35. Shear wave velocity measurements during penetration testing

Hepton P. 1988. Shear wave velocity measurements during penetration testing. *Proc. Penetration Testing in the UK, ICE,* 275-278.

P. HEPTON, BSc, University College of North Wales

Two 3 component seismic receivers have been combined with both an electric cone penetrometer and a flat dilatometer. Measurements of shear wave velocity can be carried out during penetration testing, from which the dynamic shear modulus can be assessed. The method is considerably quicker and cheaper than conventional borehole seismic investigation techniques. The results from two sites investigated with the seismic cone penetrometer and one with the seismic flat dilatometer are presented.

INTRODUCTION

1. In recent years equipment for making simultaneous seismic measurements in conjunction with standard in situ tests has been developed, for example the seismic cone penetrometer [Robertson et al (ref.1)]. Conventional seismic investigation techniques, such as crosshole and downhole testing, require the drilling and usually casing of at least one borehole. Additional equipment for lowering, orientating and clamping the geophones and energy sources in the boreholes is required, and the procedures are often slow and awkward. While the surface refraction method is considerably more straightforward, it is unable to detect lower velocity layers underlying higher velocity layers, or distinguish between thin layers with little velocity contrast. The seismic cone penetration test (SCPT), and seismic flat dilatometer test (SDMT) described herein, provide a simple and rapid means of performing 'downhole' seismic tests at the same time as carrying out the measurements normally made during penetration testing. A knowledge of the shear wave velocity, Vs, together with the relevant soil density, ρ, allows the shear modulus, G, to be calculated from equation (1).

$$G = \rho . Vs^2 \qquad (1)$$

2. The value of the shear modulus approaches a maximum for strain levels of less than approximately $10^{-3}\%$ [Hardin and Drnevich (ref.2)]. Typically seismic in situ measurements produce strains of the order of $10^{-4}\%$ [Seed and Idriss (ref.3)] and consequently the derived shear modulus can be regarded as a maximum. This parameter is necessary for assessing the dynamic behaviour of soils, but it is also possible to make strain amplitude and strain rate corrections to convert the dynamic shear modulus to a static modulus, e.g. Bennell et al (ref.4).

EQUIPMENT AND METHODS

3. Seismic cone penetration test. The seismic cone penetrometer developed at the University College of North Wales (UCNW) is based on an electric piezocone with two seismic receivers mounted in the push rod string. The lower one is positioned immediately behind the cone penetrometer, with the upper one placed 1 m above it. Each receiver contains 3 mutually perpendicular velocity transducers (or geophones) of 28 Hz natural frequency connected to the surface via a multicore cable threaded through the rods. The analogue signals from the cone are also carried in this cable and are passed to a BBC Model B microcomputer-based logging system where the data is temporarily stored in the computer's memory before being transferred to disc at the end of each 1 m run. The 6 geophone signals are monitored using an ABEM Terraloc digital seismograph which displays the signals received on a screen and allows them to be recorded on a cassette.Triggering of the seismograph is achieved by using a geophone planted close to the source.For better time resolution a 2 channel Nicolet 3091 digital oscilloscope, triggered by one of the input signals, is also used. This has a maximum sampling rate of 1 µs per point compared to 24 µs for the Terraloc, and consequently enables more accurate assessments of travel time to be made.

4. The seismic cone penetration tests described below were performed using a trailer mounted 20 tonne sounding rig, as shown in Fig. 1. The seismic cone penetrometer was advanced at the standard rate of 2 cm/s in continuous runs of 1 m, with continuous logging of the cone outputs by the microcomputer. At 1 m increments, at the end of each rod run, shear wave velocity measurements were made. The shear wave source used was a wooden plank, approximately 1600x200x100 mm, weighted down by the rear screw jacks of the rig to ensure good coupling with the ground, and struck on the end with a sledge hammer. This type of shear wave source is frequently used for surface refraction work [e.g. Morris and Abbiss (ref. 5)] as well as for downhole measurements, and has been found to produce predominantly horizontally polarised shear waves with very little compressional wave energy. This prevents disruption of the first part of the shear wave signal by earlier, faster arrivals.

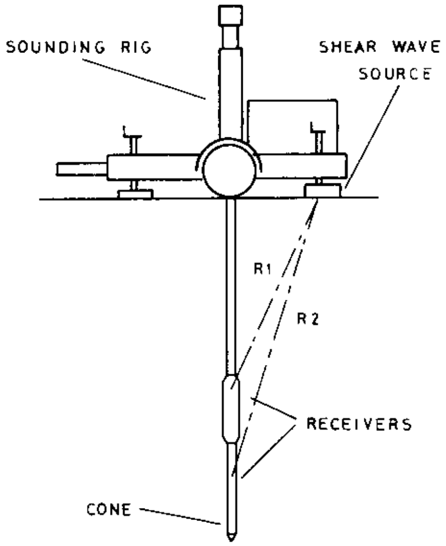

Fig. 1. Seismic cone penetration testing system

5. In order to make shear wave measurements, it was only necessary to monitor the component of each receiver aligned with the direction of particle motion, i.e. perpendicular to a line from source to receiver. The signals from the two appropriate geophones were monitored on the oscilloscope, while all the geophone signals were monitored by the seismograph. The end of the wooden plank was struck with the sledge hammer, which triggered the seismograph and generated shear waves which were detected by the geophones. The signals were displayed on the oscilloscope and seismograph so that their quality could be assessed and once a satisfactory record was made penetration was continued for another 1 m, and the process repeated.

6. The microcomputer-recorded data was transferred in the office onto a VAX mainframe computer and the results plotted out on an Hewlett Packard flat-bed plotter. No corrections were made for pore pressures acting on the unequal end areas of the cone and friction sleeve. The analysis of the shear wave records required determining the travel time delay between the top and bottom receivers for the appropriate component geophone. This was carried out in the field by using the moving time cursor on the oscilloscope to measure the time difference between an identifiable feature for the two received signals. Generally this was chosen as the first peak or trough, as sometimes the first arrival was masked by background noise or earlier arrivals. The observed travel time delay, corresponding to the difference in slant ranges R1 and R2 in Fig. 1., was converted vectorially to a vertical travel time delay along the vertical separation of the two receivers, and hence the shear wave velocity calculated.

7. Seismic flat dilatometer test. The seismic flat dilatometer developed at UCNW consists of the same two receivers detailed above for the SCPT, mounted behind a flat dilatometer, described by Marchetti (ref. 6). Monitoring and recording of the geophone signals was achieved as described above and the two pressures obtained from the dilatometer testing were recorded manually from the readout unit. SDMTs were carried out with the sounding rig used for SCPTs. Dilatometer measurements were made every 0.2 m and consisted of increasing the internal pressure until membrane liftoff occurred, followed by a further increase until 1 mm of expansion was achieved. Shear wave velocity measurements were made at 1 m centres while the next push rod was being added and were carried out as above.

8. The data reduction for the dilatometer tests was performed on a microcomputer which produced values of the corrected pressures (p0 and p1), the material index (Id), the horizontal stress index (Kd) and the dilatometer modulus (Ed). From these it is possible to derive empirically a number of soil parameters, such as overconsolidation ratio, vertical drained modulus and undrained shear strength. The analysis of the seismic data was undertaken in the same way as for the SCPTs.

BOTHKENNER TEST-BED SITE, GRANGEMOUTH

9. A research site, purchased by the Science and Engineering Research Council, is located on the western bank of the river Forth approximately 1 km south of the Kincardine bridge. The underlying strata consist of between 15 m and 22 m of soft to firm silty clay and clayey silt, overlying dense sand in a clayey silt matrix. The site has been investigated by Nash and Lloyd (ref. 7), who report moisture contents of between 30% and 80% with a plastic index of between 28% and 60%. A number of SCPTs were carried out at the site and Fig. 2 shows a typical record of cone resistance (qc) and shear wave velocity (Vs), where each vertical portion of the shear wave profile represents the average interval velocity between the two receivers 1 m apart. A gradual increase in velocity with depth can be clearly seen, with a relatively higher velocity layer close to the surface, corresponding to the dessicated crust encountered during the first 1 m of penetration. The shape of the shear wave velocity profile is well reflected by the cone resistance profile observed.

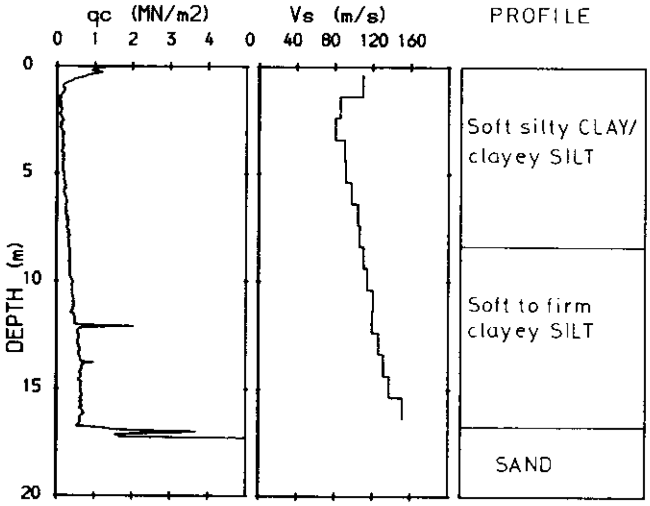

Fig. 2. SCPT data from Bothkenner site

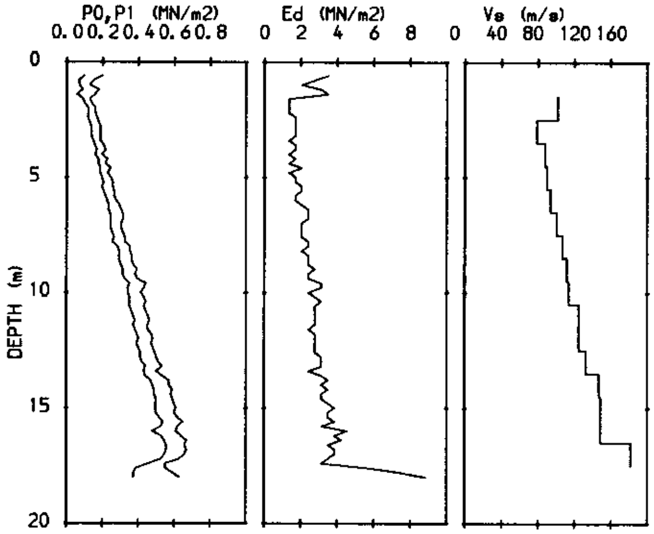

Fig. 3. SDMT data from Bothkenner site

10. Several SDMTs were also carried out on the site and a typical plot of the corrected pressures (p0 and p1), dilatometer modulus (Ed) and shear wave velocity (Vs) is presented on Fig. 3. The velocity profile is very similar to those obtained from the SCPTs described above, and corresponds well to the trend shown by the dilatometer results.

11. The results of the shear wave velocity measurements from an adjacent SCPT and SDMT are shown on Fig. 4, and for comparison a shear wave velocity profile obtained by the surface refraction method is superimposed. The refraction method involves laying out a line of geophones on the surface and generating shear waves by a similar horizontal impulse source to that described above. The variation of shear wave velocity with depth is calculated using the method of Morris and Abbiss (ref. 5). The agreement is good bearing in mind that the velocity and thickness of each layer are determined by those above and hence errors are cumulative with depth. A more accurate comparison would be to use crosshole measurements where shear waves are transmitted horizontally at specific depths between two boreholes but unfortunately no such testing has yet been carried out on the site. From the shear wave velocity profile and soil density it is a simple matter to calculate the dynamic shear modulus using equation (1). The resulting shear modulus profile based on all the SCPT and SDMT observations is given on Fig. 5.

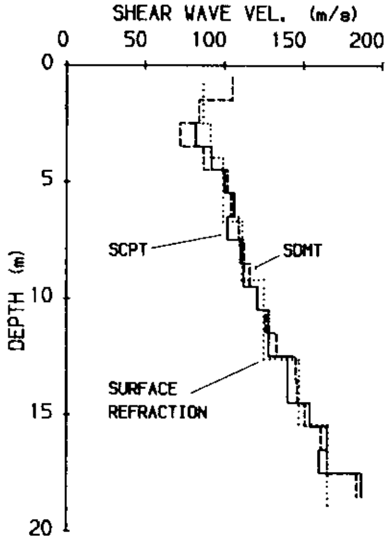

Fig. 4. Comparison of SCPT, SDMT and surface refraction data from Bothkenner site

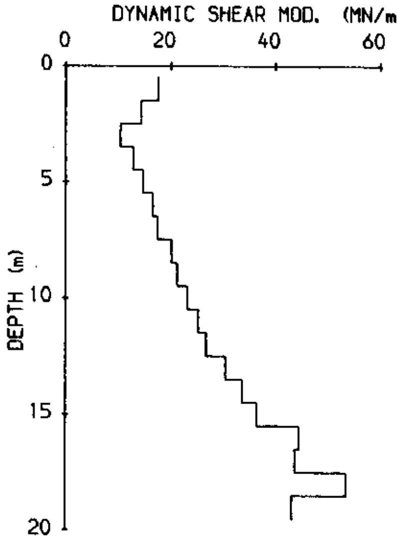

Fig. 5. Shear modulus profile based on SCPT and SDMT data from Bothkenner site

NORTH WALES SITE

12. At a site in North Wales several SCPTs were carried out in recent variable deposits of soft silty clay and sand overlying stiff sandy clay and medium dense silty sand. Figs 6 and 7 present the results of 2 of these. The shear wave velocity profile can be seen to follow the measured cone resistance, with higher velocities corresponding to the larger cone resistances in the sand and stiff clay layers. The soft clay layer shows an increase in velocity with depth. The stiff clay encountered in Fig. 6 exhibits an initial decrease in velocity followed by an increase, whereas in Fig. 7 the velocity seems fairly consistent with depth after the sudden increase on penetrating through the peat layer. Flat dilatometer testing was also carried out in the site and the results of tests adjacent to the SCPTs are shown on Figs 8 and 9. The dilatometer modulus profiles tend to confirm the trends shown by the shear wave velocity measurements.

CONCLUSION

13. The examples given above show that the seismic cone penetration test and seismic flat dilatometer test provide a rapid and simple means of determining the shear wave velocity profile during routine in situ testing. Comparisons with surface refraction measurements at one of the sites show good agreement between the surface and sub-surface methods. The trends shown by the shear wave velocity profiles are reflected by the cone resistance and dilatometer modulus profiles. Where the soil density is known the dynamic shear modulus can be calculated.

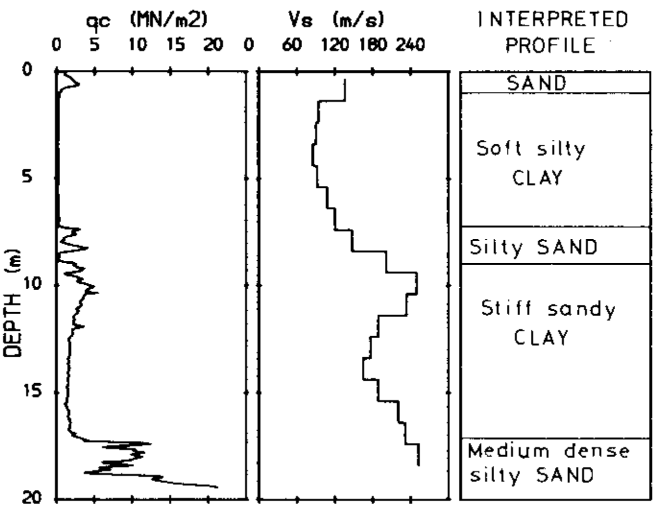

Fig. 6. SCPT data from North Wales site

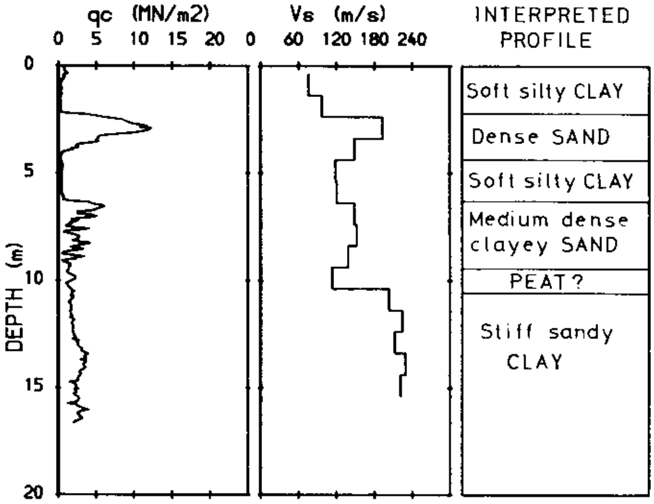

Fig. 7. SCPT data from North Wales site

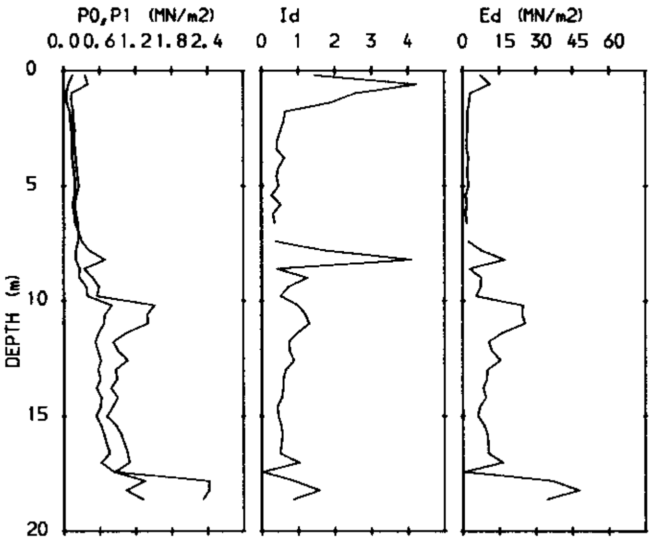

Fig. 8. Flat dilatometer data from North Wales site

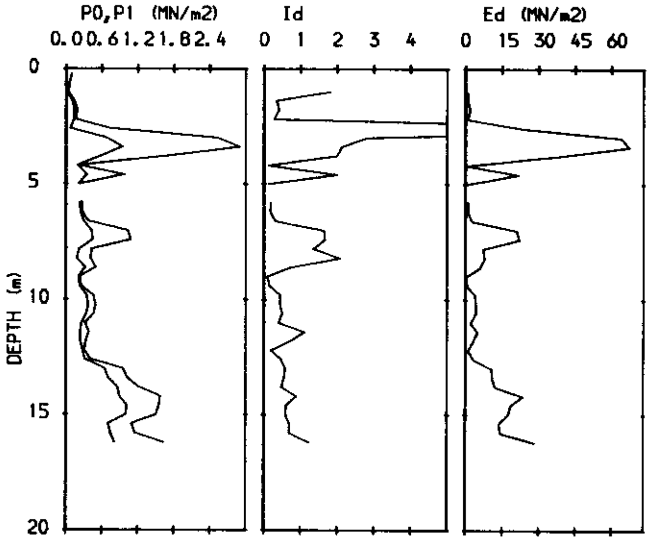

Fig. 9. Flat dilatometer data from North Wales site

ACKNOWLEDGEMENTS

The cone and dilatometer equipment was provided by Soil Mechanics Ltd. The opportunity to use the Grangemouth site was created by Dr D. Nash of Bristol University. The North Wales site was made available by Travers Morgan and Partners.

REFERENCES

1. ROBERTSON P. K., CAMPANELLA R. G., GILLESPIE D. and RICE A. Seismic CPT to measure in situ shear wave velocity. ASCE. Journal of Geotechnical Engineering, 1986, vol.112, August, 791-803.

2. HARDIN B. O. and DRNEVICH V. P. Shear modulus and damping in soils. ASCE. Journal of the Soil Mechanics and Foundation Division, 1972, vol.98, July, 667-692.

3. SEED H. B. and IDRISS I. M. Soil moduli and damping factors for dynamic response analysis. Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley. 1970.

4. BENNELL J. D., DAVIS A. M. and TAYLOR SMITH D. Resonant column testing of marine sediments. Oceanology International, Brighton. 1984, OI 1.9/1-11.

5. MORRIS D. V. and ABBISS C. P. Static modulus of Gault clay predicted from seismic tests. Ground Engineering, 1979, November, 40-50.

6. MARCHETTI S. In situ tests by flat dilatometer. ASCE. Journal of the Geotechnical Engineering Division, 1980,vol.106, March, 299-321.

7. NASH D. and LLOYD I. SERC soft clay test-bed site, Bothkenner.Report for prospective users of the site. Report No. UBCE-SM-87-1/1, Department of Civil Engineering, University of Bristol, 1987.