Journal of Applied Geophysics 86 (2012) 8–16

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Application of shear wave velocity for evaluation of equivalent radius of penetrometers

Hyung-Koo Yoon [a,1], Jong-Sub Lee [b,*]

[a] Department of Geotechnical Disaster Prevention Engineering, Daejeon University, Daejeon, Republic of Korea
[b] School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 136-701, Republic of Korea

ARTICLE INFO

Article history:
Received 20 January 2012
Accepted 18 July 2012
Available online 28 July 2012

Keywords:
CPT
Dissipation test
DMT
Equivalent radius
FVP
Horizontal coefficient of consolidation

ABSTRACT

As a penetrometer is pushed into saturated soft soils, excess pore water pressure affected by the disturbed zone is generated. This excess pore water pressure, which dissipates radially, is related to the probe size and shape. The probe size and shape may be represented by an equivalent radius. The aim of this paper is to evaluate the equivalent radius of a penetrometer using the horizontal coefficient of consolidation. Three penetrometers including the cone penetrometer, dilatometer, and Field Velocity Probe (FVP), are used within a large laboratory calibration chamber and in the field. For the calibration chamber tests, a clay–sand mixture is prepared and consolidated under a vertical stress of 160 kPa. These dissipation tests are conducted at a depth that is equal to half the height of the chamber. For the field tests, three penetrometers are penetrated into soft soils through a gravel layer and a sand mat layer. These dissipation tests are implemented at a depth of 24 m. The cone penetrometer, dilatometer, and FVP measure the change of the pore water pressure, the closing pressure value, and the shear wave velocity, respectively. From these six dissipation tests, the equivalent radii of the dilatometer and the FVP are obtained. In addition, an empirical equation for the calculation of the equivalent radius of the penetrometer is suggested.

1. Introduction

Geophysical methods have been widely used for subsurface characterisation: Frohlich et al. (1994) surveyed the groundwater pollution in a coastal environment on the basis of the surface geoelectrical resistivity sounding; Giao et al. (2003) estimated the characteristics of clay deposits using the electric imaging method; Cardarelli et al. (2003) evaluated tunnel stability using three geophysical methods including seismic refraction, seismic tomography, and ground penetrating radar (GPR). Furthermore, geophysical methods have been adopted to obtain geotechnical properties; Foti and Lancellotta (2004) suggested an analytical solution for the estimation of porosity, by using the compressional and shear wave velocities; Cosenza et al. (2006) studied the qualitative and quantitative correlations between geophysical surveys (electrical resistivity, ground penetration radar and seismic refraction) and geotechnical methods (dynamic penetrometer and in situ vane test) for obtaining mechanical properties in soils; Sudha et al. (2009) correlated the geo-electrical data with geotechnical properties for the prediction of soil design parameters; Lee et al. (2010) introduced the Field Velocity Probe (FVP), which can measure shear wave velocities in soft soils, for the evaluation of the small-strain shear modulus (G_{max}) along the depth during penetration; Yoon and Lee (2010) developed the Field Velocity Resistivity Probe (FVRP), which can simultaneously measure both elastic wave velocity and electrical resistivity, for obtaining the porosity and elastic moduli of soils; Uyanik (2011) estimated the geotechnical properties of saturated shallow sediment, by using compressional and shear wave velocities.

The shear wave velocity, which has been widely used for the investigation of subsurface characterisation and for the estimation of geotechnical design parameters, can be obtained by non-invasive and invasive seismic methods. First, non-invasive methods, which detect the shear wave velocity on the surface, include spectral analysis of surface waves (SASW), and multichannel analysis of surface waves (MASW). The vertical resolution of non-invasive methods, however, decreases with depth. Furthermore, the construction of the dispersion curve for the evaluation of phase velocity is complex. Second, invasive methods, which include the cross hole, down hole and suspension logging methods, measure the shear waves in soils, after transducers are installed or pushed into the soil. Thus, invasive methods are generally expensive, as drilling holes, grouting, casing and validating the verticality are all required. In addition, the suspension logging method produces a stoneley wave, which propagates along the stiff steel or plastic casing. The stoneley wave hinders the detection of shear waves. Recently, the Field Velocity Probe (FVP) has been employed as an invasive method for the simple and effective evaluation of shear wave velocity (Lee et al., 2010). As the FVP is

* Corresponding author.
E-mail address: jongsub@korea.ac.kr (J.S. Lee).
[1] Formerly School of Civil, Environmental and Architectural Engineering, Korea University.

0926-9851/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jappgeo.2012.07.009

directly pushed into the soils with the penetration rig, it can measure shear wave velocity profile with extremely high resolution. The shear wave velocities measured by the FVP are almost identical with those determined by the cross hole and down hole methods. The disturbance effect due to FVP penetration, however, has not been evaluated.

The horizontal coefficient of consolidation (C_h), which governs the consolidation process, is directly related to the clay behaviour (Baligh, 1985; Baligh and Levadoux, 1986; Elsworth, 1990; Houlsby and Teh, 1988; Teh and Houlsby, 1991). The horizontal coefficient of consolidation can be obtained in the laboratory using a consolidation test and in the field using a dissipation test (Holtz and Kovacs, 1981). In particular, the dissipation test continuously monitors the decay of excess pore water pressure that is generated by the penetration of a probe. As the excess pore water pressure is assumed to dissipate radially, the consolidation proceeds outwards (Randolph and Wroth, 1970). The dissipation of the generated pore water pressure has been analysed using the cavity expansion theory in which the cavity expands in a soil mass because of the penetration of the penetrometers (Salgado et al., 1997). Thus, the radius of the penetrometers, whose cross-sectional area is circular, rectangular, or another shape is required for the investigation of the relationship between the horizontal coefficient of consolidation and the dissipation of the excess pore water pressure. The determination of the radius of the cone penetrometer is simple because the cross-sectional area is circular. However, the cross-sections of the dilatometer or the Field Velocity Probe (FVP) are not circular. Thus, the equivalent radius is used, instead of the radius, to calculate the horizontal coefficient of consolidation.

Calibration chamber tests have been commonly used to verify the analytical solutions based on the establishment of engineering correlations (Lunne et al., 1997). Reconstituted uniform soils are generally used for the calibration chamber tests. However, the calibration chamber test is limited by conditions such as the boundary effect. Thus, field tests should be carried out to increase the reliability of the chamber tests.

The objective of this study is to assess the equivalent radii of the non-circular type penetrometers using the horizontal coefficient of consolidation (C_h). This paper briefly introduces the in-situ penetration testing methods and discusses the interpretation model for the calculation of the horizontal coefficient of consolidation, relying on the cavity expansion theory. The paper also discusses the experimental procedures and results of the six dissipation tests, which were carried out in the calibration chamber and in the field. Finally, an empirical equation for the calculation of the equivalent radius based on the horizontal coefficient of consolidation and the projected area of the penetrometer is presented.

2. In-situ penetration testing

2.1. Cone penetration testing

After the cone penetration concept was introduced in Sweden in 1917, modern-type cone penetration testing (CPT) was developed in the Netherlands in 1934 to estimate pile end-bearing capacity. The CPT is fast, economical, and productive, and produces a continuous profiling of soil properties. The CPT has been used to develop correlations between geotechnical properties such as soil classification, strength, deformation, and other soil indices (Lunne et al., 1997). For the CPT, many analytical solutions and models with a strong theoretical background have been presented (Ahmadi et al., 2005; Meyerhof, 1961; Salgado et al., 1997; van den Berg et al., 1996; Yu and Mitchell, 1998).

The dimensions of a standard cone with an apex angle of 60° are 35.7 mm in diameter, 10 cm^2 in the projected area, and 150 cm^2 in the friction sleeve. The cone is pushed into the ground, in order to measure the cone tip resistance (q_c), sleeve friction (f_s), and pore water pressure (u). The pore water pressure can be measured at the cone face (u_1), behind the cone tip (u_2), or behind the friction sleeve (u_3), as shown in Fig. 1(a). Note that u_2 is commonly recommended, because the measured cone tip resistance and sleeve friction can be corrected using the u_2 value (Lunne et al., 1986). The pore water pressure is generally positive when the CPT is conducted in saturated soft soils with low hydraulic conductivity (permeability). When penetration is stopped, the generated excess pore water pressure starts to dissipate, causing the pore water pressure to become static. The generation and dissipation of pore water pressure are related to the size of the cone penetrometer, and the horizontal coefficient of consolidation. The dissipation direction is assumed to be radial, in an outward direction from the cone penetrometer. The time factor, which is a function of the shear modulus and undrained shear strength, is also affected by the excess pore water pressure, since the soil moves backward in a shear plane when penetration is stopped (Randolph and Wroth, 1970).

2.2. Dilatometer test

The dilatometer test (DMT) was introduced by Marchetti in 1980 (Marchetti et al., 2001). The dilatometer has a tapered stainless steel blade, with a mounted circular flexible steel membrane. The dimensions of the blade are 220 mm in length, 95 mm in width, and 14 mm in thickness, as shown in Fig. 1(b). The steel membrane is 60 mm in diameter. The dilatometer is connected to a control unit on the ground surface by a pneumatic-electrical tube inserted through the rods. The DMT may yield a 2–3 pressure reading. The first reading, the "A-value", refers to the lift-off pressure, which denotes whether the membrane has collapsed and flattened because of the pressure of the earth. The second reading, the "B-value", represents the expansive pressure that is required to expand 1.1 mm outward from the centre of the flexible membrane. The third reading, the closing pressure or "C-value", is optionally measured by slowly decreasing the pressure on the membrane soon after the "B-value" is reached. The three measured values (A, B, and C) can be converted to the values P_0, P_1, and P_2, respectively, using correction factors for the membrane stiffness. The values P_0, P_1, and P_2 are used to calculate the DMT parameters, including the material index I_D, horizontal stress index K_D, and dilatometer modulus E_D.

Excess pore water pressure is also generated by the penetration of the dilatometer into low permeability soft soils. This generated excess pore pressure dissipates with time. The dissipation of excess pore pressure has been analysed by DMT-A and DMT-C methods. The DMT-A method uses the A-value over an elapsed time. The result, which is plotted as A-value versus log t, shows an S-shape. The "A-value" may stop when the value no longer changes with time. The time for the contra flexure point, t_{flex}, is used for interpretation. The DMT-C method uses the C-value (instead of the A-value) over an elapsed time. The analysis of the DMT-C method is similar to that of the DMT-A method. Note that the basic assumption of the DMT-C method is that P_2 (corrected C-value) is approximately equal to the pore water pressure u_2. Marchetti et al. (2001) suggested that the DMT-C method is valid for soft soils. Thus, the DMT-C method was applied to analyse the DMT test results in this study, because the dissipation tests were carried out in soft soils.

2.3. Field Velocity Probe

The Field Velocity Probe (FVP), which was introduced by Lee et al. (2008), was developed to obtain the shear wave velocities in soft soils during penetration of the probe. The FVP has one blade with two frames as shown in Fig. 1(c). The blade and frames of the FVP were designed with a tapered-shape to minimise soil disturbance during penetration. The dimensions of the blade were manufactured to be 130 mm in length, 89 mm in width, and 10 mm in thickness. The dimensions of the frames were 82 mm in length, 12 mm width, and 6 mm in thickness at the tip.

For the generation and detection of the shear waves, bender elements, which are convenient shear wave transducers, were adopted.