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In situ shear wave velocity determination using seismic cone penetrometer for evaluating soil anisotropy

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ABSTRACT: Previous research using laboratory techniques has suggested that shear wave velocity measurements may be useful for determining in situ stress conditions. To evaluate this in the field, a downhole-crosshole seismic cone test has been developed and performed at several clay research sites. While the results do indicate a stress dependency of the shear wave velocity, it appears that this parameter is much more sensitive to variations in soil fabric.

1 INTRODUCTION

The key parameter used in many constitutive models and numerical techniques for evaluating soil response to applied static and dynamic loads is the shear modulus. Various studies have demonstrated that the maximum shear modulus, G_o, is primarily a function of both stress state and soil fabric (Hardin, 1978; Yu and Richart, 1984; Roesler, 1979 and Stokoe et al., 1985).

According to elastic theory, G_o can be calculated from the elastic shear wave velocity as given by:

$$G_o = \rho V_s^2 \qquad (1)$$

where:
ρ is the density of the soil and V_s is the elastic shear wave velocity, generated at shear strain amplitudes of $10^{-4}\%$ or less.

Several techniques are currently in use to measure V_s both in the laboratory and in the field and these are reviewed by Woods (1986, 1991). In situ shear wave velocity measurements are commonly performed using both downhole and crosshole procedures in boreholes. A more recent version of the downhole test developed at the University of British Columbia (UBC) is that whereby a cone penetrometer with mounted seismometer is employed, thus eliminating the need for boreholes (Campanella and Robertson, 1984). The seismometer is incorporated into the cone body and used to detect body wave arrivals generated from a seismic source located at the surface. By modifying the equipment set-up, the seismic cone penetration test (SCPT) can also provide crosshole velocity measurements (Baldi et al., 1988).

Previous research suggests that it may be possible to use the results of V_s measurements to index and/or evaluate stress and structural anisotropy in soils. This is examined here.

2 SEISMIC CONE PENETRATION TEST

2.1 SCPT downhole procedure

Campanella and Robertson (1984) developed the downhole seismic cone penetration test (DH-SCPT) to provide a rapid and economic way for performing in situ shear wave velocity measurements. The seismometer is placed horizontally and oriented perpendicular to the source to provide maximum sensitivity to the horizontal component of the surface-generated shear wave.

The SCPT is performed by first pushing

the cone to the depth of interest. A horizontal blow to the shear beam is then applied. Hammer contact with the shear beam provides the trigger for the data acquisition system (DAS) which recovers the signal when it arrives at the receiver mounted in the cone. The time for the signal to travel from the ground surface to the cone receiver can then be obtained. The horizontally polarized wave travels vertically from the source to the receiver mounted in the cone. The direction of wave travel (vertical) is perpendicular to the direction of particle motion (horizontal). This type of wave is termed a VH wave.

Measurement of the travel times from tests at subsequent depths allows the shear wave velocity profile to be determined from the pseudo-interval travel time method (Robertson et al., 1986).

2.2 SCPT crosshole procedure

Using a dual cone system, Baldi et al., (1988) modified the downhole SCPT in order to perform crosshole velocity measurements. However, since only one receiver cone was used, the shear wave velocity has to be calculated from the first arrival time. The error in this approach may be significant, depending on the quality of the signal and the soil conditions at the test location.

A simple downhole and crosshole set-up has been developed at the University of British Columbia capable of generating different polarized shear waves with the idea of examining in situ anisotropy. The equipment and results obtained are briefly described herein.

3 UBC CROSSHOLE AND DOWNHOLE SCPT

The downhole-crosshole seismic cone penetration test set-up (DH-XH SCPT) developed at UBC employs a source and two receivers all embodied in cone penetrometers. Two receivers are considered necessary to ensure accurate determination of travel times, especially since the crosshole separation used is small (about 2-4 m). The source, in the form of a vane cone, was designed so that the horizontally polarized shear wave could be generated with either vertical (HV) or horizontal (HH) particle motion. The procedure for performing the XH-DH seismic cone test is described in detail by Sully (1991). The test configuration is shown in Fig. 1.

Three principal techniques are used for interpreting the shear wave traces obtained from DH and XH SCPT procedures, namely:

- first shear wave arrival
- crossover or reverse polarity method
- crosscorrelation method.

Details of the various techniques are given by Stokoe and Woods (1972), Campanella et al. (1989) and Gillespie (1990) and will not be discussed further here.

4 THEORETICAL CONSIDERATIONS

Previous research has shown that at small strains V_s is dependent only on σ' and fabric:

$$V_s = C_s \, \sigma'_n \qquad (2)$$

C_s is a shear wave velocity constant dependent on soil state. Little or no effect of OCR has been found from laboratory data (Hardin and Drnevich, 1972; Lee, 1985). Recent results, however, suggest that V_s is also affected by the level of shear stress in the soil (Nishio and Tamaoki, 1990; Yan and Byrne, 1990). Roesler (1979) suggested that V_s is dependent primarily on the stresses in the direction of wave propagation and in the direction of particle motion; the third principal stress having a negligible effect on V_s. This idea was extended by Knox et al. (1982) to demonstrate the effects of inherent anisotropy on V_s in the laboratory. They proposed the individual stress method for describing the dependence of V_s on the level of effective stress:

$$V_s = C_s(\sigma'_a)^{na}(\sigma'_b)^{nb}(\sigma'_c)^{nc} \qquad (3)$$

where:

σ'_a, σ'_b, σ'_c are the principal effective stresses

na, nb, nc are exponents for each of the stress directions

Based on a series of tests in a large cubical sand specimen, Lee (1985) suggests this approach correctly models the characteristic cross-anisotropic behavior of natural sands. A similar conclusion is reached by Yan and Byrne (1990).

The effective stress dependence of the shear wave velocity acting at any depth can be defined according to the following stress indices:

- mean normal effective stress
- average effective stress
- individual effective stresses

The V_S-stress relationships can be rewritten in terms of Ko for the evaluation of in situ field data, assuming that the stresses in the horizontal plane are isotropic ($\sigma_2=\sigma_3$). Consequently, a shear wave propagating horizontally with particle motion in the same plane can be considered as an isotropic shear wave and produce the velocity value $(V_S)_I$. Conversely, any wave generated with either direction of propagation or particle motion in planes where the stresses are not isotropic can be designated the anisotropic value $(V_S)_A$. The $(V_S)_A$ velocity then, defines both the downhole VH shear wave and the crosshole HV wave, whereas the $(V_S)_I$ velocity explicitly defines the crosshole HH shear velocities when evaluating the field data, the superscripts DH and XH will be used to denote the downhole and crosshole situations, respectively.

For the VH and HV shear waves, if the stress dependence is the same in the two controlling directions (travel and particle motion), then the two velocities should be the same (if the two shear wave velocity constants are also identical) i.e.

$$(V_s)_A^{DH} = (V_s)_A^{XH} \qquad (4)$$

The ratio between the anisotropic and isotropic shear wave velocities can be thus related to the lateral stress coefficient, K_O. For the three possible stress indices, the following ratios in terms of K_O are obtained:

Mean normal stress:

$$(V_s)_A/(V_s)_I = (C_A/C_I) \qquad (5)$$

Average stress:

$$(V_s)_A/(V_s)_I=(C_A/C_I)*[(1+K_o)/2K_o]^{nt} \qquad (6)$$

Individual stress:

$$(V_s)_A/(V_s)_I = (C_A/C_I)*(K_o)^{-na} \qquad (7)$$

where C_A and C_I are the anisotropic and isotropic shear wave velocity constants.

From the above relationships, it would appear feasible to evaluate the results of in situ DH and XH V_s measurements in terms of both stress-induced and structural anisotropy. The problem then is one of determining the various constants in the above equations. As an initial estimate, the C_A/C_I ratio can be taken as unity. Published data from Lee (1985) and Yan and Byrne (1990) give a range of values between 1.0 and 1.1. A review of the reported values of the exponents in Eqs. (5), (6) and (7) is given by Stokoe et al. (1985) and Sully (1991).

5 DH AND XH SCPT RESULTS

DH-XH SCPT were performed at two research sites: Lr. 232 St. and 200 St. are clay sites where an overconsolidated (OC) crust becomes normally consolidated (NC) with depth. At Lr. 232 St. the change to a NC clay profile is fairly smooth, whereas it is very abrupt at 200 St. (It was hoped that the stress history variation at 200 St. would prove ideal for mapping using DH and XH shear wave velocities). Also, if the above relationships between V_s and K_o are valid, the expectation was that the nondestructive measurements would be a useful technique for evaluating anisotropic stress conditions in sand.

Results from the tests performed at 200 St. are presented here in detail. Results from the tests at Lr. 232 St. are discussed but not presented.

5.1 Shear wave velocity measurements

5.1.1 Lr. 232 St.

Two downhole profiles were performed at the locations of the source cone and first receiver cone (R1) used for the crosshole set-up. A second receiver cone (R2) was used but problems were encountered with data capture and so arrival times at R2 are not available for interpretation. Downhole velocities were calculated from crossover and crosscorrelation travel times. Some scatter exists in the $(V_s)^{DH}$ values but it is confined to the upper 3 m of the profile. Below this depth the DH shear wave velocities obtained at both locations are in good agreement. All the DH waves are of the VH type described above.

The $(V_s)^{XH}$ values have been obtained from two types of signal as described earlier. A hit in the up or down direction produces a HV shear wave, whereas the clockwise and anticlockwise (torque) hits produce HH shear waves. The two crosshole velocities are very similar with the tendency for the VH velocity to be marginally larger than the HH velocity.

Both the downhole and crosshole velocity profiles indicate a degree of stress dependence. The high V_s in the surface OC soil reduces with depth (to about 4 m) before increasing linearly with depth.

5.1.2 200 St.

The DH and XH shear wave velocities determined at this site are shown in Fig. 2. As mentioned previously, the soil at 200 St. is heavily to moderately overconsolidated (OCR = 5-20) to a depth of about 5 m. Below 5 m the clay silt is slightly overconsolidated (OCR = 2). The V_s profiles in Fig. 2 would seem to individually reflect the stress history associated with the above description. The $(V_s)^{DH}$ is higher than both $(V_s)^{XH}$ values; the two XH velocities are again essentially identical.

Two receiver cones were used at this site so downhole and crosshole velocity determination was done by both crossover and crosscorrelation techniques.

5.2 Comparison of velocity ratios

As discussed above, a consideration of the stress effects suggests that the downhole VH and crosshole HV shear wave velocities should be the same. This does not appear to be the case for any of the sites. Conversely, this ratio appears to provide the best indicator of the known stress history profile for the sites.

For the 200 St. (and Lr. 232 St.) clay data, it is clearly evident that (Fig. 2):

$$(V_s)_I^{XH} = (V_s)_A^{XH} \qquad (8)$$

and hence the stress relationships would suggest that K_o is either constant with depth or independent of the in situ effective stress ratio.

6 DISCUSSION AND CONCLUSIONS

The theoretical relationship between velocity ratios and K_o for the various stress indices are given in Eqs. (5), (6) and (7). The mean normal stress index suggests that the anisotropic to isotropic velocity ratio is solely a function of the ratio of the velocity constants in the two planes and independent of the effective stresses. The average stress (Eq. (6)) and individual stress (Eq. (7)) indices suggest a dependence on both the effective stress and stiffness ratios. The theoretical variation of the velocity ratio $(V_s)_A/(V_s)_I$ with K_o is shown in Fig. 3 for different values of the exponents in Eqs. (6) and (7). Regarding these two plots (with C_A/C_I = 1), the following comments can be made:

- The average stress index in Fig. 3(a) appears to be a reasonable basis for using the velocity ratio concept to determine K_o when nt > 0.1. Data from the literature suggest an average nt value of 0.25 (Stokoe et al., 1985).

- The individual stress index in Fig. 3(b) is illconditioned for determining K_o irrespective of the na value. Small changes in the velocity ratio give large variations in predicted K_o.

An example of the insensitivity of the V_s ratio to variations in K_o can be appreciated by considering the data at 200 St. The surface K_o attains values of more than 2.0 in the OC soils, reducing to 0.6 in the underlying NC soils (Sully, 1991). Using Eqs. (6) and (7), the variation in $(V_s)_A/(V_s)_I$ with depth for 200 St. can be calculated. The results are presented in Fig. 4. Even at a site where the K_o profile shows considerable variation, the V_s ratio is illconditioned to index these changes.

It would appear from the results presented here for the two clay sites tested that the shear wave velocity ratio is only slightly influenced by the in situ effective stress conditions. Furthermore, the data suggest that V_s is much more sensitive to variations in the stiffness ratio, C_A/C_I. In this case, the downhole-crosshole shear wave velocity ratio may provide a good indicator of structural (inherent) anisotropy rather than stress anisotropy. Hence, it would appear reasonable to use the mean normal stress as the stress index for evaluating field data.

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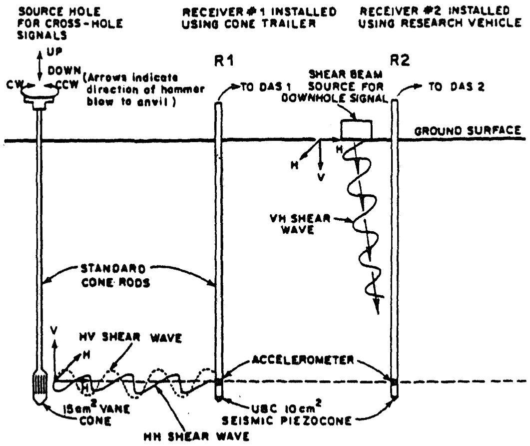

Figure 1. SCPT layout for DH and XH shear wave velocity measurements.

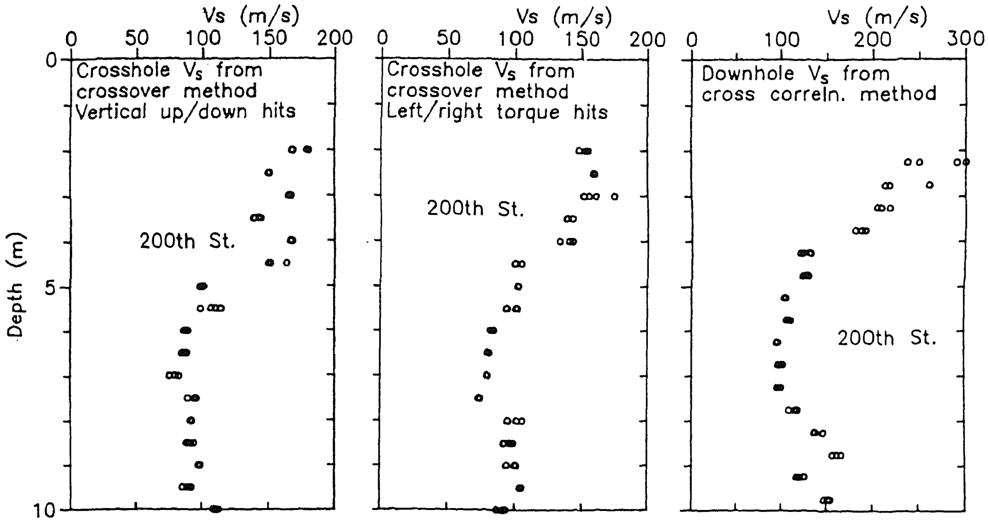

Figure 2. DH and XH V_S profiles for overconsolidated clay at 200 St.

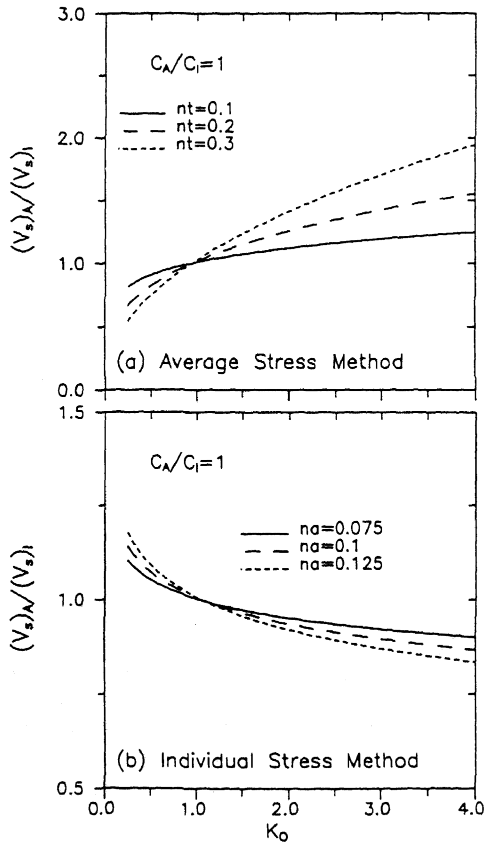

Figure 3. Theoretical dependence of $(V_s)_A/(V_s)_I$ on K_o.

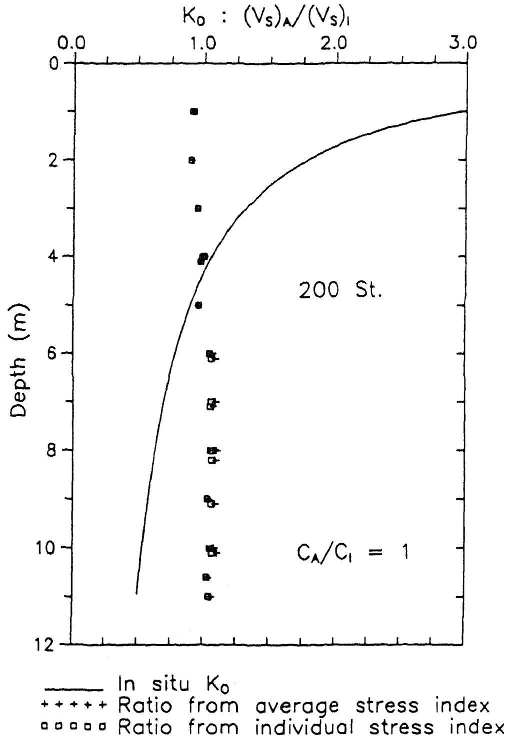

Figure 4. Profile of K_o and $(V_s)_A/(V_s)_I$at 200 St.