DISCUSSION

Evaluation of in situ anisotropy from crosshole and downhole shear wave velocity measurements


V. S. Hope, University of Surrey

The authors conclude that the in situ effective stress conditions at their test sites did not contribute to the degree of seismic anisotropy they perceived. It follows that, as a first port of call, the formulae due to Stoneley (1949) describing seismic propagation velocities as a function of the five independent elastic parameters of a transversely isotropic (cross-anisotropic) medium, with no stress terms, can be taken to apply. According to elastic theory, in transversely isotropic material having a vertical axis of symmetry, the speeds of propagation of horizontally travelling, vertically polarized shear waves ($V_{HV}$), vertically travelling, vertically polarized shear waves ($V_{VV}$) and also vertically travelling, horizontally polarized shear waves ($V_{VV}$) are equal. The speed of horizontally propagating, horizontally polarized shear waves ($V_{HH}$) has some other value which, in a material that is stiffer horizontally than vertically, will exceed $V_{HV}$ etc. Thus, Fig. 12(a) ($V_{HV}$) would be expected to match Fig. 12(c) ($V_{HH}$) and, in the presence of transverse isotropy, both would differ from Fig. 12(b) ($V_{HH}$). This is in contrast with the results presented by the authors: in the paper, Figs 12(a) and 12(b) are similar to each other, and they differ markedly from Fig. 12(c). A similar pattern is shown in Fig. 11.

To suggest, as the authors do, that their results might be explained using full anisotropy is, arguably, premature. Before that considerable step is taken, it seems preferable that more mundane— but manageable—explanations be considered. For example, is it coincidental that the data in Figs 11(a) and 12(c) were obtained using a different field method to those in Figs 11(b) and 12(a) and 12(b)?

There are always sufficient pitfalls in any seismic survey, especially one involving new instrumentation, that it is essential to include some form of independent check—no matter how crude—on the data. In the case of 200 St, for example, it is observed that the variation in $V_{HH}$ with depth between 2 and 4.5 m below ground level is slight (Fig. 12(b)). Therefore, inter-borehole measurements of the apparent velocity of horizontally polarized shear waves travelling along included paths within this zone, such as between a source at 4.5 m and a receiver at 2 m, could have been used indirectly to validate the $V_{HV}$ profile (Fig. 12(c)) and perhaps clarified whether the theoretically unexpected and sizeable difference between $V_{HV}$ and $V_{HV}$ is due to either (a) something unforeseen in the techniques used or (b) the properties of the ground. (The apparent velocity of a horizontally polarized shear wave with an inclined path in a transversely isotropic but homogeneous medium is given by a simple elliptical function of the velocities exhibited along horizontal and vertical paths, that is $V_{HH}$ and $V_{HV}$).

Finally, with reference to a subject that had been raised in the preceding issue of Géotechnique (Viggiani & Atkinson, 1995), the authors carried out their crosshole measurements at a range of 2–4 m from the source and so, no doubt, these observations fell within the near-field of the source. Did irrotation components within this zone affect the determination of the shear wave travel time? On an associated theme, at greater distances, did compressional wave energy from the impact-type source also complicate this determination?

REFERENCES


A. P. Butcher, and J. J. M. Powell.

The evaluation of in situ ground anisotropy is of considerable interest in the analysis of many geotechnical problems. Seismic measurements offer the potential to evaluate the anisotropy in situ; however interpretation is complex and the authors are to be congratulated on their interesting and valuable attempt to look at the problem. Research at the Building Research Establishment (BRE) has been working towards the same goal. However, the field data obtained show relationships between the different shear wave velocities that are very different to the authors’ results.
Butcher & Powell (1995b) showed that field measurements of shear wave velocities in two stiff heavily overconsolidated clay test bed sites, London Clay at Chattenden, and Gault Clay at Madingley, \((K_0 = 2.4\) and OCR \(= 18\)) gave \(V_{HH} > V_{HV} > V_{RH}\); the shear wave velocity data from Madingley are shown in Fig. 1 as an example. Here \(V_{SW}\) is the velocity calculated from Rayleigh wave measurements that has been found to give a useful lower-bound value of shear wave velocity. Work on normally consolidated sands (Eidsmoen et al., 1984; Dyvik, 1985) and clays (Butcher & Powell, 1995a) showed \(V_{HH} \approx V_{VH} \approx V_{SW}\) without unfortunately any \(V_{RH}\) data. The authors’ data for both their sites gave \(V_{HH} = V_{HV} < V_{SW}\) with the biggest differences at the shallowest depths. Butcher & Powell (1995a) showed that with the downhole technique, using the seismic cone as a receiver, erroneously high values of shear wave velocity can be obtained down to about 6 m if the horizontal distance between the source and the receiver is greater than 1 m. What distance was used by the authors?

Interestingly neither the authors’ nor the BRE data agree with the theoretical relationship for the velocities of shear wave propagation in a cross anisotropic media when

\[
V_{HH} \neq V_{HV} = V_{VH}.
\]

The authors quote a theoretical relationship between the in situ stresses and the shear wave velocity given by Roesler (1979) as

\[
V_s = C(a'_p)^n (a'_s)^{(1,n,a)} (a'_c)^{(1,n,b)}
\]

where

\[
\begin{align*}
\sigma'_p &= \text{principal effective stress parallel to the direction of wave propagation} \\
\sigma'_b &= \text{principal effective stress parallel to the direction of wave polarization} \\
\sigma'_c &= \text{principal effective stress orthogonal to both} \\
&\text{directions of wave propagation and polarization. Do the authors}
\end{align*}
\]

Roesler (1979) also showed that \(nc = 0\). For the \(V_{HH}\) data, where both the directions of propagation and polarization are in the horizontal plane, Roesler’s equation becomes

\[
V_s = C(a'_p)^n a'_b \text{ the in situ horizontal effective stress,}
\]

and \(nt = na + nb\). It therefore follows that by using \(V_{HH}\) data and knowing \(a'_b\), down a profile then the equation can be solved for \(C\) and \(nt\). Butcher & Powell (1995b) found that \(nt = 0.5\) for the Chattenden site and 0.62 for the Madingley site. The ratio of \(na:nb\) was also investigated in order to obtain a consistent relationship between the different shear wave velocity measurements and the in situ stresses. The best coincidence of data was found when \(na = 3nb\) as shown in Fig. 2, which includes data from both sites using four shear wave measurement techniques. This gave site specific values of \(nt\) and \(C\) and implied that the \(V_s\) measurements were dominated by stress anisotropy.

In the paper the authors have accepted the values of \(na = nb = 0.125\) which gives \(nt = 0.25\). Have the authors tried to calculate the value of \(nt\) from their field \(V_{HH}\) data? The authors concluded that the differences in the measured shear wave velocities were more likely to be related to inherent or structural anisotropy and that stress anisotropy was not important. However the BRE data imply a strong dependence on the stresses in the directions of propagation and polarization. Do the authors have any views on this?

The starting point to understanding the differences between the authors’ results, BRE results and theory is not only to study the effects of fabric and stress anisotropy on the propagation of shear waves, but also to look more fundamentally at the characteristics (frequency, amplitude, wave front

---

**Fig. 1.** Shear wave velocity – depth profile for heavily overconsolidated clay at Madingley
generation, near field effects etc.) of the shear waves as produced by the different sources. The BRE sources are quite different to the authors’ vane-type penetration source. The BRE work used a downhole vertically sliding hammer for the VHV and a downhole rotary hammer for the VHH work which give very similar amplitude and frequency spectra waves at the receivers. Are the amplitudes and frequency spectra of the horizontally polarized and vertically polarized waves generated by the vane-type source similar? Further, the BRE sources were used in boreholes with grouted liners which were surveyed for verticality. We would be interested to know how the relative horizontal positions of the source and receivers were established in the cross-hole measurements.

**REFERENCES**


**Authors’ reply**

With respect to Dr Hope’s opening comments, for a transversely isotropic (cross-anisotropic) material, we agree that the following shear wave velocity relations should apply

\[ V_{HV} = V_{VH} = V_{HH} \]

However, he also states that

\[ V_{HV} = V_{VH} = V_{VV} \]

which is incorrect since \( V_{VV} \) is no longer a shear wave but a compression wave. The \( V_{HH} \) velocity is only a shear wave if the direction of particle movement in the horizontal plane does not coincide with wave travel in the same plane. For that reason, the \( V_{VV} \) wave can only be compressional, whereas the \( V_{HH} \) can be shear or compressional.

In relation to Dr Hope’s observation that different field procedures were employed to obtain the results in Figs 11(a) and 12(c), it should be noted that the same technique was used for all the tests reported. However, as explained in the paper, the measured data can be interpreted in various ways to obtain the shear wave velocities, namely: first shear wave arrival, reference cross-over points or cross-correlation of signals. All three interpretation techniques have been used for the presented data and very similar, if not identical, \( V_s \) values are obtained. Furthermore, for the Lr 232 St data, the second receiver cone malfunctioned during the test and so only a two cone set-up was available, as opposed to the three cone set-up used at 200 St.

As suggested by Hope, inclined shear wave velocity paths may have provided additional information to help explain the unexpected relative values of the crosshole velocities—however, we did not perform the measurements. This aside, the slight variation in \( V_{HH} \) between 2–4.5 m may be due to offsetting influences of a reduction in OCR and an increase in \( \sigma^\prime \).

In both discussions, Hope and Butcher & Powell suggest near-field effects as a possible complicating factor in the determination of the crosshole velocities. These effects are important in engineering measurements, when the source and receiver are closely spaced—the term ‘close’ referring to the relative values of the source-receiver separation and the wavelength of the generated signals.
(Sanchez-Salinero, Roesset & Stokoe, 1986; Sanchez-Salinero, Stokoe & Roesset, 1986). This facet was evaluated by using two receiver cones in the crosshole set-up; the distance between the source cone and first receiver \(d_1\) was kept equal to the spacing between the first and second receiver \(d_2\) as in Fig. 8(c) \(d_1\) and \(d_2\) were tried initially at 2 m separation, but owing to space requirements between the penetration rigs, a 3 m spacing was used for the reported data.

The wavelength of the generated waves, obtained from \(V_s = \beta f\), where \(f\) is the frequency and \(\lambda\) is the wavelength, was in the range 0.2–1.5 m for the predominant energy in the frequency range of the signals (100–250 Hz). According to Sanchez-Salinero, Roesset & Stokoe (1986), for typical set-ups where the distances \(d_1\) and \(d_2\) are equal, near-field effects can be neglected if the source-receiver separation \(d_1\) is at least one wavelength. (Comparing the crosshole velocities measured at the two different receivers \(R_1\) and \(R_2\), the fact that the velocities are similar and consistent would suggest that for the source-receiver spacings used, near-field effects are not significant at the \(R_1\) location.) Similarly, compressional wave energy did not complicate the data interpretation.

In response to the points raised by Butcher & Powell regarding the downhole data, tests have shown that similar results are obtained using different \(V_s\) techniques at shallow depths. However, large scatter may exist between different test series as a result of surface wave interference and errors in measurement, especially up to depths of 2–3 m. For the UBC set-up, the source is kept at the surface as the receiver cone is progressively pushed deeper. Consequently, the source-receiver separation increases as the test proceeds. The results have been compared to standard borehole methods, both downhole and crosshole, and consistent results obtained. At all the sites we have tested, the downhole \(V_s\) measurements are remarkably repeatable below about 2 m. We have not experienced the problems mentioned by Butcher & Powell and have not seen the paper so cannot comment further. The problems may be related to some set-up conditions or ground coupling effects.

As an aside, the results of Eidsmoen et al., (1984) in the normally consolidated sands at Holmen give \(V_{HH}\) and \(V_{HV}\) relative values which are very variable: \(V_{HV} > V_{HH} \) or \(V_{HH} > V_{HV}\) depending on which data are compared (one crosshole and three downhole profiles presented). We also performed downhole–crosshole tests at a sand site in the Lower Mainland, BC. However, we did not report the data in the paper as considerable scatter exists, but the general trend gives \(V_{HH} > V_{HV} \) or \(V_{HV} > V_{HH}\).

For the plastic clay at Museumparken, the presented data suggest that \(V_{HV}\) is larger than \(V_{HH}\). These results also do not agree with the theoretical relationship for the velocities of shear wave propagation in a cross-anisotropic medium.

The fact that the authors’ data as well as the above-mentioned cases give

\[
V_{HH} = V_{HV} < V_{VH}
\]

for sites where \(K_0 < 1\), may suggest that the stress in the direction of propagation has the controlling influence over the measured velocity; this also concurs with the data presented by Butcher & Powell, since the data is for \(K_0 > 1\). The larger than expected difference between the \(V_{HH}\) and \(V_{HV}\) velocities presented by Butcher & Powell may be due to the secondary influence of the vertical effective stress and OCR.

Alternatively, the poor agreement with the theoretical relationship may result from the fact that the materials tested are not cross-anisotropic in the vertical and horizontal directions as a result of the overconsolidation process. We have not tried to backcalculate \(C_t\) and \(nt\) values from \(V_{HH}\) as suggested by Butcher & Powell. To do this, one first needs to know the horizontal effective stress—an interesting concept! Any error in this parameter would completely mask the velocity relationships. As we demonstrated on p. 278 of the paper, assuming a constant value of \(C_t\), the variation in the obtained stresses is larger than the actual values being calculated.

In terms of the necessity to evaluate the fundamental characteristics of the generated shear waves, this was standard procedure at the time the data were obtained. Frequency content, amplitude and near-field effects (as discussed above) were all considered. For the different sources used in our tests, both the surface shear beam and the downhole shear cone produced waves of similar frequency content and amplitude. The shear deformations produced with the shear beam were in the range \(1.5 \times 10^{-3}\%\) at the surface reducing to \(4 \times 10^{-4}\%\) with depth, while the crosshole shear deformations were from \(1.16 \times 10^{-4}\) to \(6.99 \times 10^{-4}\%\). All these values fall within the small strain portion of the modulus reduction curve (Fig. 16). Energy input for the crosshole signals was difficult to control, but the levels of shear deformation would suggest that reasonably constant input was attained. For the downhole data, the energy levels recorded at the receiver are higher near the surface and decrease as the receiver cone is pushed deeper.

Verticality of the cone holes was checked using the inclinometers installed in each of the seismic cones used for the study. The variation in verticality did not warrant crosshole distances to be corrected for deviations.

The authors are grateful to Drs Hope and Butcher & Powell for their interest in the paper.
and hope that the above comments have clarified their questions related to the content of the paper.

REFERENCES