survey of observation evidences in past earthquakes and a preliminary numerical analysis.

EFFECT OF WAVE TYPE

Fang and Wang [5] have obtained some aerial photographies over the locus of sand boils on the ground surface after the Tangshan earthquake, giving out a broad surfacial outlook of possible liquefaction in the vast region and revealing further the wave motion patterns of ground and groundwater. It was suggested that there should be wave types other than those vertically upward transmitted shear waves, namely, surface waves that could induce liquefaction.

It should be pointed out that, due to the lack of in-situ observation data of water pore pressure during earthquakes, sand boils on the ground surface are commonly regarded as the main evidence of liquefaction. However, as Scott [6] and Men [7] have shown by small model tests on shaking table that: (a) not only horizontal shaking but also instantly impulsive pressure loaded to pore water (for example through a pipe filled with water and connected to the sand box for testing) may cause liquefaction to occur, or, in other words, there may be two types of liquefaction namely densification liquefaction and hydraulic liquefaction as named by Men [7]; (b) sand boil and water spout would not be necessary to indicating an emergence of liquefaction or, in other words, they would by not the unique evidence of liquefaction. Therefore it is reasonable to state that sand liquefaction and sand boil in fields may be caused either by shear waves loading, making densification tendency of soils, or by pressure waves loading to soils and / or to ground water directly, increasing pore water pressure, and that sand cones' presence, size, quantity, and location do not definitely indicate where and at what depth the liquefaction has exactly occurred, especially the absence of sand cones does not absolutely mean no liquefaction.

But how about the surface waves? There are two main types of surface waves that may be closely related to liquefaction, namely Love waves and Rayleigh waves (shortly L wave and R wave in the following). L waves exist in a softer layers overlaying a harder layer or semi-space, formerly similar to SH body waves in many respects and it likely induce shear stresses with almost same order in the top layer (for example see Wolf [8]). Therefore, we will put emphasis only on the effect of R waves in what follow.

From field observations it is well known that R wave will play a greater part than body waves for shallow earthquakes because of its smaller attenuation, longer travel distance, and larger amplitude. From the epicenter to a distance beyond which R waves start to present is, though, not yet very definite as suggested not unanimously in the literature to be either 0.6-5 times of the source depth and / or 20-50km. If we take a mean value to be, for example, 35km, then the vast area of liquefaction in the 1986 Tangshan earthquake, China, would mainly be in the area where R waves played greater role. In that earthquake, Chai (9) observed that the water table variation in the wells of Beijing Wali region was close to the travel time curve of R waves and therefore it was induced by R waves. Shi (10) noted a interesting fact through field investigations that the anomalistic region of ground water pressure in shallow wells in Beijing Shiji was just the high intensity region of sand boils. So Men (11) was the first opinion that these facts showed indirectly that the water table variations in wells and the sand boils on ground surface were not due to S body waves, and the liquefaction in Tangshan earthquake was certainly caused by the R waves. This conclusion may reasonably extend to almost all the earthquakes of shallow depth and the sites with shallow deposited saturated sand layers.

In the following, let us make a tentative analysis using a total stress method based on the theory of elasticity and an effective stress method based on a theory of two phased poroelasticity to see how the R wave plays a greater role than the S body wave.

TOTAL STRESS METHOD

A rectangular coordinate system and the displacement components are shown in Figure 1. We deal with the in-plane problems in X-Z plane. And we use the potential functions Φ, $\boldsymbol{\Phi}$, and then:

$$u = \frac{\partial \Phi}{\partial x} + \frac{\partial \varphi}{\partial z} \qquad w = \frac{\partial \Phi}{\partial z} - \frac{\partial \varphi}{\partial x}$$

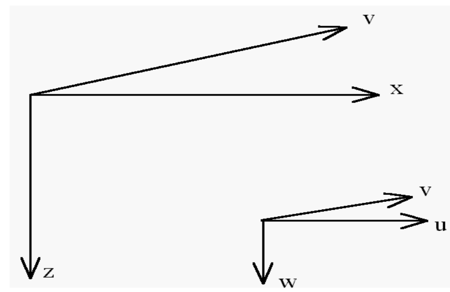

Fig.1 The corodinate system and displacement componets

And we could get:

$$\Phi = A_1 e^{-qz+i(Nx-\omega t)}, \qquad \varphi = A_2 e^{-qz+i(Nx-\omega t)} \tag{1}$$

So, omitting the detailed derivation, we only write out the principal results on the displacement and stress for R wave based on the theory of elasticity as follows:

$$u = iA_1 NU(z)e^{i(Nx-\omega t)} \tag{2}$$

$$w = A_1 NW(z)e^{i(Nx-\omega t)} \tag{3}$$

$$\sigma_z = A_1 N\{(\lambda + 2u)W'(z) - \lambda NU(z)\}e^{i(Nx-\omega t)} \tag{4}$$

$$\tau_{zx} = \mu A_1 Ni\{W(z)N + U'(z)\}e^{i(Nx-\omega t)} \tag{5}$$

$$\frac{\partial \sigma_z}{\partial z} = A_1 N\{\ \lambda + 2\mu\ )\ W''(z) - \lambda NU'(z)\}e^{i(Nx-\omega t)} \tag{6}$$

Where: u, w: displacement components in x and z direction, respectively, σ_z , τ_{zx} : stress components in x plane, λ , μ: Lame coefficient, ω: circular frequency, $C_R = \omega / N$: Rayleigh wave speed, N: constant related to the wave number.

For the Possion ratio v equal to 0.25, for example, $U(z)$ and $W(Z)$ are of the form:

$$U(z) = -e^{-0.8475(NZ)} + 0.5773e^{-0.3993(HZ)}$$

$$W(z) = 0.8475e^{-0.8475(HZ)} - 1.4679^{-0.3993(HZ)}$$

The above form may make Esq. (4)--(6) for stresses evaluable.

As a concrete example we conducted some computations for these quantities at different depths, wave lengths and wave speeds. Denoting L wave length of R wave; $M = z/L$; p soil density; Cs shear wave speed; C_R=0.9149 Cs for v=0.25; and noticing that A_1 is equivalent to 1/0.62 times of the displacement amplitude of ground surface, the results of three cases are listed in Table 1 where A_1 was taken to be 1 meter.

Table 1. Stress value without multiplier $e^{NX-\omega t}$ for single-phased media ($I=\partial\sigma_Z/\partial Z$)

Z (L)	C_S=286(m/s) L=140(m)			C_S=286(m/s), L=43.5(m)			C_S=174(m/s), L=140(m)			C_S=174(m/s), L=43.5(m)		
	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m
0.05	66.3	45.2	5.20	686.6	467.8	173.51	24.5	16.7	1.93	254.1	173.1	64.22
0.10	109.4	74.5	3.28	1132.9	771.8	109.47	40.5	27.6	1.22	419.3	285.7	40.52
0.15	135.6	92.4	1.89	1404.4	956.7	63.12	50.2	34.2	0.70	519.8	354.1	23.36
0.20	149.6	101.9	0.90	1550.0	1056.0	30.03	55.4	37.7	0.33	573.7	390.9	11.11
0.25	155.1	105.7	0.20	1606.6	1094.5	6.80	57.4	39.1	0.08	594.7	405.1	2.52
0.30	154.6	105.3	-0.27	1601.2	1090.8	-9.12	57.2	39.0	-.10	592.7	403.8	-3.38
0.60	104.9	71.5	-0.94	1087.0	740.5	-31.37	38.8	36.5	-.35	402.3	274.1	-11.61
1.00	44.9	30.6	-0.50	465.1	316.9	-16.73	16.6	11.3	-.19	172.2	117.3	-6.19

It can be seen from the Table that $\partial\sigma_Z/\partial Z$ has maximum values within the depth range from ground surface to 0.2L and shear stresses τ_{ZX} has also rather large valise between 0.05L and 1.0L and gets a maximum at 0.25L. Taking the Tangshan earthquake as an example, the wave length may be taken to be 40m (see plate7 0f [5]) approximate to the Case 4 of Table 1.

The vertical stress gradient at z=0.2L¡Ö8.7m was

$$I=\frac{\partial\sigma_Z}{\partial Z}(Z=8.7m)\approx 1.11t/m^3$$

While the critical hydraulic gradient Ier was likely abut 1.0t/m3 so we have:

$$I>I_{er}$$

According to the theory of consolidation of soil mechanics and the theory of discontinuous wave presented in [12] by Men, a suddenly applied lading should be subjected totally by pore water at the initial time instance and therefore it may be predicted that a hydraulic gradient of same order would be induced also in the pore water, which caused quick sand conditions in the top soil layer above the depth 8.7m. This means σ_Z could already cause sand boils at some instance. At the same time, the shear stress reached 573 kpa (~5.3kg/cm2) or so, which may make a densification liquefaction and sand boils possible.

Note that the above results were obtained for the R wave having amplitude of 0.62m and wave length 43.5m, whereas τ_{XZ} and $\partial\sigma_Z/\partial Z$ will be much greater when L becomes smaller.

EFFECTIVE STRESS METHOD

As we know that soil is composed of two phases, in the following, to describe the effect of water, the two-phase model will be used to analyze the soil liquefaction.

We could use the two-phase model describing the soil dynamics as following:

$$r_1 \frac{\partial^2 \vec{u}}{\partial^2 t} = (\lambda + v)\mathrm{grad}(\mathrm{div}\vec{\mathrm{u}}) + \mu\Delta\vec{u} + (1 - f)\mathrm{grad}\sigma_{\mathrm{w}} + b\left(\frac{\partial\vec{v}}{\partial t} - \frac{\partial\vec{u}}{\partial t}\right)$$

$$r_2 \frac{\partial^2 \vec{v}}{\partial^2 t} = f\mathrm{grad}\sigma_{\mathrm{w}} - b\left(\frac{\partial\vec{v}}{\partial t} - \frac{\partial\vec{u}}{\partial t}\right)$$

Where $\bar{u}$, $\bar{v}$: displacement vector of solid and liquid phase, respectively; f: porosity, k: permeability, $b=f^2/k$; $y_1 = y_s(1-f)$, $y_2 = y_w f$, y_w , y_s : density of liquid and soil grain, respectively; σ_w : pore pressure.

For the plane problem as the Fig.1, and the constitutive as following:

$$\begin{cases} \sigma_x = \lambda\varepsilon + 2\mu\varepsilon_x \\ \sigma_z = \lambda\varepsilon + 2\mu\varepsilon_z \\ \tau_{xz} = \mu\gamma_{xz} \\ \sigma_w = Q_2\varepsilon + Qe \end{cases}$$

Where λ , μ -- Lame coefficient.

And

$$\varepsilon = \varepsilon_x + \varepsilon_z \text{£¬} e = \frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z} \text{£¬} \varepsilon_x = \frac{\partial u_x}{\partial x} \text{£¬} \varepsilon_z = \frac{\partial u_z}{\partial z}$$

Where Q_2 , Q_2 --two parameters, which could be gotten in the following two ways:

a. From $\frac{\partial\sigma_w}{\partial t}\frac{1}{E_w} = f\frac{\partial e}{\partial t} + (1-f)\frac{\partial\varepsilon}{\partial t}$,

then $Q_1 = fE_w \qquad Q_2 = (1-f)E_w$;

b. From Biot model, then $Q_1 = Q_2$

Finally we have the dynamics equations:

$$r_1\ddot{u}_x = \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} + (1-f)\frac{\partial \sigma_w}{\partial x} + b(\dot{v}_x - \dot{u}_x)$$
$$r_1\ddot{u}_z = \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{xz}}{\partial z} + (1-f)\frac{\partial \sigma_w}{\partial z} + b(\dot{v}_z - \dot{u}_z)$$
$$r_2\ddot{v}_x = \frac{\partial \sigma_w}{\partial x} - b(\dot{v}_x - \dot{u}_x)$$
$$r_2\ddot{v}_z = \frac{\partial \sigma_w}{\partial z} - b(\dot{v}_z - \dot{u}_z)$$

Introducing two pairs of displacement potentials ϕ_1 , φ_1 ; ϕ_2 , φ_2 ,

$$u_x = \frac{\partial \phi_1}{\partial x} + \frac{\partial \varphi_1}{\partial z}, \quad u_z = \frac{\partial \phi_1}{\partial z} - \frac{\partial \varphi_1}{\partial x}$$
$$v_x = \frac{\partial \phi_2}{\partial x} + \frac{\partial \varphi_2}{\partial z}, \quad v_z = \frac{\partial \phi_2}{\partial z} - \frac{\partial \varphi_2}{\partial x}$$

Then

$$r_1\frac{\partial^2 \phi_1}{\partial t^2} = [\lambda + 2\mu + (1-f)Q_1]\cdot \Delta^2\phi_1 + (1-f)Q_2\Delta^2\phi_2 + b\left(\frac{\partial \phi_2}{\partial t} - \frac{\partial \phi_1}{\partial t}\right)$$
$$r_2\frac{\partial^2 \phi_2}{\partial t^2} = fQ_1\cdot\Delta^2\phi_1 + fQ_2\cdot\Delta^2\phi_2 + b\left(\frac{\partial \phi_2}{\partial t} - \frac{\partial \phi_1}{\partial t}\right)$$
$$r_1\frac{\partial^2 \varphi_1}{\partial t^2} = \mu\cdot\Delta^2\varphi_1 - b\left(\frac{\partial \varphi_2}{\partial t} - \frac{\partial \varphi_1}{\partial t}\right)$$
$$r_2\frac{\partial^2 \varphi_2}{\partial t^2} = -b\left(\frac{\partial \varphi_2}{\partial t} - \frac{\partial \varphi_1}{\partial t}\right)$$

Suppose:

$$\phi_1 = A_1 e^{-sz} e^{i(kx-\omega t)}, \quad \varphi_1 = B_1 e^{-rz} e^{i(kx-\omega t)}$$
$$\phi_2 = A_2 e^{-sz} e^{i(kx-\omega t)}, \quad \varphi_2 = B_2 e^{-rz} e^{i(kx-\omega t)}$$

Then we have

$$\left(-Pk^2 + Ps^2 + r_1\omega^2 + i\omega b\right)A_1 + \left(-Qk^2 + Ps^2 - i\omega b\right)A_2 = 0$$
$$\left(-Ak^2 + As^2 - i\omega b\right)A_1 + \left(-Bk^2 + Bs^2 + r_1\omega^2 + i\omega b\right)A_2 = 0$$
$$\left(r_2\omega^2 + i\omega b\right)B_2 - i\omega b B_1 = 0$$
$$-i\omega b B_1 + \left(r_1\omega^2 + \mu r^2 - \mu k^2 + i\omega b\right)B_1 = 0$$

And we use:

$$\alpha_1^2, \alpha_2^2 = \frac{r_1 B + r_2 P + i\frac{bH}{\omega} \pm \left\{\left[Br_1 + \mathrm{Pr}_2 + i\frac{bH}{\omega}\right] - 4(PB - QA)\left(r_1 r_2 + \frac{r_1 + r_2}{\omega} ib\right)\right\}^{\frac{1}{2}}}{2\left[r_1 r_2 + (r_1 + r_2)\frac{b}{\omega} i\right]}$$

$$\beta^2 = \frac{\mu\left(r_2 + i\frac{b}{\omega}\right)}{r_1 r_2 + (r_1 + r_2)\frac{b}{\omega} i}$$

$$H = P + Q + A + B = \lambda + 2\mu + Q_2 + R = \lambda + 2\mu + E_w$$

Where: $\xi = \frac{k}{\omega}$.

Then:

$$s = k\left(1 - \frac{1}{\alpha_1^2 \xi^2}\right)^{\frac{1}{2}} \text{ »ò } s = k\left(1 - \frac{1}{\alpha_2^2 \xi^2}\right)^{\frac{1}{2}} \text{ £¬ } r = k\left(1 - \frac{1}{\beta^2 \xi^2}\right)^{\frac{1}{2}}$$

And stresses could be gotten as followings too:

$$\sigma_z = 2\mu k^2\left[1 - \frac{\lambda + 2\mu}{2\mu}\frac{1}{\alpha^2 \xi^2}\right]\phi_1 + 2\mu k^2 i\left[1 - \frac{1}{\beta^2 \xi^2}\right]^{\frac{1}{2}}\varphi_1$$

$$\tau_{xz} = \mu\left\{-2ik^2\left(1 - \frac{1}{\alpha^2 \xi^2}\right)^{\frac{1}{2}}\right\}\phi_1 + k^2\left(2 - \frac{1}{\beta^2 \xi^2}\right)\varphi_1$$

$$\sigma_w = -\left(\frac{Q_2 A_1}{\alpha^2 \xi^2} + \frac{RA_2}{\alpha^2 \xi^2}\right)\frac{\phi_1}{A_1}$$

From: $\sigma_z = \tau_{xz} = 0$, then:

$$\begin{vmatrix} 1 - \frac{\lambda + 2\mu}{2\mu}\frac{1}{\alpha^2 \xi^2} & i\left(1 - \frac{1}{\beta^2 \xi^2}\right)^{\frac{1}{2}} \\ -i\left(1 - \frac{1}{\alpha^2 \xi^2}\right)^{\frac{1}{2}} & 1 - \frac{1}{2\beta^2 \xi^2} \end{vmatrix} = 0$$

$$\left(1 - \frac{\eta^2}{2\beta^2 \xi^2}\right)\left(1 - \frac{1}{2\beta^2 \xi^2}\right) - \left(1 - \frac{1}{\alpha^2 \xi^2}\right)^{\frac{1}{2}}\left(1 - \frac{1}{\beta^2 \xi^2}\right)^{\frac{1}{2}} = 0$$

Where $\eta^2 = \frac{\lambda + 2\mu}{\mu}\frac{\beta^2}{\alpha^2}$.

Suppose $z = \dfrac{1}{\xi}$, then

$$z^6 - \frac{1+\eta^2}{\eta^2} 4\beta^2 z^4 + \left[\frac{(1+\eta^2)^2}{\eta^4} \cdot 4\beta^4 - \frac{8\beta^4}{\eta^4}\left(\frac{2\beta^2}{\alpha^2} - \eta^2 \right) \right] z^2 + \frac{16\beta^6}{\eta^4}\left(\frac{\beta^2}{\alpha^2} - \eta^2 \right) = 0$$

The above is Rayleigh equation. For a particular case, for example, when $b/\omega > 0$, it could be provide that the equation is a cubic equation with real coefficient and has one positive real root in range of 0 and min $(\alpha^2\ ,\beta^2)$.

Taking the same material parameters as used previously in the total stress method, shear velocity Cs=286, 174(m/s), wave length $L = 2\pi/l = 140\ ,87$, and 43.5 $y_s = 2t/m^3$, $y_w = 1t/m^3$, $v = 0.25$, and developing a numerical algorithm and computer program we obtain some results of σ_Z and τ_{XZ} as shown in Fig.2 The curves of τ_{XZ} σ_Z and σ_W for two-phased media with different L and the comparison of τ_{XZ} (right up) and σ_Z (right down) for single-phased and two-phased media with L=43.5m.

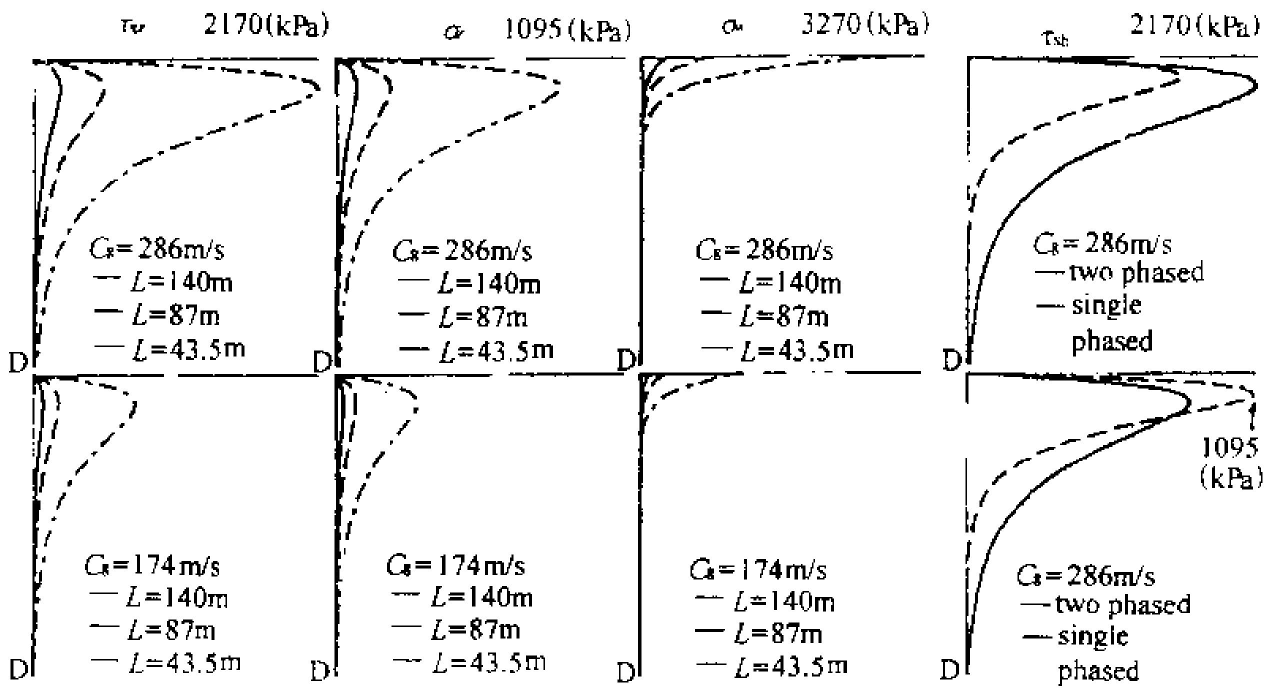

Fig.2 The curves of stress for two-phase media different L and the comparison of stresses

Fig.2 and table 2 show some numerical values for the cases of single-phased and two-phased media. It can be seen that τ_{XZ} are a little smaller and σ_Z a little larger for single-phased media than those for two-phased media but all are quite large for causing liquefaction, while in the latter σ_W has the greatest values, in comparison with τ_{XZ} and σ_Z, and exceed the sum of σ_Z and self weight stresses, enabling really liquefaction to occur at least within the top layer above 0.2L depth.

Table 2. Stress values without multiplier $e^{Nx-\omega t}$ for two-phased media

D (L)	C_S=286(m/s), L=140(m)			C_S=286(m/s), L=43.5(m)			C_S=174(m/s), L=140(m)			C_S=174(m/s), L=43.5(m)		
	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m	τ_{ZX} kpa	σ_Z kpa	I kpa/m
0.05	67.8	26.6	251.6	702.3	275.7	2606.0	25.1	9.9	93.1	260.0	102.0	964.6
0.10	117.6	46.2	200.5	1218.3	478.2	2076.6	43.5	17.1	74.2	450.9	177.0	768.6
0.15	153.4	60.2	159.8	1588.4	623.5	1654.8	56.8	22.3	59.1	587.9	230.8	612.5
0.20	178.1	69.9	1273	1845.0	724.2	1318.6	65.9	25.9	47.1	682.9	268.1	488.1
0.25	194.4	76.3	101.4	2013.4	790.3	1050.7	71.9	28.2	37.5	745.2	292.5	388.9
0.30	204.1	80.1	80.8	2113.8	829.7	837.3	75.5	29.6	29.9	782.4	307.1	309.9
0.60	191.0	75.0	20.7.	1978.9	776.8	214.4	70.7	27.8	7.7	732.5	287.5	79.3
1.00	128.0	50.2	3.4	1326.0	520.5	34.8	47.4	18.6	1.2	490.8	192.7	12.9

In summary, we may conclude from the field evidences and preliminary stress analyses, either total or effective, that R Waves would be main action for sand liquefaction especially in regions where saturated sand deposites at shallow ground below the ground surface. It can be imagined from the physical lack-ground that R wave really arises due to the presence of ground surface, inducing the interaction of P and SV waves and simultaneously leading to the presence of τ_{xz} and σ_z, and each of which has the magnitude order that can cause sand boils. Thus, the consequence of R wave must be greater than that of only P wave or of only SV wave provided with, of course, the same magnitude order. For single phased media, Wolf in his work [8] has provided certain computational curves of $|\tau_{\max}|$ due to R and SV waves, though for a different purpose, and shown R wave made much larger $|\tau_{\max}|$ than SV wave at upper depths.

And now our group are trying in series to analyze the characteristics of R wave, including its propagation in different boundary condition, constitutive and comparison between R wave and SH wave. And finially, a more detail analysis on the effect of R wave on liquefaction and some suggestion on the different characteristics with SH wave will present.

CONCLUTIONS AND DISCUSSIONS

If we recognize R waves being a main cause of sand liquefaction, how should we make microzonation of liquefaction potential for a vast region and what differences should be led in comparison with the current various methods in term of SH waves, SPT values, Cs values, etc. These, of course, are rather uneasy to answer to the knowledge at present time, as so far on the R wave field of certain earthquakes there have not been clear enough understanding and, besides, some empirical relations such as those of SPT, Cs etc. have not considered the wave type but only considered some macroscopic phenomena, such as sand boils and subsidence etc. Therefore we could present now some preliminary ideas and suggestions on the research direction in what follows:

(1) Make efforts to accumulate data on Raleigh waves, both observational and theoretical, in order to establish a reliable method that makes evaluations of real R wave fields of any earthquake possible.

(2) As an intermediate step make a slight change to those currently used methods set up on the basis of the rating of intensity, acceleration, etc. in which only horizontal shearing motions are considered to be important, by using a multiplier whose quantity must be greater than 1.0 and should be determined by evaluating and adding the effect of a suitable vertical ground motion. In this respect much effort has to be devoted in relation to R wave travel path, attenuation, reflection and refraction on discontincous interfaces, diffraction by topographical irregularities, etc.

(3) Some deeply theoretical investigations into the nature of R waves in two- phased media based on both the theory of linear poroelasticity and the nonlinear relations of sands should be conducted to provide a sound basis of making a completely new approach of micro zoning maps of liquefaction potential under R waves for the shallow deposits and under S and /or P waves for the deep deposits.

(4) Specially arranged experiments should be carried out to check the idea and theory.

It is obvious that we are dealing with a problem quite complicated but yet of much significance and that considerable effort, therefore, would be needed further to set up a logical system as well as a practicable approach of microzonation. At present we only may roughly mention some tentative guidelines for microzonation of liquefaction potential with shallow deposited saturated soils as follows:

1. Within the epicentral region (about 70km in diameter for instance) use is made of vertically upward transmitted S and / or P body waves.)

2. Beyond the epicentral region use should be made of R waves.

3. The current used methods of microzonation may overestimate the safety to some degree and a modified factor, greater than 1, should be added in, according to an estimation of the effect of the component of vertical motion in R waves, which will be made in the near future.

REFERENCES

1. Men, Fu-lu & Cui, Jie et al, Effect of saturated soil layers on seismic wave propagation. Acta Geophysical Sinica, 1992,Vol.35, No.4, P521-532.
2. Men, Fu-lu, On wave propagation in fluid-saturated porous media, Proc. Int. Conf. Soil Dyn. & Earth. Eng., Southampton, 1982,Vol.1,225-238.
3. Men, Fu-lu &Cui, Jie, Wave propagation in deformable saturated layer and its effect on imcrozonation, Proc. 4th Int. Conf. Seism. Zon., Stanford, 1991,Vol.2
4. Men, Fu-lu & Cui, Jie, Dynamic analysis of sand liquefaction, Proc. 9th ECEE, Moscow, 1990, Vol.4b.

5. Fang, Hong-gi, Wang, Zong-gi & Zao Shu-dong, Macroscopic mechanism of soil liquefaction and its influence on earthquake damage of ground, Proc. 26th Int. Geol. Cong,1979.
6. Scott, R. F., Alaska Earthquake of 1964, Engineering. Nat. acad. Sci.1973.
7. Men, Fu-lu, Roles of water in seil dynamics problems”, ASME 80-C21 / PVP-61,1980.
8. Wolf, J.P., Dynamic Soil-Structure Interaction, Printice- Hall Inc.,1985.
9. Chai, Zu-huang, Seimic wave and solid tide due to recording of water table variation in Beijing Wail deep wells, Chinese J. Seismology, 1980,Vol.2, No.2.
10. Shi, Hui-xin et al, Anomalous migration of shallow groundwater and gas in Beijing Region and Tangshan Earthquake, Chinese J. seismology, 1980, Vol.2, No.1.
11. Men, Fu-lu, Wave propagation in saturated soil layer and sand liquefaction, Collected Research papers in Earthquake Engineering, Seismology Press, Beijing, 1992.
12. Men, Fu-lu, One-dimensional wave propagation in fluid-saturated porous elastic media, Acta Mathematica Scientia, 1984,Vol.4, No.4, P467-476.

---

1 Professor, Institute of Engineering Mechanics, CSB, Harbin, China,
Email: jcui@iem.net.cn
2 Professor, Institute of Engineering Mechanics, CSB, Harbin, China,
Email: wintermd@public.hr.hl.com
3 Doctor, Institute of Engineering Mechanics, CSB, Harbin, China.