

수압변동에 의한 해저사질층의 액상화 현상연구

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요 약

변동수압에 의한 해저 포화 사질층의 연직 간극수압 분포를 이론 및 실험적으로 연구하였다. 실험에 의해 모래표면에 작용하는 수압은 모래층으로 전달되며 진폭이 감쇠하고 상이 지연되며, 유효응력이 0이 되는 액상화 현상이 특별 조건에서 발생한다. 이러한 실험결과는 탄성 대수층에 대한 지하수문제와 같은 이론으로 잘 설명된다.

해석에 의한 액상화의 주요 특징은 다음과 같다: 1) 액상화 심도는 진폭 및 변동수압의 주파수 증가에 따라 증가한다. 2) 수량(水量)을 증가시키고 모래층 내의 공기가 많아짐에 따라 액상화 심도가 증가한다. 특히, 공기의 적은 양도 액상화에 크게 영향을 미친다. 3) 압축율이 증가함에 따라 액상화 심도는 감소한다. 4) 투수 계수값이 어느 특정값 이상이 되면 투수계수값이 증가함에 따라 액상화 심도가 감소한다.

Shon, Howoong, Liquefaction of Sand Seabed Induced by Water Pressure Wave

ABSTRACT : The vertical distribution of pore water pressure in the highly saturated sand layer under the oscillating water pressure (water wave) is studied theoretically and experimentally. By the experiments it is shown that the water pressure acting on the sand surface propagates into the sand layer with the damping in amplitude and the lag in phase, and that the liquefaction, the state that the effective stress becomes zero, occurs under certain conditions. These experimental results are explained fairly well by the same theoretical treatment as for the ground water problems in the elastic aquifer.

The main characteristics of liquefaction clarified by the analysis are as follows: 1) The depth of the liquified layer increases with the increase of the amplitude and the frequency of the oscillating water pressure. 2) The increase of the volume of the water and the air in the layer increases the liquified depth. Especially the very small amount of the air affects the liquefaction significantly. 3) The liquified depth decrease rapidly with the increase of the compressibility coefficient of the sand. 4) In the range beyond a certain value of the permeability coefficient the liquified depth decrease with the increase of the coefficient.

Introduction

Under the oscillating water pressure (water wave), especially in the marine environment (Fig. 1a), normal to the surface of the saturated sand layer, the pore water pressure in the layer changes with time and according to this circumstances the excess pore pressure occurs. The increase of the excess pore pressure brings to the decrease of the effective stress. Then, under certain conditions the effective stress becomes to be equal to zero, that is, the state of liquefaction occurs (Shon, 2000a). The liquified sand is removed easily by the flow tangential to the surface, and the sand layer will be scoured successively. Therefore, the clarification of the dynamical mechanism of such liquefaction is very important to design of hydraulic structures surrounded by the sand layer.

In this paper as a basic study for the explanation of the local scouring mechanism around the hydraulic structures and for the establishment of the prevention works against the scouring, the influence of the oscillating water pressure on the sand layer is investigated theoretically and experimentally.

Derivation of Fundamental Equation for Pore Water Pressure

To treat theoretically the vertically one-dimensional sand layer is considered as shown in Fig. 1b. The sand layer is highly saturated with water and is placed on the impermeable bed. The depth of the sand layer

is D . The oscillating water pressure $\rho g h_s$ acts on the surface of the layer.

The behavior of water and sand in the sand layer is analyzed by the same method as for the ground-water problems in the elastic aquifer (Inoue, 1975; Kundu, 1990; Rouse, 1950; Shon, 2000a). That is, it is assumed that sand and water are compressible, and then that the density of water, the porosity of the sand and the thickness of the layer are variable. But lateral strain of the sand is assumed to be negligible. The void in the sand layer is occupied by water and air. Then, the porosity λ is composed of the part for the water λ_w and the part for the air λ_a . The flow of water is considered through the faces of an elemental volume as shown in Fig. 1b. By the law of conservation of mass, the net inward flux must be equal to the rate at which water is accumulating within that volume. That is,

$$\frac{\partial}{\partial t}(\rho \lambda_w \delta y \delta A) = - \frac{\partial}{\partial y}(\rho \nu \delta A) \delta y \quad (1)$$

where ρ : density of water, ν : velocity of flow, δA : horizontal cross-sectional area.

The left hand side of the above equation is transformed as follows:

$$\begin{aligned} \frac{\partial}{\partial t}(\rho \lambda_w \delta y \delta A) = \\ (\lambda_w \frac{\partial \rho}{\partial t} \delta y + \rho \frac{\partial \lambda_w}{\partial t} \delta y + \rho \lambda_w \frac{\partial \delta y}{\partial t}) \delta A \end{aligned} \quad (2)$$

The vertical dimension δy varies with the vertical component of compressive stress σ_y in

accordance with,

$$d(\delta y) = -\alpha \delta y d\delta y \quad (3)$$

That is,

$$\frac{\partial(\delta y)}{\partial t} = -\alpha \delta y \frac{\partial \sigma_y}{\partial t} \quad (4)$$

where α is the vertical compressibility of sand.

Since the compressibility of the individual sand grains is small compared to the compressibility of water and the change in the porosity, it can be considered that the volume of solid material remains constant (Shon, 2000a). That is

$$[1 - (\lambda_w + \lambda_a)] \delta y \delta A = \text{constant}.$$

Differentiating the above equation by time variable t , the following equation is obtained.

$$\frac{\partial(\lambda_w + \lambda_a)}{\partial t} = -\alpha [1 - (\lambda_w + \lambda_a)] \frac{\partial \sigma_y}{\partial t} \quad (5)$$

If the inertia force of the sand is negligibly small, the vertical component of compressive stress and the pore water pressure can be equated to the downward acting force on the plane of contact of the sand. That is,

$$\sigma_y + \rho g h = \gamma_s y + \rho g h_s \quad (6)$$

The pore water pressure $\rho g h$ and the weight of the sand column above the plane of contact $\gamma_s y$ are represented as follows:

$$\rho g h = \rho g (h_s + y + h') \quad (7)$$

$$\gamma_s y = \rho_s g y (1 - \lambda) + \rho g y \lambda_w \quad (8)$$

where h' : excess pore water pressure, $\rho_s g$: weight of unit volume of the individual sand grain, g : acceleration due to gravity.

Substituting Eqs. (7), (8) into Eq. (6), and considering $\lambda_w \cong \lambda$,

$$\begin{aligned} \sigma_y + \rho g h' &= \\ (\rho_s - \rho) g y (1 - \lambda) &= \text{constant} \end{aligned} \quad (9)$$

Accordingly,

$$\rho g \frac{\partial h'}{\partial t} = -\frac{\partial \sigma_y}{\partial t} \quad (10)$$

Then the following equation is obtained from Eqs. (4) and (10)

$$\frac{\partial \delta y}{\partial t} = \rho g \alpha \delta y \frac{\partial h'}{\partial t} \quad (11)$$

From Eqs. (5) and (10)

$$\begin{aligned} \frac{\partial(\lambda_w + \lambda_a)}{\partial t} &= \\ \rho g \alpha [1 - (\lambda_w + \lambda_a)] \frac{\partial h'}{\partial t} & \end{aligned} \quad (12)$$

It is assumed that the volume of air in the layer changes in accordance with Boyle's law. That is,

$$\begin{aligned} \lambda_a \delta y \delta A (\rho g \bar{h} + p_0) &= \\ \overline{\lambda_a} \delta y \delta A (\rho g \bar{h} + p_0) &= \text{constant}, \end{aligned} \quad (13)$$

where p_0 : atmospheric pressure, $\overline{\lambda_a}$: porosity occupied by the air under the standard pressure $(\rho g \bar{h} + p_0)$.

Differentiating Eq. (13) by t , and using Eq. (10), the follow equation is obtained.

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$$\frac{\partial \lambda_a}{\partial t} = - \frac{\lambda_a}{\left(h + \frac{p_0}{\rho g}\right)} \frac{\partial h}{\partial t} - \rho g \alpha \lambda_a \frac{\partial h'}{\partial t} \quad (14)$$

From Eqs. (12), (14),

$$\frac{\partial \lambda_w}{\partial t} = \rho g \alpha (1 - \lambda_w) \frac{\partial h'}{\partial t} + \frac{\lambda_a}{h + \frac{p_0}{\rho g}} \frac{\partial h}{\partial t} \quad (15)$$

The density of water changes in accordance with the following equation,

$$\frac{d\rho}{\rho} = \beta dp, \quad p = \rho gh + p_0 \quad (16)$$

where β : compressibility of water, p : absolute pressure.

Accordingly,

$$\frac{\partial \rho}{\partial t} = \beta \rho^2 g \frac{\partial h}{\partial t} \quad (17)$$

Substituting Eqs. (11), (15), (17) into Eq. (2),

$$\frac{\partial}{\partial t} (\rho \lambda_w \delta y \delta A) = \rho^2 g \left[\left(\beta \lambda_w + \frac{\lambda_a}{\rho gh + p_0} \right) \frac{\partial h}{\partial t} + \alpha \frac{\partial h'}{\partial t} \right] \delta y \delta A \quad (18)$$

It is assumed that the velocity of water in the layer follows Darcy's law (Kundu, 1990; Shon, 2000b),

$$v = -k \frac{\partial h'}{\partial y} \quad (19)$$

where k is permeability coefficient.

Substituting Eqs. (18), (19) into Eq. (1), finally the fundamental equation for the water

pressure in the layer is obtained as follows:

$$\begin{aligned} & \left(\beta \lambda_w + \frac{\lambda_a}{\rho gh + p_0} + \alpha \right) \frac{\partial h'}{\partial t} + \\ & \left(\beta \lambda_w + \frac{\lambda_a}{\rho gh + p_0} \right) \frac{\partial h_s}{\partial t} = \frac{k}{\rho g} \frac{\partial^2 h'}{\partial y^2} \end{aligned} \quad (20)$$

By solving the above equation under the following boundary conditions, the pore water pressure and the effective stress in the sand layer are obtained.

$$\begin{aligned} h' &= 0 \quad \text{at } y = 0 \\ \frac{\partial h'}{\partial y} &= 0 \quad \text{at } y = D \end{aligned} \quad (21)$$

The liquefaction occurs under the following condition,

$$\frac{\sigma_y}{(\rho_s - \rho) g y (1 - \lambda)} = 0 \quad (22)$$

For the case that the water pressure acting on the surface changes sinusoidally, that is,

$$h_s = h_0 + a_0 \sin 2\pi ft \quad (23)$$

Eq. (20) becomes,

$$\begin{aligned} & \left(\beta \lambda_w + \frac{\lambda_a}{\rho gh + p_0} + \alpha \right) \frac{\partial h'}{\partial t} \\ & + 2\pi f a_0 \left(\beta \lambda_w + \frac{\lambda_a}{\rho gh + p_0} \right) \cos 2\pi ft \\ & = \frac{k}{\rho g} \frac{\partial^2 h'}{\partial y^2} \end{aligned} \quad (24)$$

where h_0 : head of mean water pressure on the sand surface, a_0 : amplitude of oscillating water pressure, f : frequency of oscillating water pressure.

Eqs. (20) and (24) are nonlinear differential equation. Since it is difficult to solve these equations analytically, they are solved numerically.

Experiments on Liquefaction

Experimental procedure

For the experiment the vertical cylinder as shown in Fig. 2 was used. The inside diameter of the cylinder is 8.9cm and its height is 1.5m. It is filled with the highly saturated sand up to about 43% of its height. The water depth from the sand surface is about 80cm. The periodically oscillated air pressure acts on the water surface. Its amplitude is 95cm in water head. The frequency changes from 1.37 Hz to 5.66 Hz. The nearly uniform sand which 50% of grain size is 0.25mm was used. Two kinds of sand sample concerning to the volume of air in the layer was used. That is, the one is the sample which $\overline{\lambda}_a$ is about 0.5% at $\overline{h} = 0.3\text{m}$ and the other is the sample which $\overline{\lambda}_a$ is very small comparing with the former sample. In the following description each sample is called the aerated and the deaerated sample respectively. The value of λ_w is about 40%. The coefficient of permeability is about $2 \times 10^{-2} \text{ cm/s}$. The water pressures in the water and sand layer are measured by the semi-conductor pressure transducer attached to the side of the cylinder.

Experimental results

In Figs. 3(a) and (b), the changes of the pore water pressure for the deaerated and aerated sands are shown. These figures show that water pressure on the sand surface propagates into the sand layer accompanied with the damping in amplitude and

the lag in phase. The damping rate and lag in the aerated sand is larger than those in the deaerated sand. Figs. 4(a) and (b) show the damping ratio of the amplitude for both samples. The symbol a in the figures represents the amplitude in the sand layer. These figures show that the amplitude decreases with increasing frequency. Figs. 5(a) and (b) show the change of the effective stress, and that the state of the liquefaction ($\sigma_y = 0$) appears at the point 1 for the deaerated sample and at all measuring points for the aerated one. Figs. 6, 7 and 8 show the calculated curves of the pore water pressure, the damping ratio and the effective stress corresponding to Figs. 3, 4 and 5 respectively. In the calculation it is assumed that the compressibility of sand α is $1.8 \times 10^{-6} \text{ cm}^2/\text{g}$. The calculated curves match fairly well with the experimental results. The differences between the experimental results and the calculated curves are considered to be mainly due to the approximation of the oscillating water pressure and the compressibility in the calculation.

Characteristics of Liquefaction

Factors affecting liquefaction

The characteristics of the liquefaction depend on the properties of water, sand layer, oscillating water pressure and field conditions. For convenience adopting the sinusoidal excitation like Eq. (23) as the oscillating water pressure, the characteristic parameters influencing on the phenomenon are as follows:

- 1) water: $\rho, \beta;$
- 2) sand layer:

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$\rho_s, \alpha, \lambda_w, \bar{\lambda}_a, k, D, \bar{h}$; 3) water pressure: a_0, f, h_0 ; 4) field condition: g, p_0 .

Accordingly the quantitative property A of the liquefaction is given by the following functional relation.

$$A = F(a_0, f, h_0, \rho_s, \alpha, \lambda_w, \bar{\lambda}_a, k, D, \rho, \beta, g, p_0, \bar{h}; y, t) \quad (25)$$

By the dimensional analysis using ρ, g and D as the fundamental quantities of dimensions the above equation is transformed to,

$$\pi_A = \Phi\left(\frac{a_0}{D}, f\sqrt{\frac{D}{g}}, \frac{h_0}{D}, \frac{\rho_s}{\rho}, \alpha(\rho g D), \lambda_w, \bar{\lambda}_a, \frac{k}{\sqrt{gD}}, \beta(\rho g D), \frac{p_0}{\rho g D}, \frac{\bar{h}}{D}, \frac{y}{D}, t\sqrt{\frac{g}{D}}\right) \quad (26)$$

Maximum depth of liquified layer

Here the maximum depth of the liquified sand layer y_{\max} is dealt as one of the properties of liquefaction, and analyzed theoretically under the following conditions,

$$\rho_s/\rho = 2.65, \bar{h}/D = 0.3, p_0/\rho g D = 10.3,$$

$$\beta(\rho g D) = 0.41 \times 10^{-5}$$

In Figs. 9 to 14, the changes of the maximum depth y_{\max} with $a_0/D, \bar{\lambda}_a, \bar{\lambda}_w, k/\sqrt{gD}, \alpha(\rho g D)$ and h_0/D are shown with the parameter $f\sqrt{D/g}$.

Figs. 9, 10 and 11 show y_{\max} increases with the increase of $a_0/D, \bar{\lambda}_a, \bar{\lambda}_w$ and frequency. Especially a very small amount of air in the sand affects the liquefaction

considerably.

Fig. 12 shows that y_{\max} decreases with the increase of the coefficient of permeability beyond certain value of the coefficient. Fig. 13 shows that y_{\max} decreases rapidly with the increase of the compressibility of the sand. Fig. 14 shows that the increase of the mean water pressure decreases the liquified depth, although its degree is very small.

Conclusion

From the experiments and the theoretical analysis, following conclusions are achieved: 1) Experiments show that the oscillating water pressure acting on the surface of the highly saturated sand layer propagates into the layer with the damping in amplitude and the lag in phase, and that under certain conditions the liquefaction appears. It is obvious that the damping ratio and the phase lag depend mainly on the volume of the air involved in the layer. These experimental results are matched fairly well with the theoretical analysis. 2) By the theoretical analysis several properties on the liquefaction are obtained as follows: The maximum depth of liquified layer increases with the increase of the amplitude and the frequency of the oscillation water pressure and the volume occupied by the air and the water in the sand layer. Especially a small amount of the air affects on the liquefaction significantly. The increase of the coefficient of permeability beyond certain value decreases the depth of liquefaction. With the increase of the mean

water pressure and the compressibility of the sand, the liquefied depth decrease.

Acknowledgement

The author extends his gratitudes to Prof. Shiro Maeno in the Dept. of Civil and Environmental Engineering at Okayama University, Japan, and Prof. Tokuo Yamamoto in the Division of Applied Marine Physics at University of Miami, USA for their review and supports to experiment.

References

- Inoue, R., 1975, Propagation of pore water pressure in sand layer of high degree of saturation, Proc. JSCE, No. 236.
- Kundu, P. K., 1990, Fluid Mechanics. Academic Press.
- Rouse, H., 1950, Engineering Hydraulics. John Willey & Sons.
- Shon, H., 1995, Reconstruction of the Wave Speed and Density from Reflection Coefficients by Downward Continuation Algorithm. Econ. Environ. Geol., 28(6), p. 553-558
- Shon, H. and Jeong, G. C., 2000a, Results Analysis and Application of Ground Investigation and Soil test, Pub. of Engineers (in press).
- Shon, H, Kim, J. S., Sung, I. H., Woo, N. C., Lee, D. H., Jeong, G. C., Ham, S. Y. and Lee, H. S., 2000b, Applied Groundwater (in press).