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Engineering Geology 68 (2003) 225–236
ENGINEERING GEOLOGY
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Determination of silica sand stiffness

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Received 13 March 2002; accepted 5 September 2002

Abstract

Site investigation and evaluation of properties of soil or rock are important aspects of geotechnical design. Determination of the ground stiffness is one of the important parameters in geotechnical engineering. Since the measurement of shear modulus is very sensitive to soil disturbance, especially for sand, determination of the stiffness of soil in the field is more reliable than in laboratory tests on sampled specimens. Measurement of shear modulus is one of the most common applications of self-boring pressuremeter testing. As an in situ device, the pressuremeter provides a unique method for assessing directly the in situ shear modulus of a soil. This paper describes a laboratory study of silica sand stiffness, which varies with stress level and strain amplitude. The results show that the elastic shear modulus value is mainly dependent on the value of the mean effective stress and relative density.

Keywords: Shear modulus; Pressuremeter; Silica sand; Stiffness

1. Introduction

Knowledge of the elastic deformation of the ground prior to failure is of considerable importance in geotechnical design. The shear modulus of a soil is a measure of its elastic deformation characteristics, and from it, soil compressibility may be estimated. One of the most common uses of the self-boring pressuremeter test in sand is for the derivation of the soil moduli (Wroth, 1982). As an in situ device, pressuremeter provides a unique method for assessing directly the in situ shear modulus of a soil (Bellotti et al., 1989; Fahey and Jewell, 1990).

As quoted by Schnaid et al. (2000), there is scarce experience in materials other than clays and sands, and interpretation is constrained to measurements of soils stiffness (Martin, 1977; Rocha-Filho and Carvalho, 1998). However, Ortigao et al. (1996), Schnaid (1997) and Schnaid and Mantaras (1998) have just recently shown that the non-textbook materials, such as residual soils, allow shear strength parameters to be derived from the test.

The behavior during unload–reload loops during the expansion portion of a pressuremeter test (or reloading–unloading loops during the contraction section) provides information on the stress and strain level-dependent shear modulus of soils (Campanella et al., 1990). The shear modulus can be determined by using the slope of the pressure–expansion curve. If the soil is perfectly elastic in unloading, then the

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PII: S0013-7952(02)00229-6

unloading–reloading cycle will have a gradient of $2G_{ur}$, where G_{ur} is the unload–reload shear modulus. The gradient of a curve of pressure (ψ) versus cavity strain (ε) is equal to $2G$. The following equation presents the relevant expression:

$$G = \frac{1}{2}\frac{d\psi'}{d\varepsilon} \tag{1}$$

Eq. (1) implies that the soil surrounding the probe is subjected to shear, and the test measures the "elastic" shear modulus of soil, G (Wroth et al., 1979; Mair and Wood, 1987; Schnaid, 1990).

However, the interpretation of the shear modulus obtained by pressuremeters is not simple. The moduli vary with stress level and strain amplitude (Wroth et al., 1979; Jamiolkowski et al., 1985; Robertson and Hughes, 1986; Bellotti et al., 1989; Schnaid, 1990), and the effect of pressuremeter length on shear modulus value deduced from the pressuremeter test is not clear. These issues will be discussed in the following sections through the analysis of the pressuremeter data.

2. Correction of shear modulus

Calibration of pressuremeter data is an important operation in deriving the corrected pressure–volume curve. This correction has a considerable influence on the measured shear modulus because the amplitude of strain (a loading–unloading loop) is so small. This is especially the case for soil with higher stiffness in which any small error in measurement of cavity volume can result in large errors in shear modulus value. This error is a result of the compressibility of the pressuremeter system ,and calibration has to be carried out. This issue has already been discussed by Mair and Wood (1987), Fahey and Jewell (1990) and Schnaid (1990).

In order to correct the pressure readings, the membrane resistance has to be subtracted from the raw pressure at the same volume. The correction of the system compliance consists of subtracting the volume due to compressibility of the system from the raw volume readings at the same pressure. This correction technique was applied to raw pressuremeter data to obtain the correct pressure–expansion curve. This issue has been discussed by Ajalloeian and Yu (1998).

The procedure proposed by Fahey and Jewell (1990) for determining the compliance of the strain-measuring system has been followed in the present study to obtain the correct shear modulus.

3. Measurement of shear modulus

The shear modulus is generally calculated from the slope of the unload–reload loops using Eq. (1). In order to interpret the shear modulus measured by pressuremeter tests, it is assumed that the pressuremeter is sufficiently long for the cylindrical cavity to expand radially under plane strain conditions in the axial direction. The possible effect of the finite pressuremeter length on shear modulus will be discussed in the following section.

The measurement of the elastic shear modulus of silica sand deduced from a number of pressuremeter tests in a calibration chamber is presented in this paper. Generally, in every pressuremeter test, the following three types of shear moduli have been obtained:

(a) initial shear modulus, G_i
(b) unloading–reloading shear modulus, G_{ur}
(c) reloading–unloading shear modulus, G_{ru}.

The initial shear modulus is determined from the initial slope of the pressure–expansion curve. The elastic shear modulus of the sand is also measured by performing one or two unloading–reloading loops during a pressuremeter expansion test. Another method for determining the shear modulus consists of performing a reloading–unloading loop during the pressuremeter unloading test (Houlsby and Withers, 1988).

Since G_i is measured in the early part of the expansion curve, this value is sensitive to soil disturbance due to installation. For this reason, it is generally thought to be a less reliable measurement. In the present study, although the pressuremeter was placed in the calibration chamber prior to the soil preparation, it seems that in some tests the pressuremeter membrane did not exactly touch the soil cavity wall at the beginning of the test. Therefore, the initial shear modulus deduced from pressuremeter tests in calibration chamber may not be reliable.

As a result of this problem, the following discussion will be mainly focused on the values deduced from unload–reload loops. Based on the discussion made by Hughes (1982) and Wroth (1982), the unloading–reloading loop was performed during the expansion test to obtain the elastic shear modulus. This method is more accurate than the initial shear modulus if the unloading in loop is carried out in elastic conditions to avoid the failure of the soil at the cavity wall. Experience has shown that G_{ur} is largely independent of the initial shape of the expansion curve. Therefore, soil disturbance will have little effect on G_{ur} (Robertson and Hughes, 1986; Bellotti et al, 1989; Schnaid, 1990).

According to experiences of Bellotti et al. (1989), which were performed in calibration chamber and in a natural sand deposit, the values of G_{ur} were scaled to small strain determined from resonant column test and field cross-hole tests are in good agreement. However, the accuracy of the strain measurement and the test procedure in determination of G_{ur} are important. Therefore, considerable attention to probe design was required for reliable strain measurements.

It is necessary to expand the membrane far enough to test undisturbed ground if the modulus of intact ground is required (Clarke, 1995). The unload–reload loops are carried out after more than 2% cavity strain to minimise the effect of initial disturbance on shear modulus values (Mair and Wood, 1987). The inflation usually was interrupted one or two times and, in few cases, three times to carry out small unload–reload loops. The cavity strain amplitudes for all loops were similar and the range was typically about 0.12–0.16%. Generally, the shear modulus adopted for the curve fitting varies within the range of values measured from unload–reload cycles performed in each individual test. Measured G values reflect the relevant mean stresses and strain amplitudes for a given test and should in theory provide a realistic fitting to pressuremeter pressure–expansion curve (Schnaid et al., 2000).

The amount of creep deformation during pressuremeter tests in sands should also be considered. This amount increases as the cavity stress increases (Hughes, 1982; Robertson, 1982; Withers et al., 1989). In this study, the following procedure has been followed in performing unload and reload–unload loops to take into account creep deformation.

Before performing the unloading–reloading loop, the cavity strain was held constant for 1 min until the pressure became constant. The purpose of this was to minimise the apparent hysteresis in the unload–reload loop due to soil creep and to allow for a more accurate determination of shear modulus (Briaud et al., 1983). In addition, the membrane was inflated and deflated at a very slow rate, about 0.46% per minute, to keep the creep strains to a minimum.

It is recognized that if the surrounding soil prevents the soil from failing during each loop, then the value of G_{ur} and G_{ru} gives a reliable value of elastic shear modulus (Fahey and Randolph, 1984; Bruzzi et al., 1986). Based on Wroth's (1982) suggestion, the magnitude of the change in cavity stress in the unloading section should not exceed a pressure change ($\Delta\psi'$) given by the following equation:

$$\Delta\psi' = \frac{2\sin\phi'_{ps}}{1+\sin\phi'_{ps}}\psi'_{c} \tag{2}$$

where ψ'_{c} is the effective cavity stress at the beginning of unloading–reloading loop. This equation defines the elastic range of behavior for unloading in sands.

Fahey (1992) suggested that the value of $\Delta\psi'$ should be limited to half the value given by Eq. (2), to stay within the elastic range of behavior for unloading in sand. In the present experimental work, the value of cavity stress change was usually about $0.4\psi'_{c}$, which was less than the value deduced from Eq. (2). The slopes of unloading–reloading or reloading–unloading loops are calculated by conducting a simple linear regression analysis based on the least-square fit through all the data points.

4. Interpretation of shear modulus

The application of shear modulus deduced from the pressuremeter test in engineering design is complicated, because the value of stiffness varies with both stress level and strain amplitude (Wroth et al., 1979;

Jamiolkowski et al., 1985; Bellotti et al., 1986; Robertson and Hughes, 1986). Hence, the shear modulus should be normalised to mean effective stress level existing around the pressuremeter cavity. Thereafter, the value of G_{ur} can be applied in engineering design. Another factor that affects the measured stiffness is the age of deposit. As Soliman and Fahey (1995) stated, the stiffness of natural deposits tends to increase with age, both in "engineering" time and "geological" time.

Interpretation and analysis of the shear modulus was made using a database obtained from 44 pressuremeter tests carried out in the Newcastle calibration chamber in which more than 100 loops were performed through the strain-controlled pressuremeter tests. In all cases, the pressuremeter tests were performed in dry silica sand with the probe having been cast in place during sample preparation (ideal installation).

In the following sections have been evaluated the influences of mean effective stress and finite length of probe on shear modulus measured with a pressuremeter. As was mentioned in the previous section, the creep deformation and strain amplitude were also considered. Inspection of the literature suggests that the creep rate and strain increment size have only had a secondary influence on the shear modulus (Withers et al., 1989).

4.1. Effect of mean effective stress on stiffness

The influence of the mean effective stress on shear modulus has been studied by performing unload–reload loops at different values of cavity stress during the tests. The shear strain amplitude of the loops was mainly kept within a constant range to ensure that the moduli are obtained over the same strain range.

Since the sand in the calibration chamber was dry and free draining, there was no pore pressure during the test and the mean effective stress increased as the test progressed. For this reason, the shear modulus value increases as the position of the unloading–reloading loop moves further from the beginning of the test (Wroth, 1982; Fahey and Randolph, 1984; Robertson and Hughes, 1986; Bellotti et al., 1989; Schnaid, 1990).

The effect of the stress level was studied by Janbu (1963) and Duncan and Chang (1970). Based on their results, Robertson and Hughes (1986) proposed the following expression for granular materials, which suggests that the value of elastic modulus is dependent on the value of the mean effective stress (P') and is usually proportional to $(P')^n$, where n is typically 0.5.

$$\frac{G}{P_{\mathrm{a}}} = K_G\left(\frac{P'}{P_{\mathrm{a}}}\right)^n \tag{3}$$

where: K_G = modulus number, n = modulus exponent, typically 0.5, P_{a} = reference stress (i.e. $P_{\mathrm{a}} = 100$ kPa), P' = mean effective stress that is equal to:

$$P' = \frac{1}{3}(\sigma'_r + \sigma'_\theta + \sigma'_z) \tag{4}$$

In using Eq. (3) to evaluate the effect of mean effective stress on shear modulus value, the mean effective stress at the beginning of each unloading–reloading loop should be calculated.

In the plastic zone, the mean effective stress decreases with increasing distance from the probe. At some distance from the expanding cavity, the mean effective stress value becomes equal to the in situ stress (Fahey, 1980; Robertson and Hughes, 1986; Yu, 1990). Robertson and Hughes (1986) proposed that the unload–reload response is dominated by the value of stress existing at the interface of soil–instrument. Therefore, the G values should be normalised by the maximum mean effective stresses around the probe.

It is assumed that the soil around the pressuremeter behaves elastically during the unloading–reloading performance. This means that the radial stress decreases by the same amount as the circumferential stress increases. Therefore, the mean effective stress is constant during the unloading–reloading loop.

Through a large number of self-boring pressuremeter test results in sand, Robertson and Hughes (1986) suggested that the mean effective stress at the face of the pressuremeter (when the soil is at failure) is approximately one-half of the effective radial stress. Based on a simplified assumption of an elastic–perfectly plastic behavior of sand, the ratio of the principal stresses can be expressed as:

$$\sigma'_\theta = \sigma'_r\left(\frac{1-S}{1+S}\right) \tag{5}$$

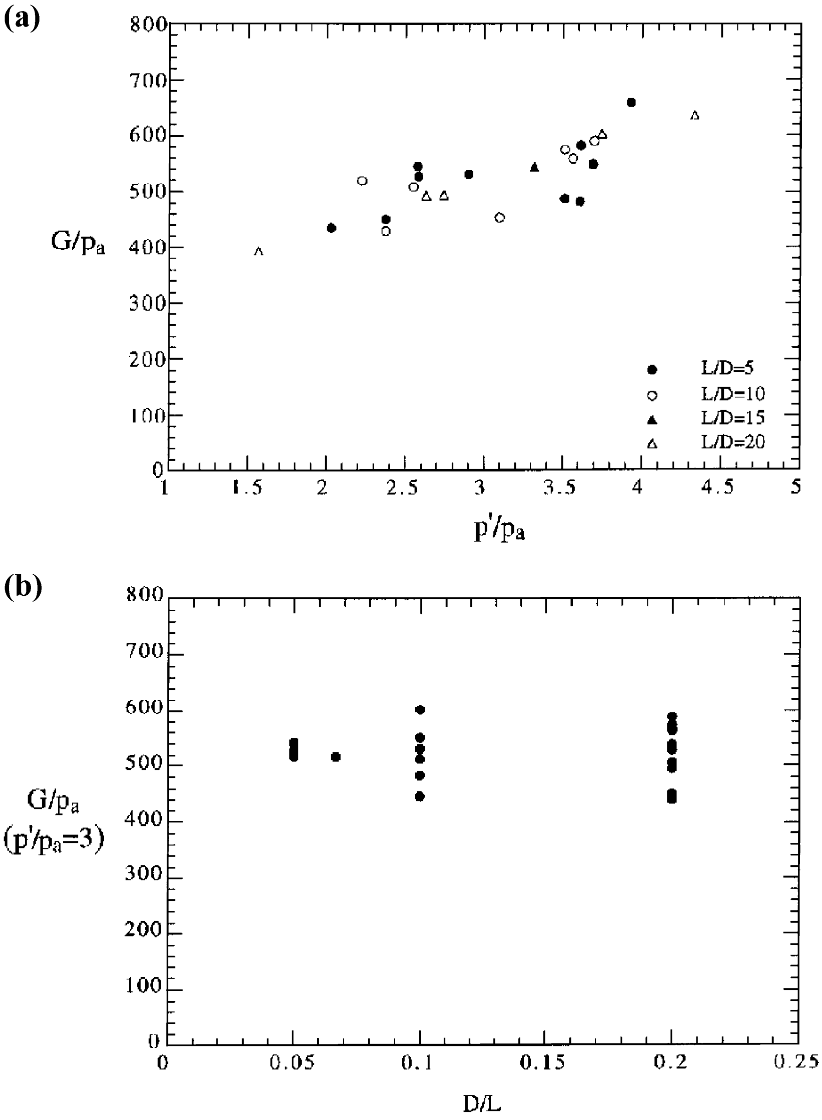

Fig. 1. Influence of geometry of pressuremeter on shear modulus deduced from tests in loose sand; (a) present shear modulus values deduced from tests with different pressuremeter lengths, (b) illustrates that there is not a considerable effect of pressuremeter length on shear modulus value.

where

$$S = \sin\phi'_{\mathrm{ps}} \qquad (6)$$

Burd (1986) gives the following equation to determine the intermediate principal stress σ'_z from and σ'_θ.

$$\sigma'_z = (\sigma'_\theta \, \sigma'_r)^{1/2} \qquad (7)$$

The average mean effective stress at the edge of the expanding cavity at the start of the unload–reload loop can be given by combining Eqs. (5) and (7):

$$P' = \frac{\sigma'_r}{3}\left[1 + \frac{1-S}{1+S} + \left(\frac{1-S}{1+S}\right)^{1/2}\right] \qquad (8)$$

Eq. (8) can be written as:

$$P' = \alpha\sigma_r' \qquad (9)$$

where in the case of pressuremeter tests on silica sand and through the result correlations, it is found $\alpha = 0.63$ for $\phi'_{ps} = 31$ (loose sand), $\alpha = 0.56$ for $\phi'_{ps} = 40$ (medium sand) and $\alpha = 0.52$ for $\phi'_{ps} = 46$ (dense sand).

For the reload–unload loops performed in the contraction portion, Eq. (8) has also been used to calculate the mean effective stress because all reloading–unloading loops were performed before plastic unloading occurs.

As Robertson (1982) proposed, with a knowledge of mean effective stress (P'), the unload–reload modulus can be corrected for in situ stress level G_{ur}^{c}

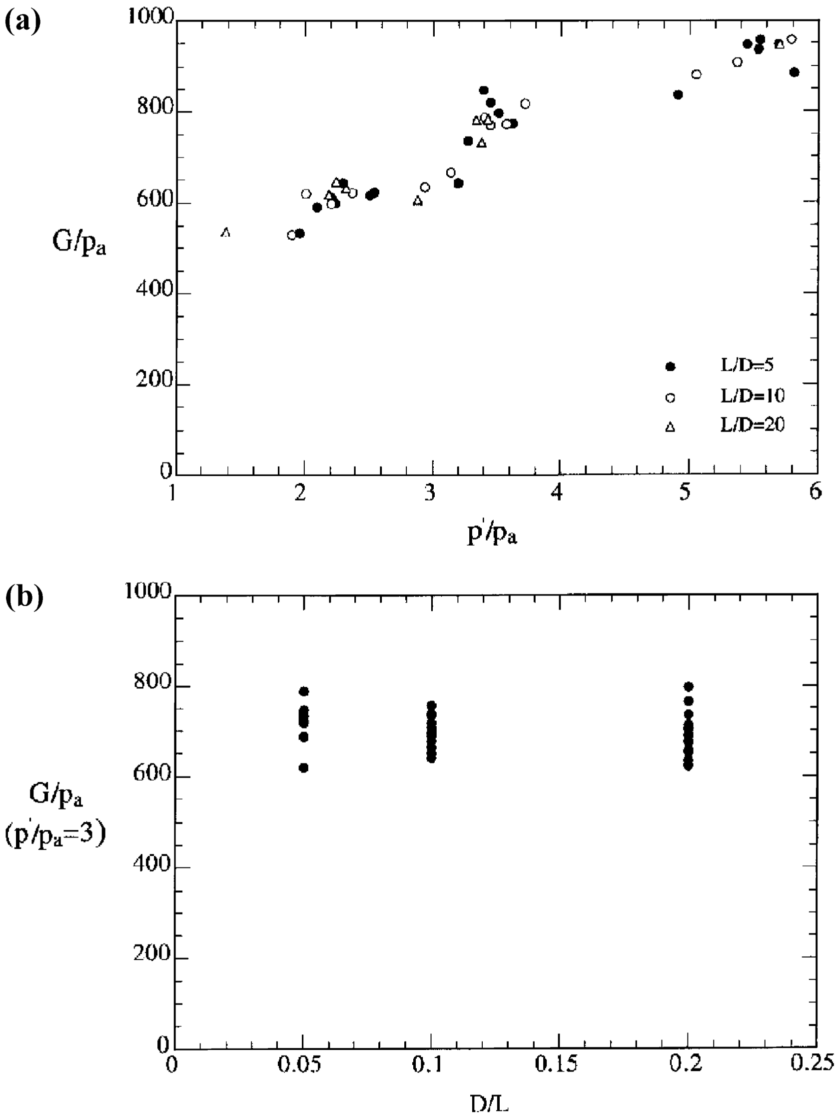

Fig. 2. Influence of geometry of pressuremeter on shear modulus deduced from tests in medium sand; (a) present shear modulus values deduced from tests with different pressuremeter lengths, (b) illustrates that there is not a considerable effect of pressuremeter length on shear modulus value.

using the following formula proposed by Janbu (1963)

$$G_{ur}^{c} = G_{ur}\left(\frac{P'_O}{P'}\right)^{n} \tag{10}$$

where P'_O is in situ mean effective stress and n is the modulus exponent that is typically equal to 0.5.

4.2. Effect of pressuremeter length on stiffness

The influence of the geometry of the probe on the shear modulus has been studied by performing unload–reload and reload–unload loops at various *L*/*D* ratios.

Figs. 1a, 2a and 3a present shear modulus values deduced from tests with different pressuremeter

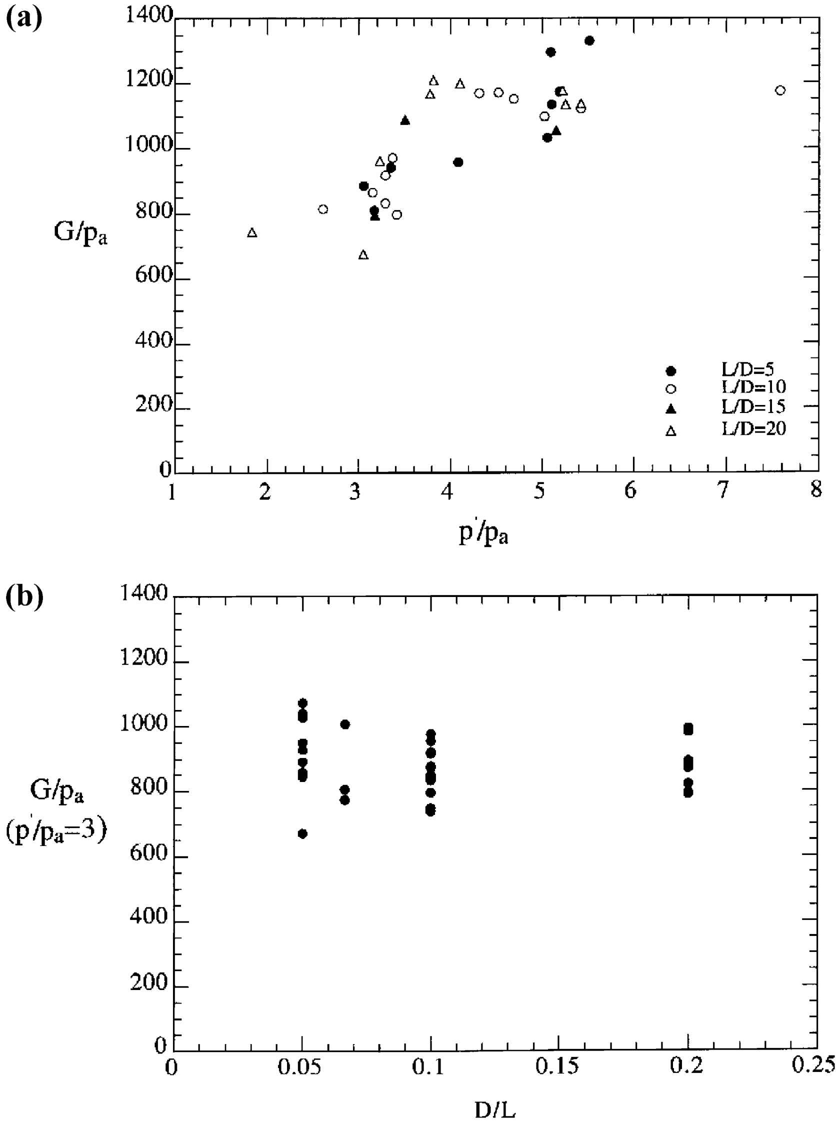

Fig. 3. Influence of geometry of pressuremeter on shear modulus deduced from tests in dense sand; (a) present shear modulus values deduced from tests with different pressuremeter lengths, (b) illustrates that there is not a considerable effect of pressuremeter length on shear modulus value.

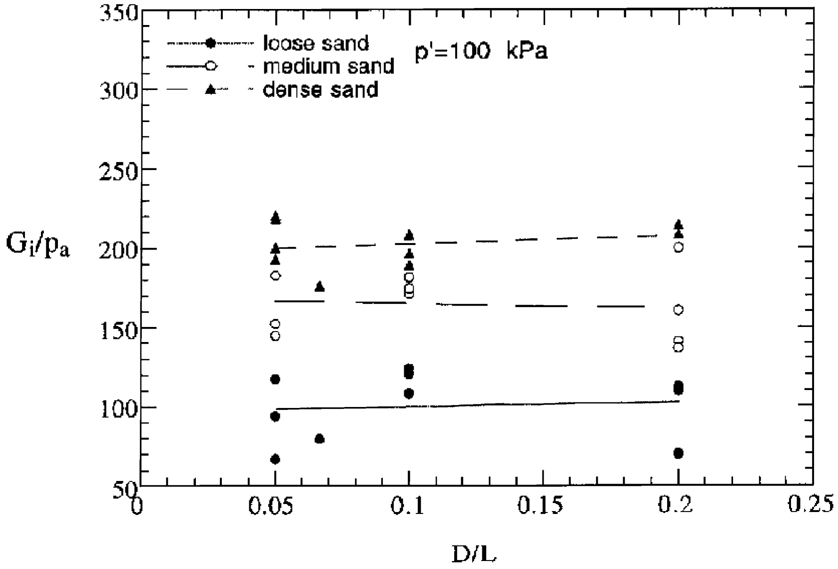

Fig. 4. Pressuremeter length effect on initial shear modulus in different densities ($P' = 100$ kPa).

lengths in different relative density in which they are loose (30–35%), medium (50–60%) and dense (70–90%) sands, respectively. By using Eq. (10), it is possible to convert the shear modulus measured at different mean effective stresses to shear modulus at a given mean effective stress (e.g. $P'/P_a = 3$). Figs. 1b, 2b and 3b illustrate that pressuremeter length has no considerable effect on shear modulus value.

The initial shear modulus values deduced from different pressuremeter lengths in various densities

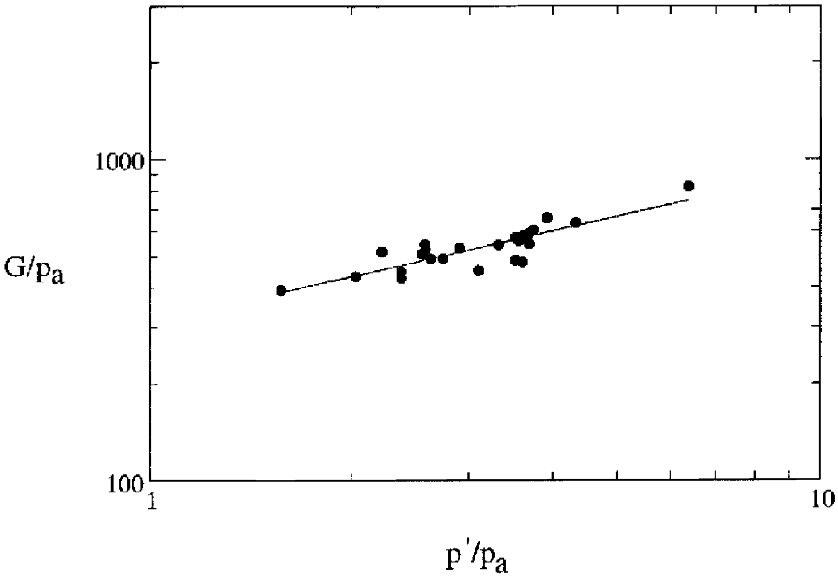

Fig. 5. Correlations between shear modulus and mean effective stress (in loose sand).

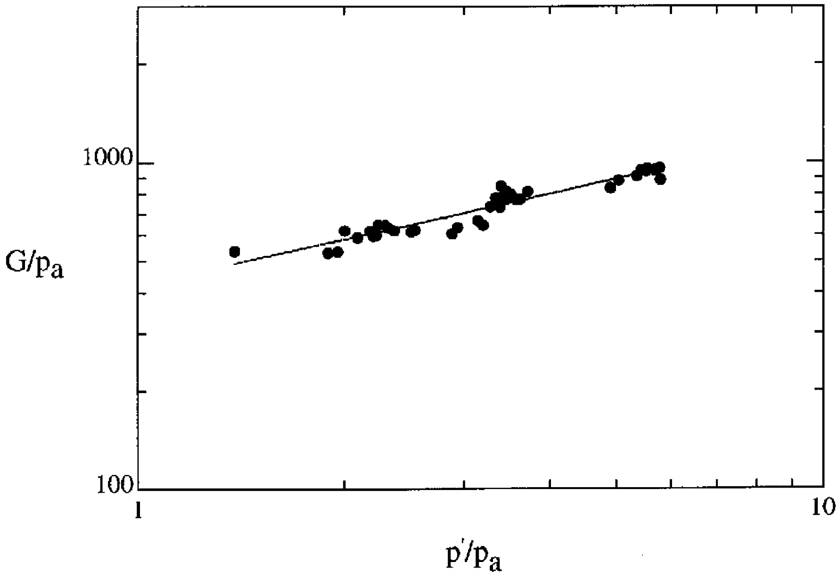

Fig. 6. Correlations between shear modulus and mean effective stress (in medium sand).

and with the same mean effective stresses ($P' = 100$ kPa) show that the initial elastic shear modulus is also not sensitive to the geometry of the probe (Fig. 4).

Generally, the results in dry sand using four different *L*/*D* ratios show that finite length of the pressuremeter probe has no significant effect on shear modulus. The numerical studies carried out by Yu (1990) and Houlsby and Carter (1993) support this finding. They showed in their numerical studies that the finite length of the pressuremeter has only minor effects on the apparent value of the shear modulus. The Houlsby and Carter (1993) results

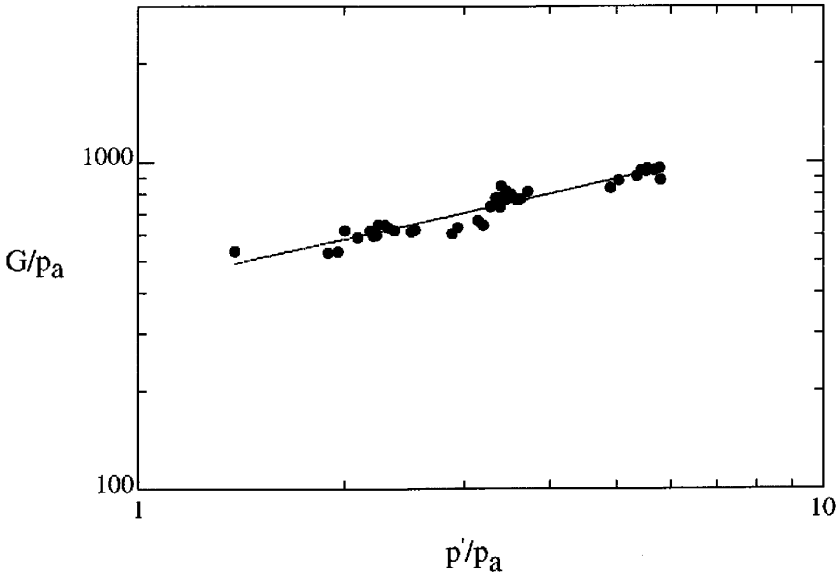

Fig. 7. Correlations between shear modulus and mean effective stress (in dense sand).

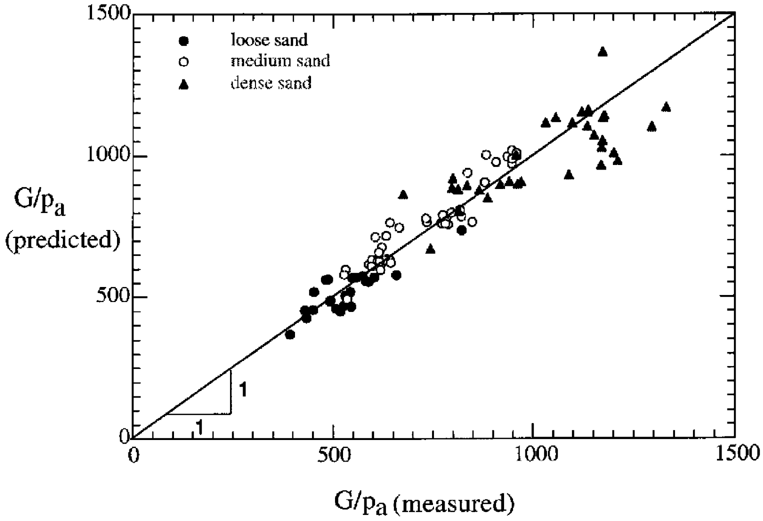

Fig. 8. Shear modulus (measured vs. predicted) at different densities.

showed an overestimation of stiffness of only 1.4% for $L/D = 6$. Laier (1973) also concluded through an experimental study that the finite pressuremeter length has no significant influence on the measurement of pressuremeter modulus values. Hartman (1974) (quoted by Briaud (1992)) found that for an $L/D = 6.5$, the G calculated from the pressuremeter test was 5% larger than the modulus of the soil.

5. Analysis of results

According to Eq. (3), a general correlation between shear modulus and mean effective stress level can be established for data from different densities. Figs. 5, 6 and 7 show these correlations for loose, medium and dense sands. For each of the three densities, there is an approximately unique modulus exponent relationship between shear modulus and mean effective stress with different modulus numbers:

$K_G = 313$ (for loose sand)
$K_G = 422$ (for medium sand)
$K_G = 516$ (for dense sand).

In the present experimental study, the relationship between modulus number and density is well fitted by a linear correlation. Generally, the dependence of the elastic shear modulus on the mean effective stress and relative density for silica sand can be expressed in a dimensionless form by the following equation:

$$G/P_a = (183 + 3.68R_d)(P'/P_a)^{0.5} \tag{11}$$

where the R_d is expressed as a percentage and P_a is equal 100 kPa. Fig. 8 illustrates the comparison between the measured shear modulus and shear modulus estimated by Eq. (11). There is relatively good agreement between these two values.

6. Conclusions

The pressuremeter is a suitable device for in situ measurement of shear modulus of cohesionless soils. In practice, the unload–reload or reload–unload shear modulus can be used instead of initial shear modulus (G_i). This procedure is helpful in reducing or eliminating the effect of soil disturbance that is caused by insertion of the device.

Over 100 loops have been performed during a series of pressuremeter tests. All pressuremeter tests were carried out in a calibration chamber under controlled conditions of mean effective stress, stress ratio and density. One of the important aims of the present study was to investigate the effects of mean effective stress and pressuremeter length on shear modulus results deduced from a pressuremeter.

The results show that the elastic shear modulus value is mainly dependent on the value of the mean effective stress and the relative density as expressed in Eq. (3). For each of the three densities, there is an approximately unique modulus exponent relationship between shear modulus and mean effective stress with different modulus numbers. The modulus is number correlated with sand density.

The effect of the geometry of the pressuremeter on the shear modulus was also examined. After analyzing the results, it was found that the finite length of the pressuremeter has no significant effect on shear modulus obtained from calibration chamber pressuremeter tests. This finding is supported by the numerical studies reported by Yu (1990) and Houlsby and Carter (1993). They concluded that, whilst the influence of the finite length on strength parameter measurements is significant, it results in negligible overpredictions of stiffness.

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