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SYNOPSIS: Based on the wave equations established by the authors, the dispersion characteristics of elastic waves in saturated soils are analzed and verified by laboratory test and seismic survey in the field. The results can be used for determination of physical and mechanical parameters of saturated soils, such as , Poisson's ratio, depth for first appearance of full saturation , porosity and unit weight by measurement of wave velocities.

I. Introduction

The wave velocities are related to physical and mechanical properties of the medium through which the wave propagates, which drop a hint that wave velocity method may be used for geotechnical exploration. Soil is a complicated three- phase material, its porosity, degree of saturation, permeability coefficient and frequency of wave will affect the velocities of elastic wave in the soil. Researchers have studied propagation of elastic wave in soils and other porous materials filled with fluids for decades, therefore, their theoretical results could hardly be used because of either theorization or simplism. On the other hand, although the empirical equations based on the experimental data showed their valuable for application, they could only be used qualitatively for verifying the theoretical results.

The main subject of this paper is the dispersion characteristics of elastic waves in saturated soils, induding derivation of elastic wave equations taking the coupling effects between soil skeleton and pore water into account, and applications for determination of Poisson's ratio, depth for first appearance of full saturation, porosity and unit weight by measurement of velocities of P-wave and S-wave.

II. Elastic Wave Equations in Saturated Soils

1. Basic Assumptions

It is neccssary to have some assumptions for simplification to obtain theoretical relationship between wave vclocitics and characteristic paramcters of satuated soils.

(1) Soil skeleton is of ideal elastic and porous continuum and soil particles imcompressible;

(2) Pore water is compressible and Darcy's law valids for movement of pore water in voids;

(3) Soil is of statistically isotropic and all pores continuous;

(4) Maximum size of the pore is less than the wave length;

(5) The effects of temperature on wave equations are ignored.

The fourth item mentioned above is the key one which enables the principles of continuum mechanics to be approximately valid for saturated soils. If the order of P-wave veocity in saturated soil is 10^3m/s, the following can be obtained based on the fourth item for the relationship between maximum allowable frequency, f_{max}, and pore diameter, d: when $d=0.1-0.001$cm, $f_{max}=1-100$MHz. The frequencies of most vibrations in soil dynamics are less than this range.

2. Equations of Elastic Waves

(1) Continuity equation

From the assumption, the continuity equation could be cited: volume change of unit soil mass in unit time interval $\dot{\varepsilon}$ is equal to the sum of content change of pore water due to seepage, $\dot{\varepsilon}_v$, and volume change of pore water due to compressibility, $\dot{\varepsilon}_w$, in the same unit time interval. , i. e. ,

$$n\,div\dot{\underset{\sim}{u}} + (1-n)\,div\dot{\underset{\sim}{w}} - n\dot{u}_w/E_w = 0 \qquad (2.1)$$

Where n—porosity, u_w— pore water pressure, E_w— bulk modulus of water, $\underset{\sim}{u}$—displacement vector of pore water, $\underset{\sim}{w}$—displacement vector of soil skeleton, then, $\dot{\varepsilon}=div\dot{\underset{\sim}{w}}$, $\dot{\varepsilon}_v=n\,div(\dot{\underset{\sim}{u}}-\dot{\underset{\sim}{w}})$, $\dot{\varepsilon}_w=n\dot{u}_\omega/E_\omega$.

(2) Motion equations

The zigzag paths of pore in the soil make not all pore water move in one direction with the same microscope acceleration; as a result, there is complex inertial coupling effect between two phases. It is considered in two ways in this paper.

Model 1 (Chen, et al, 1987): In Cartesian coordinates, because of uniform distribution of pore, only one third of pore water within unit volume of soil moves in the direction of one axis with the same microscope acceleration of the pore water, while the other two thirds of the pore water move with microscope acceleration of soil skeleton in the same direction.

Model 2: Soil skeleton and pore water are two continuous mediums with mass densities of ρ_1 and ρ_2, respectively. The accelerations of these two phases are independent of each other and the permeability force is only a body force. Herein, $\rho_1 = (1-n)\rho_s$, $\rho_2 = n \cdot \rho_w$, ρ_s and ρ_w are mass densities of soil particles and pore water, respectively.

The motion equations of saturated soil element and pore water are as follows:

For Model 1:

$$\sigma'_{ij,j} + (u_w)_{,i} = (\rho_1 + \frac{2}{3}\rho_2)\ddot{w}_i + \frac{1}{3}\rho_2\ddot{u}_i \quad (2.2)$$

$$(u_w)_{,i} - b(\dot{u}_i - \dot{w}_i) = \frac{2}{3}\rho_2\ddot{w}_i + \frac{1}{3}\rho_2\ddot{u}_i \quad (2.3)$$

For Model 2:

$$\sigma'_{ij,j} + (u_w)_{,i} = \rho_1\ddot{w}_i + \rho_2\ddot{u}_i \quad (2.4)$$

$$(u_w)_{,i} - b(\dot{u}_i - \dot{w}_i) = \rho_2\ddot{u}_i \quad (2.5)$$

where σ'_{ij} is the stress component of soil skeleton, $b = n\gamma_w/k$, $\gamma_w (= \rho_w g)$ is unit weight of water (g, acceleration of gravity), k is the permeability coefficient. For simplicity, the detail analyses for Model 1 are presented in this paper, while only the results for Model 2 are presented if necessary.

For the elasticity of soil skeleion,

$$\sigma'_{ij} = 2\mu' e_{ij} + \lambda' \varepsilon\delta_{ij} \quad (2.6)$$

where $\varepsilon_{ij} = (w_{j,i} + w_{i,j})/2$, $\varepsilon = div\underset{\sim}{w}$.

From Eqs. (2.2), (2.3) and (2.6), the motion equations can be rewritten as

$$\mu'\nabla^2\underset{\sim}{w} + (\lambda' + \mu')grad(div\underset{\sim}{w}) + grad(u_w) = (\rho_1 + \frac{2}{3}\rho_2)\ddot{\underset{\sim}{w}} + \frac{1}{3}\rho_2\ddot{\underset{\sim}{u}} \quad (2.7)$$

$$grad(u_w) + b(\dot{\underset{\sim}{w}} - \dot{\underset{\sim}{u}}) = \frac{2}{3}\rho_2\ddot{\underset{\sim}{w}} + \frac{1}{3}\rho_2\ddot{\underset{\sim}{u}} \quad (2.8)$$

in which λ' and μ' are Lame's constants of soil skeleton.

3. Wave equations

Eqs. (2.1), (2.7) and (2.8) derived above are elastic wave equations in saturated soil corresponding to Model 1. To discuss the nature of compression wave (P-wave) and shear wave (S-wave), dilatational potential φ and rotational potential $\underset{\sim}{\psi}$ are introduced, i. e.,

$$\left.\begin{aligned} \underset{\sim}{w} &= grad\varphi_1 + rot\underset{\sim}{\psi_1} \\ \underset{\sim}{u} &= grad\varphi_2 + rot\underset{\sim}{\psi_2} \\ div\underset{\sim}{\psi_1} &= div\underset{\sim}{\psi_2} = 0 \end{aligned}\right\} \quad (2.9)$$

Substituting Eq. (2.9) into wave equations for Model 1, P-wave and S-wave equations in saturated soil can be obtained, respectively.

$$\left.\begin{aligned} \nabla^2\varphi_1 &= (-\nabla^2\varphi_2 + \dot{u}_w/E_w)n/(1-n) \\ \Box_P^2\varphi_1 &= (-u_w + \frac{1}{3}\rho_2\ddot{\varphi}_2)/(\lambda' + 2\mu') \\ u_w + b(\dot{\varphi}_1 - \dot{\varphi}_2) &= \frac{2}{3}\rho_2\ddot{\varphi}_1 + \frac{1}{3}\rho_2\ddot{\varphi}_2 \end{aligned}\right\} \quad (2.10)$$

$$\left.\begin{aligned} \Box_S^2\underset{\sim}{\psi_1} &= \frac{\rho_2}{3\mu'}\underset{\sim}{\psi_2} \\ b(\dot{\underset{\sim}{\psi_1}} - \dot{\underset{\sim}{\psi_2}}) &= \frac{2}{3}\rho_2\ddot{\underset{\sim}{\psi_1}} + \frac{1}{3}\rho_2\ddot{\underset{\sim}{\psi_2}} \end{aligned}\right\} \quad (2.11)$$

in which

$$\Box_j^2 = (\nabla^2 - \frac{1}{v_j^2}\frac{\partial^2}{\partial t^2}) \qquad (j = P, S)$$

Ⅲ. Dispersion Characeristics of Elastic Waves in Saturated Soils

Dispersion characteristics of elastic waves in saturated soils mean the effects of frequency, f, and permeability coefficient, k, on elastic wave velocities. It is obvious that it is the only way to analyze dispersion characteristics of wave from Eqs. (2.10) and (2.11) by means of numerical method.

For plane wave, $\underset{\sim}{n}_1$ is the unit normal vector of wave front; $\underset{\sim}{r}$, radius vector; $\omega = 2\pi f$; circular frequency; l, a complex constant.

Substituting

$$\varphi_j = A_j exp[-i(l\underset{\sim}{r} \cdot \underset{\sim}{n}_1 - \omega t)] \qquad (P\text{-}wave)$$

$$\underset{\sim}{\psi_j} = \underset{\sim}{B_j} exp[-i(l\underset{\sim}{r} \cdot \underset{\sim}{n}_1 - \omega t)] \qquad (S\text{-}wave)$$

into Eqs. (2.10), and Eqs. (2.11), respectively, we obtain

$$A(\frac{l}{\omega})_P^4 + B(\frac{l}{\omega})_P^2 + C = 0 \qquad (P\text{-}wave) \quad (3.1)$$

$$(\frac{l}{\omega})_S^2 = \frac{(\rho_1\rho_2^2\omega^2/9b^2 + \rho) + i_1\rho_2^2\omega/3b}{\mu'(1 + \rho_2^2\omega^2/9b^2)} \qquad (S\text{-}wave) \quad (3.2)$$

in which

$$A = (\lambda' + 2\mu')\omega/b,$$

$$B = -[(\rho_1 + \frac{\lambda' + 2\mu'}{3E_w}\rho_2)\frac{\omega}{b} + i_1(\frac{1}{n} + \frac{\lambda' + 2\mu'}{E_w})],$$

$$C = (\rho_1\rho_2\omega(3b)^{-1} + i_1\rho)/E_w, \quad i_1 = \sqrt{-1},$$

$\rho = (\rho_1 + \rho_2)$. is mass density of saturated soil.

Phase velocities of P-wave and S-wave in saturated soil can be written:

$$v_j = 1/Re(l/\omega)_j \qquad (j = P, S) \quad (3.3)$$

in which Re represents the real part of the complex. $(l/\omega)_s$ can be obtained form Eq(3.2), while $(l/\omega)_P$ can be obtained by

$$(\frac{l}{\omega})_P = \pm\sqrt{\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}} \quad (3.4)$$

From Eqs. (3.1)—(3.4), two positive values of v_P and one positive value of v_s can be obtained. It shows there are two kinds of P-wave and one S-wave existing in the saturated soil, among which only one P-wave propagates through pore water. It can be seen from the above equations that the effects of frequency and permeability can be expressed by one parameter, $\rho_w\omega/b$, which can also be expressed in dinensionless frequency $f/f_c = \rho_w\omega/b$, if Ishihara's characteristic fre-

quency (Ishihara, 1970) $f_c = ng/2\pi k$ is used.
For saturated soil, $(\lambda' + 2\mu') \ll E_w$, as a result, P-wave velocity through pore water is greater than that through soil skeleton. In practical view, only P-wave velocity through pore water will be discussed, which is generally called P-wave velocity of saturated soil.

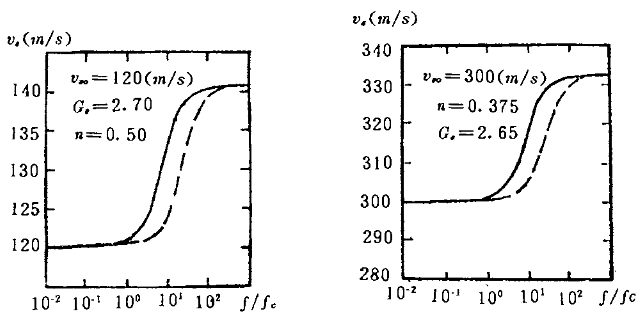
1. S-Wave
From Eqs. (3. 2) and (3. 3) we have S-wave velocities for $f/f_c \to 0$ and ∞, respectively,

$$v_{s0} = \sqrt{\mu'/\rho}; \qquad v_{s\infty} = \sqrt{\mu'/\rho_1} \qquad (3.5)$$

Dispersion curves of shear wave drawn from Eqs. (3. 2) and (3. 3) are shown in Fig. 1, in which parameters are chosen based on the typical value, v_{s0} (Imai, 1977), for saturated clay and sand. The dotted curve in Fig. 1 represents Model 2. It can be seen from Fig. 1 that there is no large difference for S-wave dispersion between two models. They have the same nature: there is little difference between v_s and v_{s0} for $f/f_c < 1$; $c_s \approx v_{s\infty}$ for $f/f_c \geqslant 10^2$; v_s increases with f/f_c for $1 < f/f_c < 10^2$. The variation of v_s with f/f_c results from variation of participating mass of pore water added to the soil skeleton. $\triangle v_s/v_{s0} = (v_{s\infty} - v_{s0})/v_{s0} = \sqrt{1+e/G_s} - 1$ can be used to evaluate the dispersion of S-wave, where e and G_s represent void ratio and specific gravity, respectively. Values of $\triangle v_s/v_{s0}$ for Fig. 1(a) and (b) are 17. 1% and 10. 7%, respectively.

2. P-Wave
From Eqs. (3. 1), (3. 3) and (3. 4), we have P-wave velocities for $f/f_c \to 0$, and ∞, respectively,

$$v_{p0} = \sqrt{\frac{E_w/n + (\lambda' + 2\mu')}{\rho}}; \qquad v_{p\infty} = \sqrt{\frac{3}{n}} v_w \qquad (3.6)$$



(a)Clay (b)Sand

Fig. 1 Dispersion Curves of S-Wave in Saturated Soils

where v_w is wave velocity in pure water. For Model 2, v_{p0} has the same expression as Eq. (3. 6), while $v_{p\infty} = \sqrt{1/n}\, v_w$. Generally, the mechanism of P-wave dispersion in saturated soil is more complicated than that of S-wave, and the choice of model has a great effect on P-wave velocity at high frequency. the exact P-wave velocity has a value between two extreme ones mentioned above.
Solid dispersion curves of saturated soil based on Eqs. (3. 1), (3. 3), and (3. 4) are shown in Fig. 2, and the dotted curve represents Model 2. It can be seen that the characteristics of dispersion of P-wave are the same for the two models, i. e., v_p is approximately equal to v_{p0} as $f/f_c < 1$; v_p increases with f/f_c increasing, as $1 \leqslant f/f_c < 10^2$; and $v_p \approx v_{p\infty}$, as $f/f_c \geqslant 10^2$. It should be pointed out that the depree of dispersion of P-wave for Model 1 is more dramatic than those of P-wave for Model 2 and for S-wave in Fig. 1.

Ⅳ. Applications for Determination of Soil Panameters

1. Poisson's ratio of saturated soils (Wu, et al, 1989)
As $2\pi fk/ng < 1$ is satisfied, there is no relative motion between solid and fluid phases dispite how low or how high of the value of permeability. the velocities for compression wave and shear wave can be expressed as:

$$v_p = \sqrt{\frac{(E_w/n) + (\lambda' + 2\mu')}{\rho_w[(1-n)G_s + n]}} \qquad (4.1)$$

$$v_s = \sqrt{\mu'/\{\rho_w[(1-n)G_s + n]\}} \qquad (4.2)$$

in which λ' and μ' are Lame constants. There exists formula related to effective Poisson's ratio

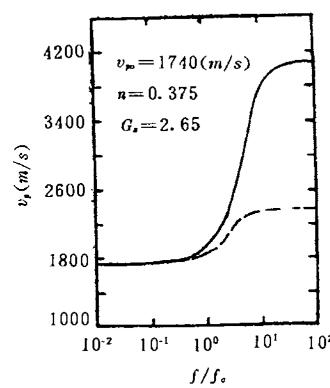


Fig. 2 Dispersion Curves of P-Wave in Saturated Soil

$$\lambda' + 2\mu' = \frac{2(1-\nu')}{1-2\nu'}\mu' \qquad (4.3)$$

From Eq. (4. 1) to (4. 3), the effective Poisson's ratio of saturated soils can be obtained

$$\nu' = \frac{1}{2}\frac{(v_p/v_s)^2 - (E_w/n\mu') - 2}{(v_p/v_s)^2 - (E_w/n\mu') - 1} \qquad (4.4)$$

It is obvious that the effective Poisson's ratio of saturated soils not only is affected by velocities, v_p and v_s, also by the porosity, n.
We already have classical expression for fotal Poisson's ratio of saturated soils from theory of clasficity.

$$\nu = \frac{1}{2}\frac{(v_p/v_s)^2 - 2}{(v_p/v_s)^2 - 1} \qquad (4.5)$$

It can be seen that Eq(4. 5) is a special case of Eq(4. 4) when $E_w/(n\mu')$ equal to zero, consequently, it is convenient to compare values of ν' and ν. Substituting Eq(4. 1) and (4. 2) into Eq(4. 5) and taking into account the fact that confined modulus of soil skelton, $(\lambda' + 2\mu')$, is much smaller than E_w/n, the total Poisson's ratio can be simplified as

$$\nu \approx \frac{1}{2}(1 - n\mu'/E_w) \qquad (4.6)$$

which is exactly the same as that (Ishihara, 1970) derived through a series of approximate calculations. Because the value of elastic effective Poisson's ratio of soil is smaller than 0. 35, it can be seem that Eq(4. 5) is little different from Eq(4. 6) if $(n\mu'/E_w) \leqslant 0.1$.

Fig. 3 shows a series of curves based on Eq. (4. 4) If $E_w/n\mu'$ keeps constant, saturated soil with high value of velcity ratio, (v_p/v_s), is of high value of effective Poisson's ratio. If (v_p/v_s) keeps constant, the larger the value of $E_w/n\mu'$, the lower for the effective Poisson's ratio. Generally speaking, the effective Poisson's ratio is smaller than the fotal one. Since velocity ratio, (v_p/v_s), and $E_w/n\mu'$ are affected by the soil modulus, the values of effective Poisson's ratio for saturated soft soil and stiff soil will be not easily determined. Some examples can be seen in the other papers (Chen, 1987; Wu, et al, 1989,a; Wu, et al, 1989,b).

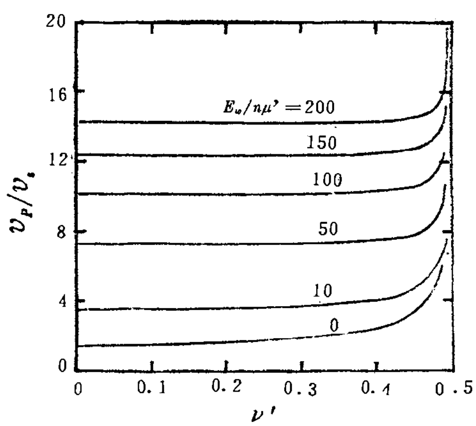


Fig. 3 The Relationship between Effective Poisson's Ratio, ν', and Velocity Ratio, v_p/v_s, for Saturated Soils, as $2\pi fk/ng < 1$.

2. Determination of Depth for First Appearance of Full Saturation

It is very important to determine the state of saturation at certain depth for practical engineering problems, such as, fully safurated sand deposit has wuch lower strength than unsaturated condition under earthquake loading.

It is known that a small amount of air in soil voids will affect compression wave velocity, v_p, though soil dramatically, and this influence varys with the frequency of the wave. There exists a resonant frequency, f_0, for air bubbles, as $f < f_0$, P-wave velocity in high saturated soil, v_p^*, is affected by amount of air in the soil voids. v_p^* for high saturated soil and v_p for fully saturated soil are the same, as $f > f_o$. f_o increases with decreasing of radius of air bubbles and increasing of soil shear modulus, and it can be estimated as following (Anderson, 1980):

$$f_o = \frac{1}{2\pi r}\left(\frac{3P_0 + 4\mu'}{\rho^*}\right)^{1/2} \qquad (4.7)$$

where P_o for pressure of air bubbles, $\rho^* = \rho_w[(1-n)G_s + S_r n]$ Values of f_o are usually greater than 1. 0 KHz, which is in good agreement with those by Allen (1980) and Strachen (1985).

Based on the bulk modulus of mixture of air and water, E_{wa},

$$\frac{1}{E_{wa}} = \frac{S_r}{E_w} + \frac{1 - S_r}{E_a} \qquad (4.8)$$

the velocity for high saturated soil ($S_r > 85\%$) can be derived as $2\pi fk/ng < 1$ and $f < f_o$:

$$v_p^* = \sqrt{\frac{E_{wa}/n + (\lambda' + 2\mu')}{\rho^*}} \qquad (4.9)$$

$$v_s^* = \sqrt{\mu'/\rho^*} \qquad (4.10)$$

Since $E_a/E_w = \rho_a v_a^2/\rho_w v_w^2 = 1.29 \times 340^2/(1000 \times 1450^2) \approx 0.71 \times 10^{-4}$, Eq(4. 8) can be rewritten as

$$E_{wa} \approx E_w/[1.41 \times 10^4(1 - S_r) + S_r] \qquad (4.11)$$

It can be known that $E_{wa} = 0.014E_w$, as $S_r = 99.5\%$ from Eq(4. 11), which illustrates that a small amount of air causes dramatic decrease of bulk modulus of fluid in soil voids. Based on the conclusion drawn above and the fact the dominant frequencies of P-wave in seiemic survey in-situ, such as reflection, refraction survey and cross-hole test, are always in the range from 1 to 10^2 Hz, the conditions of $2\pi fk/ng < 1$ and $f < f_o$ are often satisfied. People can judge whether or not the soil stratum at certain depth is fully saturated from P-wave velocity measured in the field, while degree of saturation in soil has no effect on P-wave velocity. Several cases can testify the conclusion herein, Fig. 4 is the one of them, which shows a result of cross-hole test in Hangzhou. Field and laboratory test illustrated the soil stratums within 8 meters below ground sarface were unsaturated, soil stratums lower than 10 meters were fully saturated, and the ones ranged 8~10 meters were unsaturated, but very high degree of saturation.

3. Determination of Porosity and Unit Weight of Saturated Soils by Wave method.

As mentioned above, in most seismic survey methods dominant frequencies of P-wave are low, the expression $2\pi fk/ng < 1$ is satisfied for most stratums of saturated soil. According to Eqs.(4.1)to(4. 3), a theoretical expression of porosity, n, for saturated soils in terms of velocities (Chen, et al, 1988), v_p and v_s.

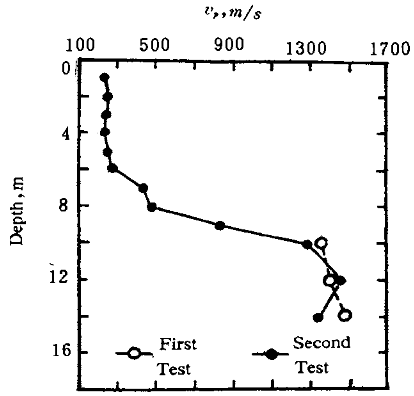


Fig. 4 P-wave Test Data Measured in Hangzhon Site (Chen, et al, 1990)

$$n = \frac{G_s - \sqrt{G_s^2 - \dfrac{4(G_s - 1)v_w^2}{v_p^2 - a v_s^2}}}{2(G_s - 1)} \tag{4. 12}$$

in which $a = 2(1-\nu')/(1-2\nu')$ (4. 13)

Unit weight of saturated soil can be expressed as following from Eq(4. 12):

$$\gamma = \rho g = [(1-n)G_s + n]\rho_w g \tag{4. 14}$$

In Eq(4. 14), three parameters, G_s, v_w, and a are required except v_p and v_s. G_s, specific gravity of soil particles, can be measured in laboratory with disturbed soil samples, its value ranges from 2. 65~2. 75. v_w, compression wave in water, generally increases with increasing temperature. v_w is around 1450~1480m/s, as the temperature of pore water varies from 10~25℃. a, a parameter varying with effective Poisson's ratio, is showed in Fig. 5.

Fig. 6 presents the comparison of test results in the laboratory and in the field by wave velocity method and SPT at a site of silt deposit in Hangzhou. There is some scattering of the data points, but it's in normal range.

V. Discussions

1. It is verified theoretically that S-wave velocity in saturated soil is mainly governed by Lame's constant of soil skeleton or shear modulus, μ'. Therefore, it is reasonable to evaluate engineering properties by S-wave velocity. It is pointed out that the calculated value of μ' with $\mu' = \rho v_s^2$ by ultrasonic test as $f/f_c > 1$ without consideration of dispersion will be greater than the exact one.

2. It shows both from theoretical analysis and tests that P-wave velocity is affected not only by pore water, but also by soil skeleton, as long as $f/f_c = 2\pi fk/ng < 1$, no matter how high the values of permeability coefficient and wave frequency are. The above condition is satisfied in most cases encountered in engineering (Chen, 1987). The idea then no longer exists that the data of P-wave velocity in saturated soil is of little significance (Hardin, 1978).

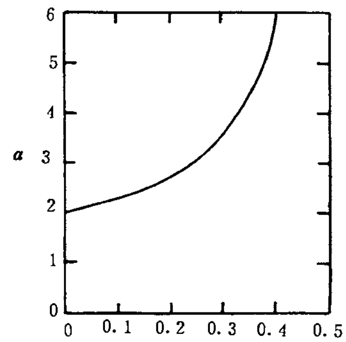


Fig. 5 The Relationship between a and Effective Poissin's Ratio, ν'

3. When $n < 60\%$ or $(\lambda' + 2\mu')/E_w \geq 0.1$, it could be concluded from Fig. 2 and the first expression of Eq. (3. 6) that v_p is always greater than v_w, which can explain why the velocities measured in the saturated soil are close to or greater than that in pure water ($v_w = 1450 m/s$).

4. Under the condition, $2\pi fk/ng < 1$, wave velocities measured in the field by seismic survey, cross-hole test, spectral analysis of surface wave technique and other methods can be

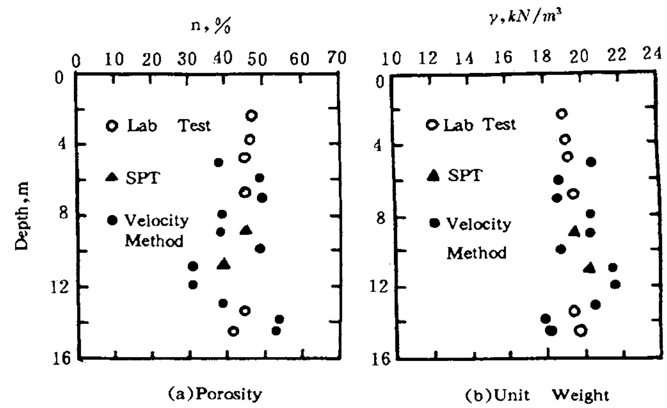


Fig. 6 Test Data of Porosity and Unit Weight at a Site of Silt Deposit in Hangzhou

used for determination of Poisson's ratio, depth of first appearance of full saturation, porosity and unit weight of fully saturated soils, particularly, the use of P-wave was hardly seen in the literature. Wave velocity method has a future in geotechnical exploration specially for some soil deposits with difficulty in sampling.

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