A DEVICE FOR THE IN-SITU MEASUREMENT OF THE DYNAMIC MODULI OF SOILS AT LARGE STRAINS

ROGER C. H. SIDEY[I] and RICHARD H. BASSETT[II]

SUMMARY

This paper discusses the results of a design study and some prototype development work on a new type of in-situ soils testing apparatus. Known as the Borehole Shear Device (BSD), the apparatus is a means for determining the response of undisturbed soils to shear loading. The configuration of the apparatus allows for measurement over a large range of strains, and the data is characteristic of a relatively well defined state of stress in the soil.

INTRODUCTION

State of the Art. Increasingly sophisticated and powerful numerical analysis techniques are being applied to soil mechanics and soil/structure interaction problems. Soils testing, however, has not kept pace with these developments, and hence important input data to describe the governing constitutive behaviour of the soil is lacking.

It is known that conventional laboratory tests often yield a low estimate of the stiffness characteristics of soils, and consequently much effort is now directed towards the in-situ determination of soil properties under static loading. Penetrometer, Vane and Pressuremeter (Wroth et al; 1975) techniques are examples of this type of testing.

For the determination of the properties of dynamically loaded soils, however, the situation is not straightforward. Dynamic soil properties over the range of strains required are currently "assembled" from low strain seismic data and from laboratory tests on disturbed samples. Correlation of the results is often poor, and the procedure is complex requiring much interpretive effort.

The Borehole Shear Device is an attempt at a tool capable of determining the dynamic properties of the soil over the complete range of strains of interest. The loads applied to the soil result in a state of stress which is relatively well defined and is essentially the same over the entire spectrum of strain.

Principle of Operation of the Borehole Shear Device. The basis of the Borehole Shear Device is a cylinder which is emplaced into the soil at the specified measurement location by means of an integral self-boring head. As shown in Fig. 1., the cylinder is coupled to an actuator at the ground surface via a length of tubing through which torsional load is transmitted. The dominant state of stress thus created is shear in the plane normal to

I Senior Engineer, Dames & Moore, 123 Mortlake High Street, London SW14

II Lecturer, King's College (Dept. of Civil Engineering), The Strand, London

the axis of the cylinder. In order to maintain coupling with the soil, the surface of the cylinder is arranged to expand radially by means of a hydraulic system. This allows the apparatus to recover or to maintain the undisturbed lateral stress in the soil. Torque, and hence shear load to the soil can in principle be applied in any manner either monotonically or cyclically increasing. The shear stress/strain (τ,γ) characteristic of the soil surrounding the cylinder is determined from measurement of applied torque and resultant rotation (T,θ) of the cylinder.

The concept of using a rotating cylinder for applying shear loading to soils is not new. Hardin has described a device which is electromagnetically driven and appears to be the in-situ counterpart of the well known resonant column laboratory test. Boyer and Oien have investigated the concept analytically and have dealt with the effects of the geometry of the apparatus and of depth of placement. Included in their comprehensive study is the effect of frequency of torsional drive to the cylinder. These approaches are, however, limited to the domain of elastic strain levels. To the authors' knowledge, a satisfactory characterization by field measurement of the change in shear modulus with increasing strain has yet to be achieved. Despite the relatively simple concept of the torsional cylinder, the practical problems in producing a workable field tool are numerous.

Background to the Development of the Borehole Shear Device. As a first step towards the problem, a design and feasibility study was carried out (Sidey et al.). This was a broad study which looked at practical aspects of design and of the instrumentation requirements for a generalized torsional cylinder system. From this work, a design specification was produced which was to serve as the basis for the detailed hardware design. A design set of soil properties and site conditions were assumed and a range of depth of operation was established for the test. The following were among the specifications developed :

- (i) range of drive torque required;
- (ii) range of angle of rotation of the cylinder;
- (iii) drive power required by the coupling cylinder and the downhole transmission system as a function of (i) and (ii) above and of frequency of operation;
- (iv) range of vertical loads required to overcome friction at the soil interface and to affect self boring;
- (v) range of lateral jacking stress required.

As a result of this study, the configuration of the BSD test discussed in this paper evolved. A prototype design for the radially expanding cylinder was achieved; so too was the means for subjecting it to the design loading under laboratory conditions.

A major portion of this work was an analytical study in which the effects of non-linearity of soil behaviour were included. The means for determining soil properties from the measured values of torque applied to the cylinder and the resultant rotation were derived. A summary of the analytical aspects of the study appear in a paper presented to this Conference by Marti and Rodriguez.

DESCRIPTION OF THE APPARATUS

General. A schematic of the probe section (i.e. the in-situ portion) of the BSD apparatus is shown in Fig. 1. It will be evident that it is essentially comprised of five basic sections :

(i) the torque drive tube - the lower section of this item also serves as a catch tank for the soil cuttings removed during emplacement;

(ii) a strain gauge transducer section for measuring the applied torque to the coupling cylinder. This transducer is also used to measure axial load on the cylinder;

(iii) the radially expanding or coupling cylinder section;

(iv) the rotation measurement transducer;

(v) the self boring head.

The Torsion Tube. The functions of the torque tube in the system are surprisingly broad. First and most obvious, it is required to transmit the cyclic torque downhole from the actuator to the coupling cylinder. Secondly, it must withstand the push down loads incurred during self boring placement, and the pull out loads required to retrieve the apparatus. The final principal function is that of a tank for storage of the soil cuttings produced by the self boring process.

The current design for this section of the apparatus utilizes a relatively highly stressed thin-walled tube of outside diameter equal to that of the self bored section of the probe. Hence the apparatus is a continuous cylinder in profile.

Measurement of Torque. The torque and normal load transducer is a strain gauge device utilizing a thin-walled tube section. Strain gauge bridges are bonded to the inside of the tube to sense compression and torsional loading. As shown in Fig. 2., the transducer is located directly above the coupling cylinder. Thus torsion applied to the cylinder is sensed directly, and the measurement is independent of frictional effects from the torsion tube. The normal load transducer serves no purpose during testing, but is an essential measurement for monitoring the self boring phase of the field procedure.

The Coupling Cylinder. Here the design is based around a series of beams keyed into the surface of a hollow cylinder (see Fig. 2.). The keys are rectangular in section and are ground to a precision fit with corresponding grooves in the surface of a thick-walled cylinder. Lateral jacking forces are derived from a system of single-acting hydraulic pistons and cylinders located within the body of the keys and arranged at regular intervals along their length. Shear stress is coupled from the keys to the cylinder/soil interface by means of shoes which are attached to the outer faces of the keys. These shoes are curved in outside profile to achieve uniform contact with a circular opening, and are provided with a fine splined surface in order to enhance frictional coupling capabilities.

The concept of this design evolved from the reasoning that the maximum strength and torsional stiffness would be realized from a mechanism that approached as closely as possible the optimum configuration of a thick-walled hollow cylinder. Apart from the locations of the jacking piston, the section of the design described above is a continuous, virtually solid thick-walled tube. Shear and compression forces are applied to the components of the cylinder uniformly and over large contact areas. Hence the design attempts to minimize stress concentrations with their inherent penalty of inefficiency of load rating and reduced service life.

Torsion is applied by means of another set of keys located at one end of the grooved cylinder. These keys are similar in section to the laterally moving keys, but they are force-fitted into the cylinder and are utilized only in coupling load to the walls of the cylinder grooves. The keys are tapered leading axially out of the cylinder, the taper forming part of an anti-backlash high torque coupling which employs wedges to eliminate clearances. These wedges bear on the faces of the keys protruding from the cylinder, and are preloaded by means of a spring assembly.

The Rotation Transducer. Measurement of the rotation of the coupling cylinder is perhaps the most demanding feature of the apparatus, at least, from the instrumentation point of view. The cylinder rotates through particularly small angles and the dynamic range required of the measurement is large. It is not feasible to cover the entire range of the measurement with one transducer. The spectrum from elastic deformations to failure of the soil entails a great range of strain and, correspondingly, of rotation of the cylinder. To solve this problem, two systems have been devised :

(i) a low strain inertial measurement system;
(ii) a higher range direct measurement system.

To avoid the problems of drift and noise inherent in making an absolute rotation measurement at very small strains, a vibratory scheme is under development. An oscillatory torque is applied to the coupling cylinder and the resultant rotation is sensed as a tangential acceleration at the end of a radius arm. Being a steady state technique, many opportunities exist to enhance the resolution of the measurement. It is expected that by the use of this method, a good characterisation of the elastic response of the soil will be obtained.

The higher range measurement is more straightforward. It employs high sensitivity transducers to sense relative rotation between the coupling cylinder and the self boring head. This method exploits the fact that the strain disturbances introduced by the cylinder diminish rapidly in the axial direction, and hence the lower part of the probe can be utilized as a rotation datum.

Self Boring. Perhaps the major limitation to the ability of the system to obtain repeatable and accurate measurements is disturbance of the soil introduced by emplacement of the probe. The dominant characteristic of the measurement will be due to the soils subjected to the largest strains. In the BSD test these strains occur at the soil/cylinder interface, and hence the output data is representative of the relatively small volume of soil adjacent to the coupling cylinder. It is to minimize disturbance to this critical volume of soil that the self boring system is incorporated into the BSD probe. This method of emplacement was developed at Cambridge University for use on their self boring pressuremeter. Essentially, the technique minimizes disturbance to the soil by maintaining the in-situ stresses throughout the drilling process. This is achieved in practice by applying a controlled and constant push-down load to the cutting head. The cutting head is shaped such that soil is extruded into the probe before it is broken up by a conventional cutter. These extrusion pressures can be controlled by altering the geometry of the cutting head and can be arranged to approach the distribution of the undisturbed stresses. The soil cuttings removed by the rotating cutter are lifted through the coupling cylinder and deposited into the lower section of the torsion tube. Two alternative methods are under evaluation for this process, and they are shown in the schematic illustrations of Figs. 1. and 2. In Fig. 1. an auger is used to raise the soil through the probe, and in Fig. 2. a water flush method is depicted. For highly permeable or loose soils, there may be problems with the water flush technique in eroding the soil ahead of the probe. The auger, on the other hand, may be subject to jamming or fouling with certain soil types. It is likely, therefore, that the final design for the probe will allow for both types of soil lifting systems.

For much of the testing, it is envisaged that the BSD probe will self bore only for the final two metres or so into the desired measurement region. Initial access will be provided by means of a conventional boring. The system currently under development is designed to work from within an 8 inch (213mm) cased borehole.

STATUS OF DEVELOPMENT OF THE BSD

Much of the above development work on the BSD is completed. A prototype coupling cylinder has been designed and manufactured to full operational specification. The unit has performed satisfactorily in laboratory trials. A field trial for the system awaits completion of the current phase of development of the apparatus.

ACKNOWLEDGMENT

This work has been funded by the United States Air Force AFWL (contract numbers F29601-78-C-0058 and F29601-79-C-0044).

REFERENCES

BOYER, G.R. & OIEN, M.A. (1972): "Steady Motion of a Torsional Oscillator Clamped in a Borehole", Journ. Sound and Vibration, Vol. 23, No. 2, pp 175-186.

HARDIN, B.O. (1972): "Apparatus for Testing Soils In-Situ", United States Patent 3,643,498. February 22, 1972.

MARTI, J. & RODRIGUEZ-OVEJERO, L.R. (1980): "Analysis of a Device for In-Situ Measurement of the Shear Modulus of Soil at Large Strains", to be presented at the VII World Conference on Earthquake Engineering, Istanbul, Turkey.

SIDEY, R.C., MARTI, J., RODRIGUEZ, L. & WHITE, D.C. (1979): "Borehole Shear Device - Feasibility and Preliminary Design Study", United States Air Force, AFWL, Contract No: F29601-78-C-0058.

WROTH, C.P. (1975): "The In-Situ Measurement of Initial Stresses and Deformation Characteristics". Proc. ASCE. Speciality Conf. on In-Situ Measurement of Soil Properties, Rayleigh, North Carolina, V.2. p 181-230.

WROTH, C.P. & WINDLE, D. (1975): "Analysis of Pressurementer Test Allowing for Volume Change". Geotechnique 25. No. 3. p 598-604.

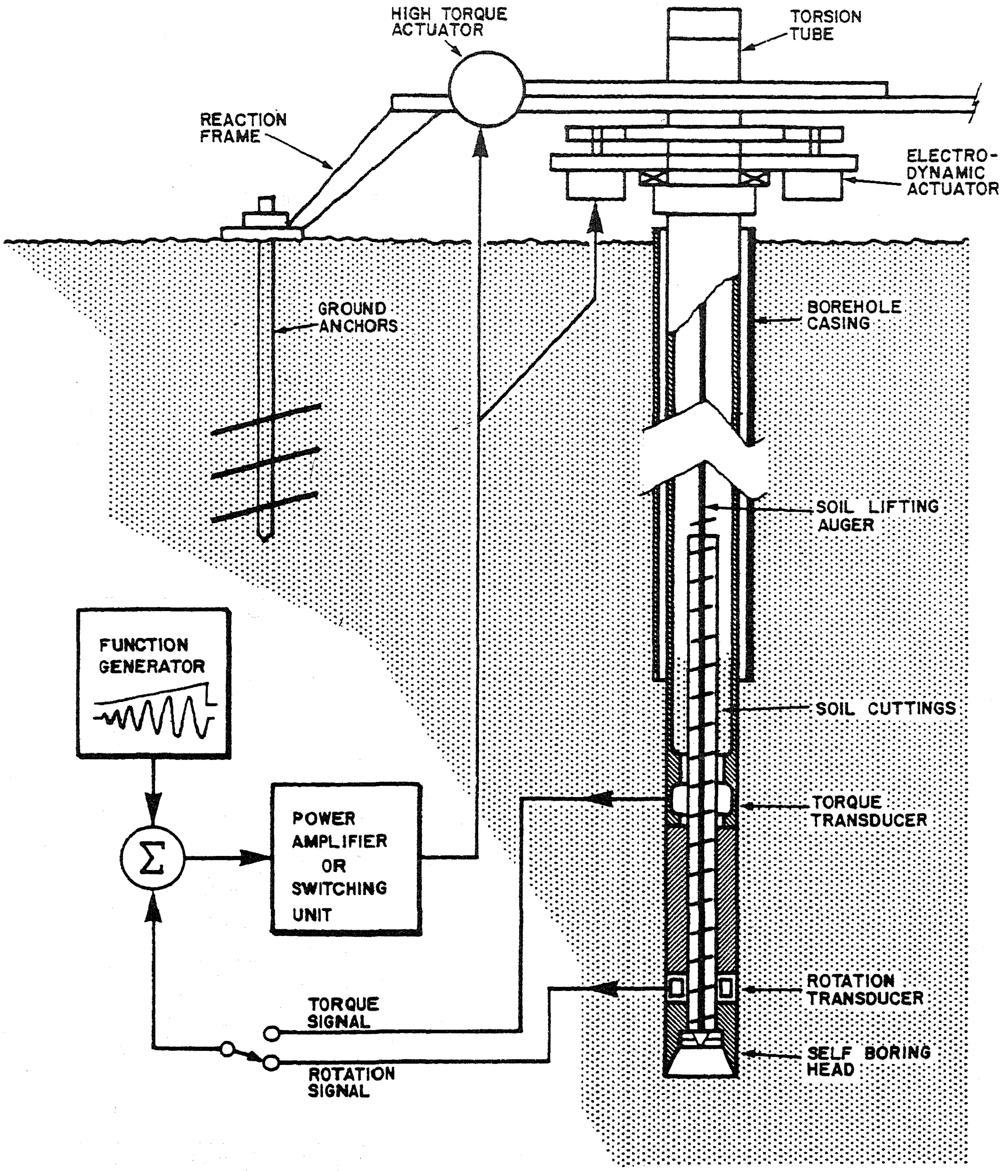

FIG. 1. SCHEMATIC OF THE BSD TEST.

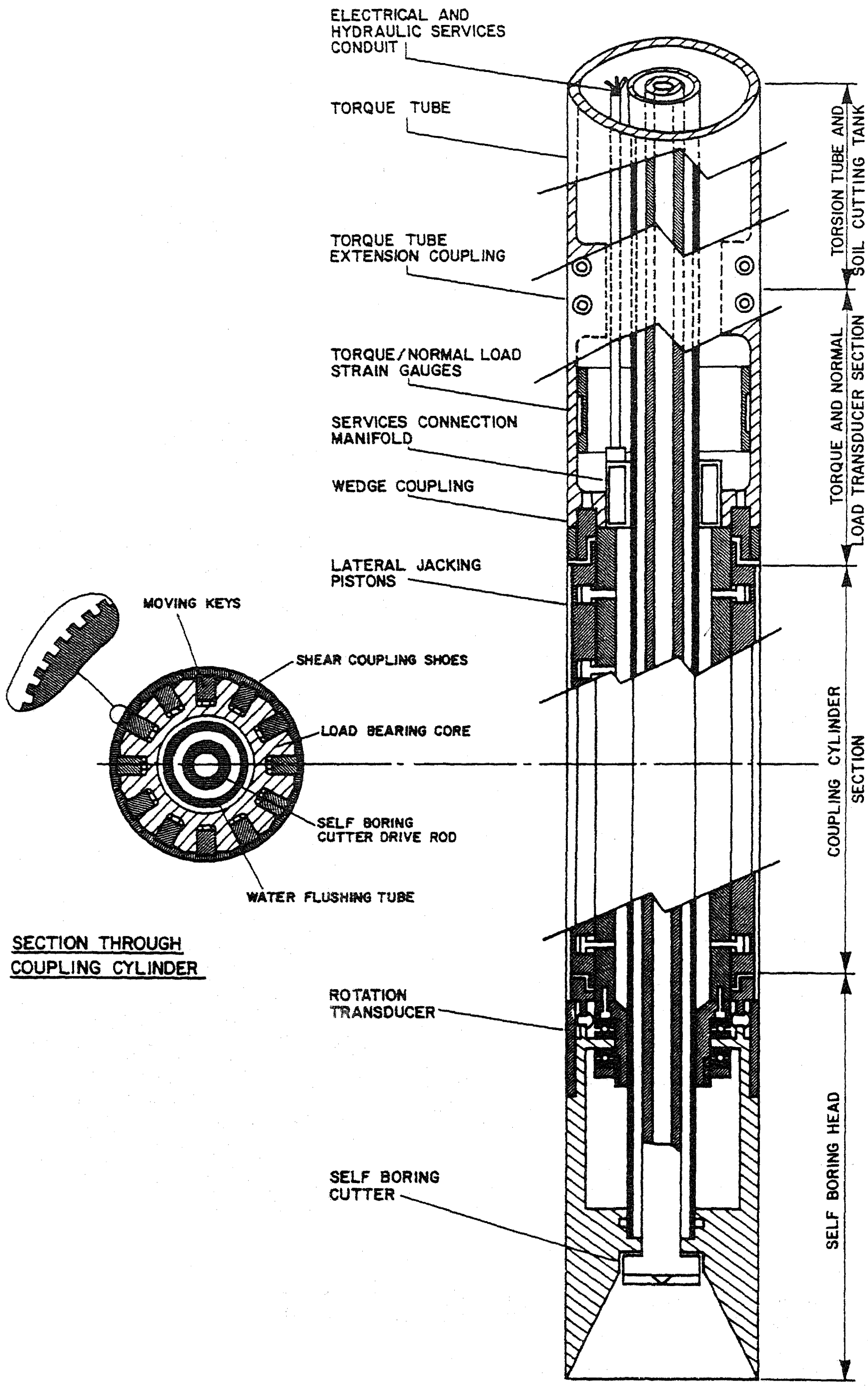

FIG. 2. DETAILED SCHEMATIC OF THE BSD PROBE