Estimation of soil permeability using acoustic techniques

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ABSTRACT

Permeability of soils is one of the major geotechnical parameters used for designing and analyzing geotechnical structures. However, the procedure for the determination of the permeability is not easy. Considerable advancements have been made, both in the theoretical and the experimental arenas for accurate determination of the permeability in soils, however, it is still time consuming and expensive. The conventional tests used in most laboratories and in situ also may not avoid the tendency of breaking the textures of soils related to drilling or sampling.

This study tries to develop a new method of estimating the permeability of soils using the acoustic wave technique. The estimated permeability constructed from the characteristic frequency. Compared with laboratory test, constant water head test, the permeability obtained by acoustic wave provides reasonable data. This test may be widely applied due to the non-destructive nature of the technique.

INTRODUCTION

Seismic wave is one of the most conveniently used tools in profiling geotechnical condition of the ground. Cross Hole technique is used for an accurate and direct measurement of seismic wave velocities while SASW(Spectral Analysis of Surface Wave) technique is used for convenient and quick determination of seismic wave velocities. There are also intermediate methods such as Down Hole technique, Up Hole technique, and many others. Seismic wave velocities obtained by such methods are used for the estimation of modulus, the evaluation of liquefaction potential, the profiling of ground layers, and many other areas.

Another application of the seismic wave velocity is proposed in this study. Estimation of permeability of soils using seismic wave technique is proposed here. The

P-wave (compression wave) velocity for a saturated soil has been known to be very difficult to measure. This is because the P-wave velocity of water is much faster than that of the media itself, and the first arrival wave is always close to the P-wave through the water. The P-wave through the media itself or partly through the water and partly through the media arrives later, and that signal is typically hidden in the first arrival signal. By this reason, a (wrong) myth is originated, that is “P-wave velocity of the saturated soil is nothing but P-wave velocity of the water.” The truth is that other P-waves except the P-wave through the water exist in their place but hidden in the P-wave propagated through the water.

Recently, it is reported that a P-wave velocity for the saturated media can be distinguished from the P-wave velocity of the pore water. Soil grains have slower P-wave velocity than that of the pore water; therefore, the combination (average) of wave propagation velocity through the pore water and the soil grains gives a slower P-wave velocity. The combined wave will arrive after the first arrival of the P-wave that traveled through the water. This second P-wave is called the slow P-wave velocity (while the first P-wave is called the fast P-wave). The slow P-wave velocity is governed by the volume ratio of the soil grains and the pore voids. Therefore, the slow P-wave velocity contains the information of the pore voids, and therefore it can present the information of the permeability of soils.

Theoretical background for the relationship between the slow P-wave velocity and the hydraulic conductivity can be found in Biot (1956 a, b, Sabatier et al, 1990, Attenborough, 1983). Biot (1956 a,b) developed macroscopic equations for the propagation of elastic waves in poro-elastic medium. Besides the existence of a fast compressional (P) wave and a shear wave, Biot’s theory predicted the existence of a third wave mode referred to as the slow compressional (P) wave.

Works by Smeulders (1992) and others have shown that the slow wave is diffusive at low frequencies and propagatory at high frequencies. The Biot characteristic frequency is the one frequency near which propagation and diffusion effects have approximately equal contributions. The fast P wave is characterized by the simultaneous compression of the pore fluid and the matrix material. The slow compressional wave is characterized by the out of phase movement of the pore fluid and matrix material (Kelder and Smeulders, 1997, Kelder 1997, Cheng and Cheng 1996, Lu et al, 2004)).

This latter phenomenon explains again why slow P-wave behavior is coupled so closely to permeability. Observations show that the slow P wave always has a velocity slower than the P wave velocity of the pore fluid. This makes intuitive sense because the slow P wave velocity can be considered as the average velocity of the pore pressure pulse traveling the torturous path of the sample's pore structure. Following this logic, the ratio of the connate fluid P wave velocity to the bulk slow wave velocity should give a direct measure of tortuosity. This result can be further extrapolated to steady state permeability.

THEORETICAL WORK

Soil consists of an assemblage of particles with different sizes and shapes which forms a skeleton whose voids are filled with water and air or gas. Hence, soil must be looked upon as a multiphase material whose state is to be described by the stresses and displacements within each individual phase. The theory that deals with the coupling of this mixture is called coupled theory of mixtures. Biot (1956 a, b) initiated the coupled theory of mixtures. Biot (1956 a, b) formulation is for the linear elastic behavior of the soils. Later the coupled theory of mixtures was developed into the plastic behavior of the soils (Prevost, 1980), Voyiadjis and Abu-Farsakh (1996), Voyiadjis and Song (2000, 2002).

This proposal deals with the seismic wave, and that is a small strain problem. Therefore, Biot (1955) linear elastic formulation will be used. Biot (1955) also developed the equation for the propagation of seismic waves in the saturated soil was developed by Biot. Biot (1956 a, b) predicted the existence of slow P-wave, however, the slow P-wave was not easy to detect. Recently slow P-wave is detected by some researchers (Yamamoto 2003, Bouzidi and Schmitt 2002, Batzle et al. 2001) due to the enhanced equipments and endeavoring research. Biot (1956 a, b) coupled theory of mixtures for linear elasticity is now revisited.

$$\omega_c = \frac{\eta \phi}{k \rho} \qquad (1)$$

In above equation, ω_c is the characteristic frequency (approximately, the boundary between high and low range), η is the viscosity, ϕ is the porosity, k is the permeability, and ρ is the fluid density. Therefore, one can determine ω_c from the experiment, one can estimate the permeability k form equation (1).

Modification of equation (1) for soils will be expressed in equation (2)

$$f_c = \frac{\phi \cdot g}{2\pi \cdot k} \qquad (2)$$

In the above equation, g is the gravity, f_c is the characteristic frequency in hertz, and k is the permeability in m/sec unit. From the above discussions, it is clear that one can estimate the permeability when we measure the characteristic frequency f_c.

EXPERIMENTAL OBSERVATIONS

Many existing researches focused on finding the characteristic frequency from the velocity of slow P-wave. However, Biot (1956 a, b)'s research showed that the characteristic frequency is also obtained from the fast P-wave showing the attenuation is maximum at the characteristic frequency for the fast P-wave. Therefore experimental set up was configured to capture the attenuation at different excitation frequencies. Figure 1. shows equipment set ups. A wave generator sent signal to the amplifier. Hence, underground actuator could send a wave form to the two receivers. The digital oscilloscope recorded two received signals which were captured by two receivers. These two signals were shown in the computer screen, and the amplitude of signal was recorded. Each frequency shows different amplitude of signal which is related damping ratio. That is used to compute the "damping equivalent". Damping equivalent is computed by amplitude of receiver 2 divided by amplitude of receiver 1. The geometrical damping between receivers 2 and 1 was not filtered out. This is the reason why we call it damping equivalent.

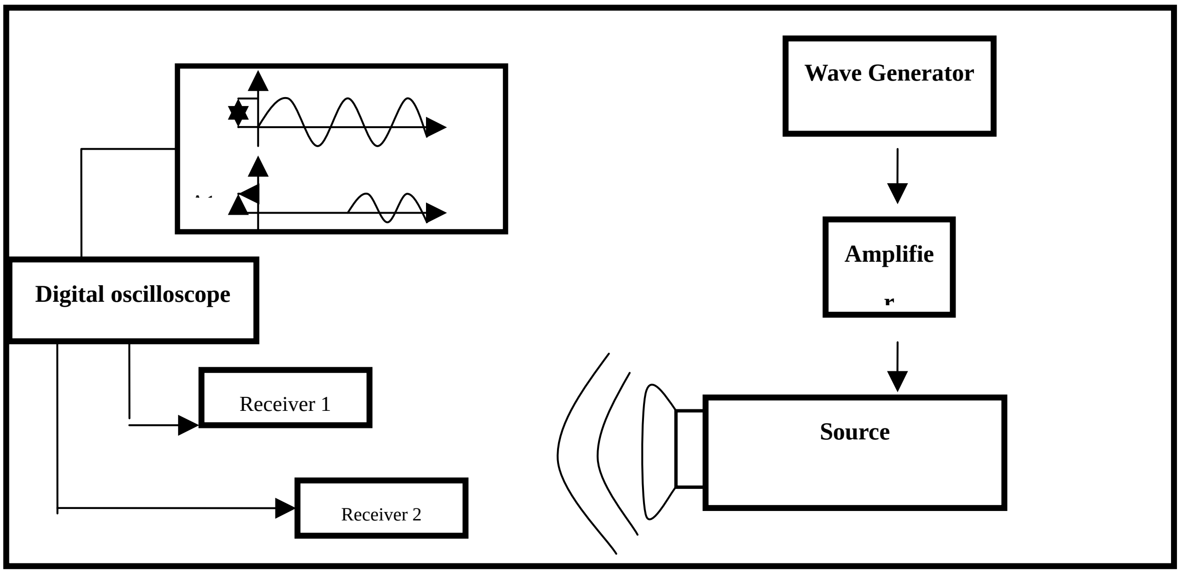

Figure 1, Experimental Set Ups

Figure 2 and 3 are captured at two different frequencies. From Figures 2 and 3, frequency 900 Hz and 3000 Hz, we can notice remarkably different amplitude. When the difference of amplitude of signal is the highest, the frequency is nothing but the characteristic frequency.

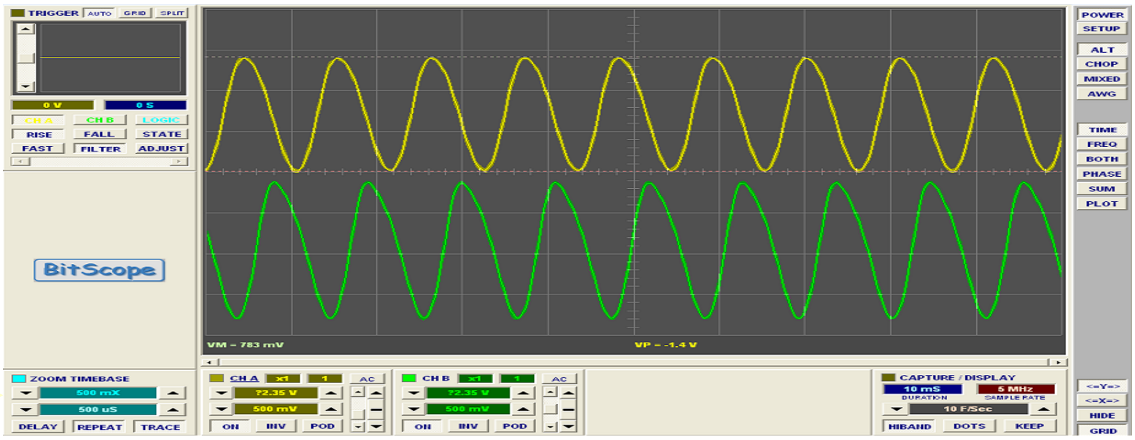

Fig. 2 measured signal form at 900 Hz frequency

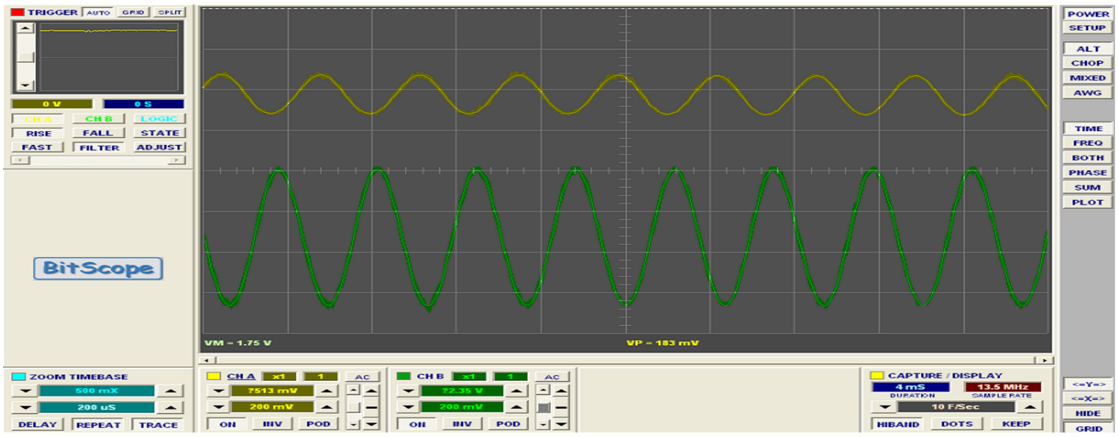

Fig. 3 measured signal form at 3000 Hz frequency

RESULTS AND DISCUSSION

By continuing the experiment for different frequencies, Figure 4 is obtained. This plot is almost the same as the expected shape which are proposed by Biot (1956 a, b) shown Figure 5. The characteristic damping obtained at the 3.4 kHz frequency.

Furthermore, the calculated permeability of this research using Biot's equation (2) was 0.000176 m/sec. The permeability from laboratory test using constant head test, was 0.0000542 m/sec that is about 3.8 times smaller than estimated value from Biot (1956 a, b) equation. This difference may come from the different compaction or experimental error. Or it may be due to the difference between the dynamic permeability and static permeability. However, when one considers the typical error range of the permeability measurements is substantial, the estimated value of permeability using acoustic wave is valuable.

Table 1 Comparison of soil permeabilities

Average soil permeability (from lab.)	Estimated soil permeability (from Biot's equation)
$K = \dfrac{Q \times l}{A \times h \times T}$	$k = \dfrac{\phi \cdot g}{2\pi \cdot f_c}$
0.0000542 m/sec	0.000167 m/sec

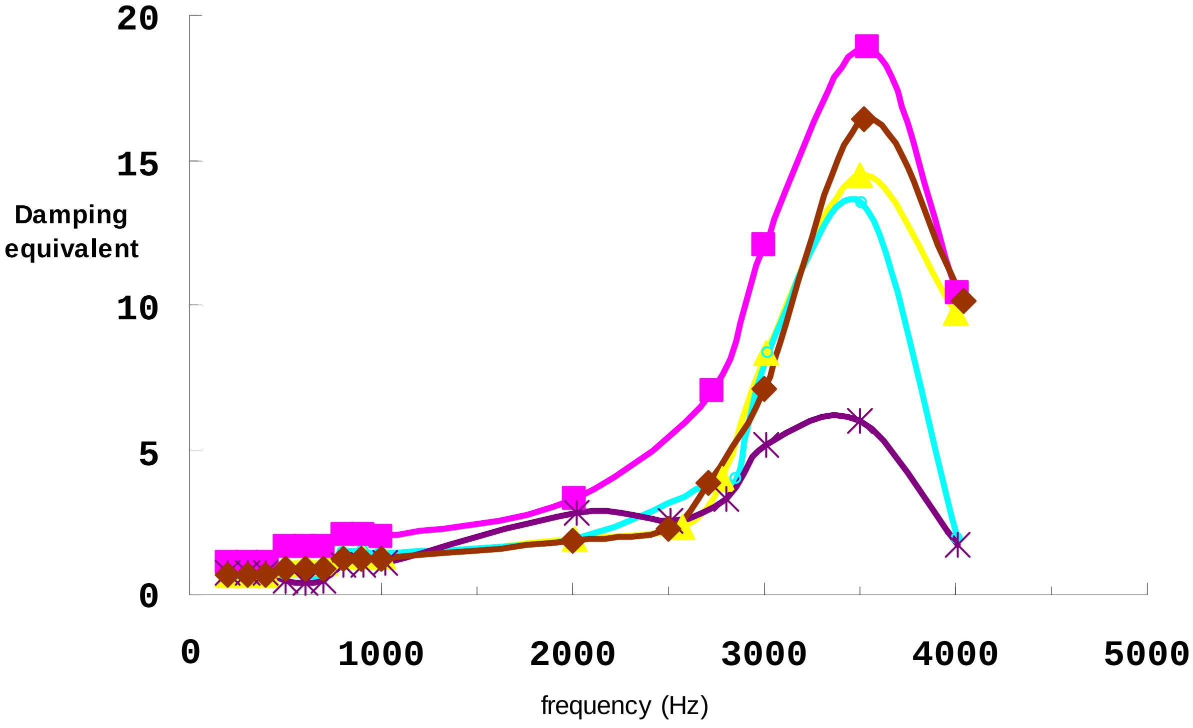

Figure 4 Equivalent damping and excitation frequency relationship

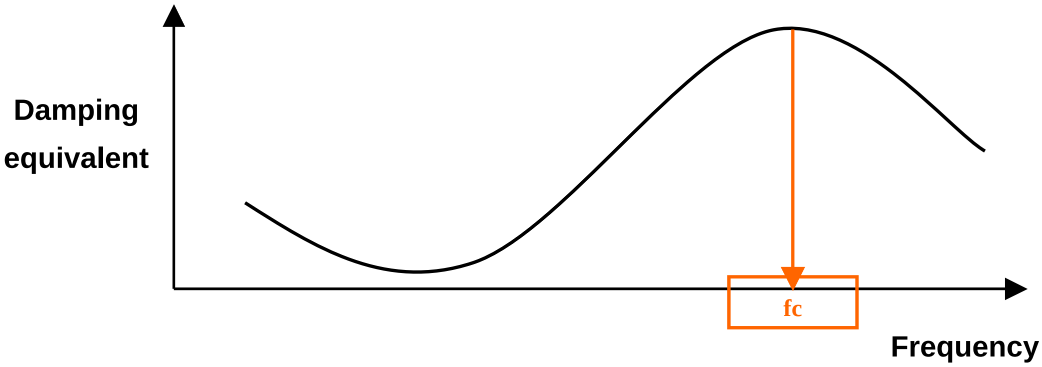

Fig. 5 Expected frequency response from Biot's theory

CONCLUSIONS

The estimation of a soil permeability from the fast P-wave attenuation is tried in this research. Unlike other research (Yamamoto 2003), this study used the damping equivalent and obtained the clear characteristic frequency. From the characteristic frequency, the soil permeability is calculated. The calculated permeability was a little higher than the laboratory measured value, but within the expectable error range. Result of this research is experimentally complicated but not impossible. Moreover, this method eventually will lead to a more accurate design and analysis of geo-structures. Lastly, application of the proposed method may be feasible for other soils.

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