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Application example: Field Velocity Resistivity Probe (FVRP) for predicting pore pressure parameter B

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A R T I C L E I N F O

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A B S T R A C T

Even though the pore pressure parameter B is essential to understand the soil condition, directly obtaining this value in a field test is difficult. The objective of this study is to propose a method for deducing B based on the elastic wave velocity measured in the field. In this study, the Field Velocity Resistivity Probe (FVRP), which has already been introduced in "Journal of Soil Dynamic and Earthquake Engineering", is selected to demonstrate the extension of the application. The wave propagation theory is applied, and B is rewritten in terms of the bulk moduli of the skeleton (K_{sk}), grain (K_g), and mixture (K_{mix}). This high-sensitivity parameter is ordered as K_{mix}, K_g, and K_{sk}. The bulk moduli of the skeleton and grain are determined by referring to a previously performed study, and the bulk modulus of the mixture is calculated using the compressional and shear wave velocity. B is close to unity with the average B value being calculated to be 0.9867. Even though the site is completely saturated, the reason for the small B value is the characteristic of the soil, which is highly compacted and in a consolidated condition. This result demonstrates that it is possible to determine B in the field through the elastic wave velocity, and the applicability of FVRP is excellent.

1. Introduction

The pore water pressure is the pressure of the fluid filling the pores of a soil medium; the value of the pore water pressure is necessary to assess the soil behavior under dynamic loading, including earthquakes and liquefaction. Among numerous parameters for reflecting the condition of the pore water pressure, the pore pressure parameter B, known as Skempton's B value, is most commonly used. It is defined as the ratio between the changed pore water pressure (P_f) and the confining pressure (P_C), as shown in Eq. (1) [12]. Eq. (1) is rewritten as a function of the compressibility of the soil (C_d), the porosity (n), and the compressibility of the pore fluid (C_u) under an isotropic condition [9,2].

$$B \cong \left(\frac{\partial P_f}{\partial P_C}\right)_{\partial m_f=0} = \frac{1}{1+\frac{nC_u}{C_d}}, \tag{1}$$

where m_f is the fluid mass per unit volume. The compressibility of water is nearly a constant $4.75 \times 10^{-5}\ cm^2/kg$ under a completely saturated condition [9]. However, the compressibility of soil varies with the soil type and stress condition. It is known that the compressibility of soil is higher than the compressibility of water. Hence, parameter B will be close to unity when the soil is completely saturated, whereas it will be zero when the soil is in a dry condition because there is no pore water pressure in the soil medium. Although parameter B is an important value for reflecting the saturated condition, limitation of parameter B is that it can only be deduced from laboratory tests. If the B value can be measured in the field, then the saturation of the field can be deduced at every depth. Characterizing the saturation in the field enables one to directly predict various design parameters, including electrical conductivity [5], water content [7] and dielectric constant [1].

When compressional and shear waves propagate in a completely saturated soil, the pore fluid is compressed and expanded via the wave propagation in a low-strain range. The soil behavior is related to the compressibility of the soil and fluid, and thus, it is possible to predict B by varying the ratio of the compressibility estimated by the elastic wave velocity. Among various methods, the field velocity resistivity probe (FVRP) was selected because the objective of this study is to demonstrate an application example of the FVRP, which was reported in "Journal of Soil Dynamic and Earthquake Engineering", to predict soil behavior. Initially, the measured elastic wave velocity through FVRP was used to estimate the design parameters, including the constrained modulus, the shear modulus and the porosity of soil and after this step, we attempted to expand the application of FVRP to observe the behavior of the ground and obtain various design constants in one experiment. FVRP is an invasive method to generate elastic waves in soil that

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has the advantage of obtaining detailed data at a depth of ≈10 cm. FVRP was developed to produce elastic waves in field tests, and the design concerns, experimental method, disturbance effect during penetration, and measured data have already been addressed and verified by Yoon and Lee [13]. A detailed explanation of the FVRP is omitted because it is beyond the scope of this study, for more details, the reader is referred to the article by Yoon and Lee [13].

In this study, the elastic wave velocity, as measured by the FVRP, is used to examine the possibility of evaluating the soil behavior of B, to the best of our knowledge, this is the first prediction of the parameter B using data measured in the field. The study introduces the background theory to illustrate the possibility of predicting B through elastic waves. The measured elastic wave velocity is plotted, and the field condition is also described. Finally, the results pertaining to B are analyzed with respect to the soil condition.

1.1. Possibility of estimating the pore pressure parameter B using the elastic wave velocity

Biot suggested that linear wave propagation occurs in porous media at a range of low and high frequencies (1956a, b). The theory follows Lagrangian and Hamiltonian formulations for explaining the viscous loss of the pore fluid when the wave propagates in a medium. Biot [3] demonstrates wave propagation in a medium in terms of the internal energy.

$$2E = \frac{[P_C^2 - 2\alpha P_C P_f + \frac{\alpha P_f^2}{B}]}{K_d}, \tag{2}$$

where P_C and P_f denote the confining pressure and the pore water pressure, respectively. K_d is the bulk modulus of the medium in a drained condition, B is the pore pressure parameter, and α is the Biot–Willis parameter, which is defined as $\alpha = 1\text{-}(K_{sk}/K_g)$ based on the bulk moduli of the skeleton (K_{sk}) and grain (K_g).

Eq. (2) is rearranged to yield Eq. (3) by considering the strain ($e = -\partial E/\partial P_C$) and increment of the fluid ($\xi = \partial E/\partial P_f$).

$$2E = K_u[e^2 - 2Be\xi + \frac{B\xi^2}{\alpha}], \tag{3}$$

where K_u is the bulk modulus of the medium in an undrained condition. The relationship between the bulk moduli of the medium in drained and undrained conditions is $K_u = K_d/(1\text{-}\alpha B)$, which is known as Gassmann's equation [6]. Finally, Skempton's B value is defined in Eq. (4) because the bulk moduli in drained and undrained conditions have nearly the same values as the bulk moduli of the skeleton (K_{sk}) and soil–water mixture (K_{mix}), respectively [11].

$$B = \frac{-K_d + K_u}{\alpha K_u} = \frac{-K_{sk} + K_{mix}}{(1 - \frac{K_{sk}}{K_g})K_{mix}} \tag{4}$$

The sensitivities of each parameter including the bulk moduli of the skeleton (K_{sk}), mixture (K_{mix}), and grain (K_g) in Eq. (4) are analyzed. The true values of K_{sk}, K_{mix}, and K_g are selected as 7.778×10^7 Pa, 43×10^8 Pa, and 20×10^9 Pa, respectively, referring to the data obtained by Yoon and Lee [13]. Next, the true values are increased and decreased up to 100% to obtain the modified values, and the modified values are normalized with the corresponding true value. Hence, the “0”, “1”, and “2” of the x-axis in Fig. 1 denote 100% decreased, true, and 100% increased values, respectively. Fig. 1 shows that the order of the highly affected parameters in the equation is $K_{mix} > K_g > K_{sk}$. The sensitivity results demonstrate that an accurate measurement is required to obtain K_{mix} because it is a function of the elastic wave velocities, and the value of K_{sk} can be assumed to be a general one. The value of K_g shows a high sensitivity when smaller values than the assumed value are used. However, a higher K_g value than the assumed value is generally used [10]. Hence, in this study, it is reasonable to use the K_g value assumed as the true value.

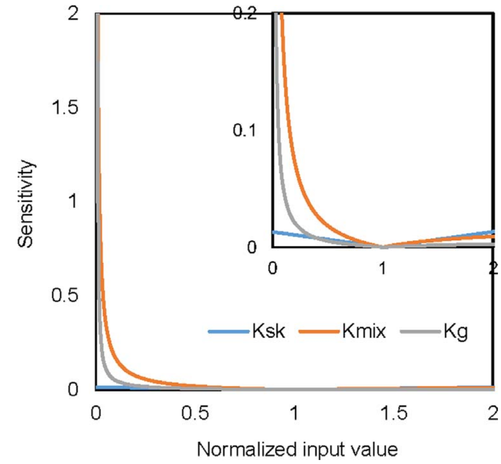

Fig. 1. Sensitivity analysis. K_{sk}, K_{mix}, and K_g denote the bulk moduli of the skeleton, mixture, and grain, respectively.

1.2. Profiles of the measured elastic wave velocity

The FVRP was used to collect the elastic wave velocity data, and a piezo disk element and bender element were installed for measuring the compressional and shear wave signals. The FVRP was made to penetrate the soil at every 10 cm of depth to increase the resolution from 6.5m to 20.1 m under the water level, as shown in Fig. 2. Note that the elastic wave was recorded in silty sand and clay. The elastic wave velocity was calculated using the first arrival time and travel distance, and the values are plotted in Fig. 3. The average compressional and shear wave velocities are 1557 m/s and 129 m/s, respectively, and thus, the relationship between the two velocities is determined to be V_S (shear wave velocity) = $0.08 \cdot V_P$ (compressional wave velocity).

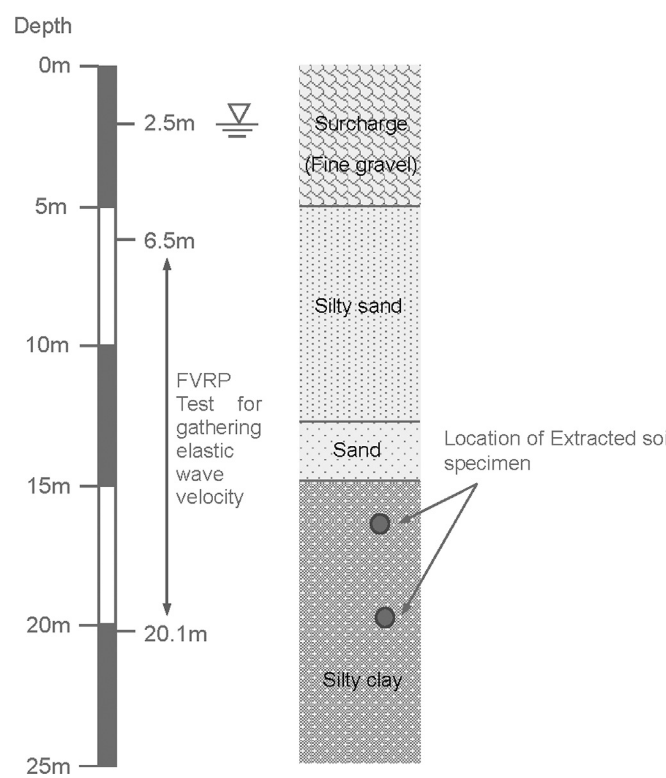

Fig. 2. Site description.