GDS software-based dynamic and seismic laboratory soil testing systems

A GDS publication by Bruce Menzies, Patrick Hooker, Karl Snelling and Jerry Sutton.

1. Overview

We have written this paper in response to the many requests we have had to advise on dynamic and seismic soil testing in the laboratory. Below we consider the background to dynamic testing, particularly for the study of soils under conditions of earthquake loading i.e. at frequencies in the 0.1 to 10Hz range. We then move on to evaluate the different test means: pneumatic, hydraulic and electromagnetic, and ask the question "which is best?" We then review the role of seismic methods for determining soil stiffness in the laboratory - the uses of seismic methods in the field are considered in a separate paper published on our web site. Bender elements are described that can measure shear modulus in any triaxial test whether it be a quick undrained test or a dynamic test. Finally we reproduce in an Appendix to this paper, a set of notes on the triaxial test that includes typical results from dynamic triaxial testing.

2. Dynamic triaxial testing to simulate earthquake conditions Introduction

Earthquakes are a part of our planet's geology and we must protect ourselves from them. Good engineering principles can be applied to mitigate the effects of earthquake ground movements on structures. Either existing or planned structures can be improved with better connections between structural members and appropriate connections between joined structures of different stiffnesses and hence periods of vibration. In addition, the behaviour of the ground needs to be assessed. Hard ground will transmit vibrations to structures. On the other hand, soft ground will absorb vibrations more but might be subject to liquefaction. Soft soils are often saturated. During vibration, pore pressure can increase. Effective stress therefore decreases, with corresponding reduction in strength and stiffness. In the extreme, pore pressure can rise to equal total stresses and the soil becomes a fluid like a quicksand. Here, build up of pore pressure is independent of frequency and depends on amplitude and number of cycles only. In unsaturated soils, however, pore water pressure and pore air pressure increases with consequent strength reductions can only be assessed in the undrained state by testing at realistic frequencies.

Clearly there is a need to measure soil properties before, during, and after high frequency cyclic loading. We need to know if our soils are prone to pore pressure build-up with consequent reduction in strength and stiffness. If so, then we need to measure the reduced properties, to see if our structures can still be supported.

The American Society for Testing Materials, (ASTM), in their Designation D3999-91 "Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus" specify the performance requirements of this equipment. They state that "These test methods are used for the performance evaluation of both natural and engineered structures under dynamic or cyclic loads such as caused by earthquakes, ocean wave, or blast".

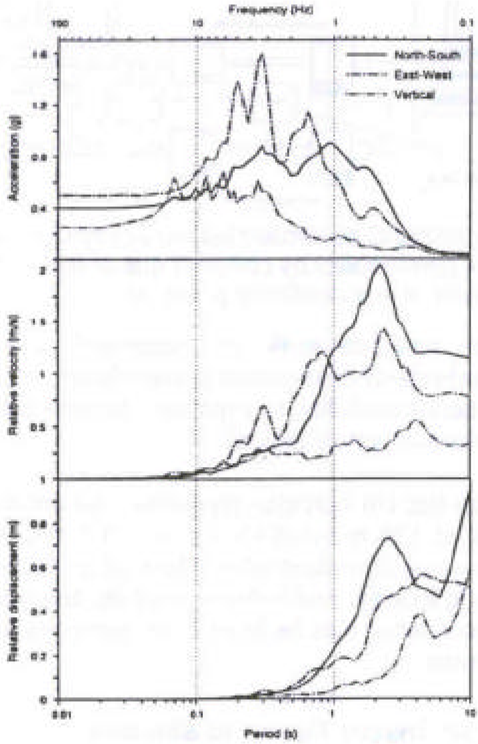


Fig.1 Five per cent damping response spectra of strong motion record captured at Erzincan ground response station approximately 10kM from earthquake epicentre, Erzincan Tuerkey earthquake, 13 March 1992..

Earthquake waves are produced in a range of frequencies up to the low range of audibility at about 10Hz. Referring to the response spectra in Fig. 1, it can be seen that while accelerations peak in the 0.1–10Hz range, relative velocity and relative displacement peak in the 0.1–2Hz range. As specified in ASTM D3999-91, the ideal triaxial testing system therefore requires control facilities that give the ability to test at frequencies in the range of maximum structural damage, i.e. about 0.1- 2Hz.

Fig. 2 and Fig. 3 show typical plotted results from such tests on a saturated Hostun RF sand. Axial force was varied sinusoidally at a frequency of 0.2Hz. The resulting stress paths are shown in Fig. 2. Liquefaction occurred at the 16th cycle as shown in Fig. 3. For saturated soils, undrained tests are not sensitive to frequency and the build up of pore pressure with time (or lowering of strength) is related to amplitude and number of cycles only i.e. it is independent of frequency. For partially saturated soils, rapid loading can be partly drained and so frequency is an important test parameter. Typical test results are shown in Appendix I: Short Course Notes: Triaxial Test (after Simons, Menzies and Matthews, 2002).

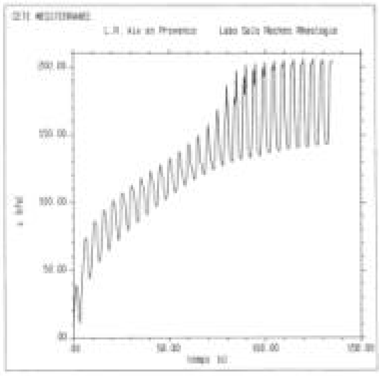


Fig.2 Build up of pore water pressure (Courtesy of CETE Mediterranee).

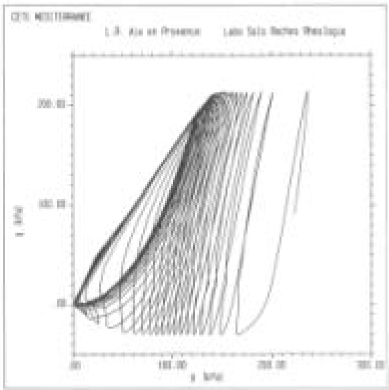


Fig.3 Stress Paths as 0.2Hz (Courtesy of CETE Mediterranee).

PC controlled high frequency triaxial testing systems which conform to ASTM 3999-91 are shown in Fig. 4 and Fig. 5.

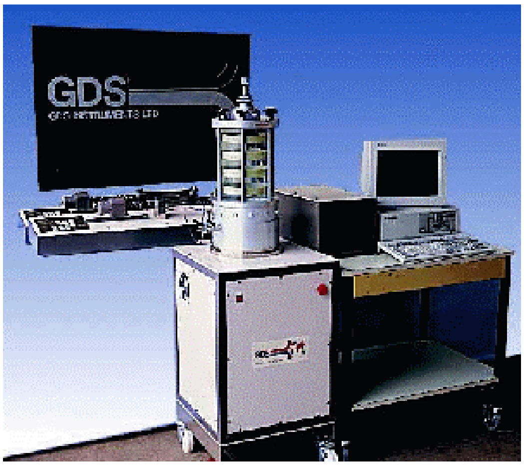


Fig.4 GDS 2 Hz / 50kN 38/50/70/100mm Dynamic Triaxial Testing System.

Fig.5 GDS 10 Hz / 20kN 70mm Dynamic Triaxial Testing System.

Sometimes, for reasons that are not understood, seismic energy is released slowly, taking minutes, days or years; no earthquake is generated, and the rocks slide past each other in a process known as aseismic slip or creep. At other times, the energy is released violently over a period of seconds as the rock ruptures, producing an earthquake. The seismic energy is emitted from the rupture in three main types of waves. The fastest are the primary or P waves, which are compression-dilation waves (Fig. 6) and travel in average crustal rocks at about 5 kilometres per second. The slower, secondary or S (shear) waves cannot pass through a liquid and do not penetrate the Earth’s outer core. The slowest waves are surface waves, comprising principally Rayleigh and Love waves, whose depths of penetration are dependent on their wavelengths. Surface waves transmit the bulk of the energy in shallow earthquakes, so that often it is their amplitude which is used to determine magnitude. In the Chilean earthquake of 1960, surface waves were so powerful they were still being recorded on seismograms 60 hours after the event, having gone round the earth 20 times.

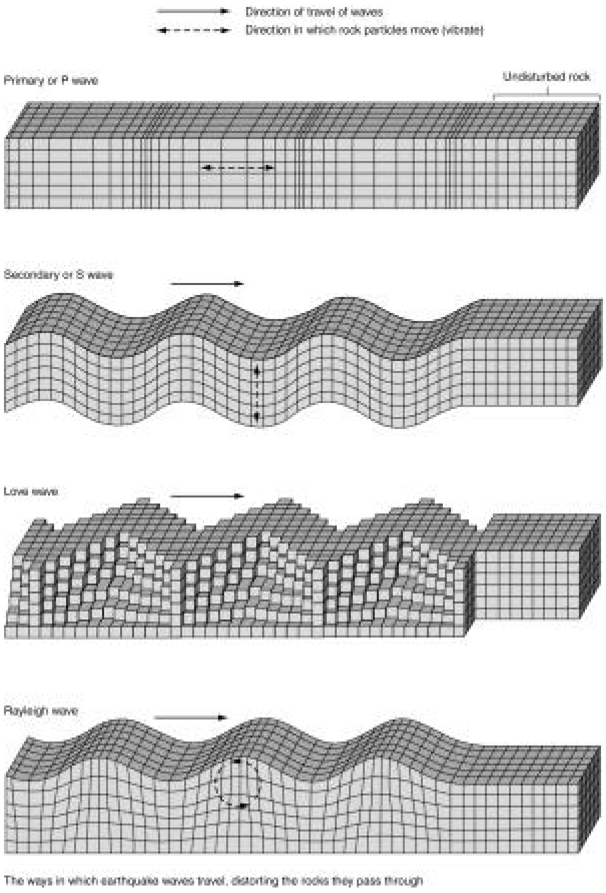


Fig.6 The ways in which earthquake waves travel, distorting the ground they pass through.

It would seem logical therefore that soil investigations should include not only dynamic triaxial tests under carefully controlled laboratory conditions but also some kind of field testing using surface waves such as the GDS SASW(Spectral Analysis of Surface Waves) and CSW (Continuous Surface Wave) systems.

3. Electromechanical, hydraulic or pneumatic control means – which is best?

3.1 Introduction

Different manufacturers of dynamic triaxial systems use different means of control. These are: pneumatic, hydraulic and electromechanical. These control systems have different properties that affect the choice of system depending on the application. In particular, they have different performance characteristics in static and dynamic situations. It is therefore critical to the user’s research programme that they make the correct choice of system and the corresponding means of control.

When we consider dynamic triaxial systems, the main area of discussion is related to the *dynamic performance of machines* – a subject that is widely taught in colleges and universities and well documented in text books and technical journals. Undoubtedly, hydraulic or pneumatic machines appear to out-perform (and are much cheaper than) electromechanical control at frequencies above 10Hz. The lack of precise control at these higher frequencies is the key consideration, however, and the user must decide the degree of inaccuracy they are prepared to accept. It is our experience that some suppliers of dynamic triaxial apparatus specify their equipment in terms of the performance of the system means of *input* e.g. the performance of a compressed air actuator or hydraulic valve. They do not specify the *output* i.e. what actually happens to the test specimen. This gap between the supplier-specified input and the actual output at the test specimen level is an area of uncertainty that the user can only resolve by testing and then it is too late because the system has been purchased! It is better, therefore, to purchase equipment from a supplier who specifies their equipment in terms of output and not input. Closed loop control whereby the test is controlled from a transducer on the test specimen (e.g. internal submersible load cell) is one obvious bench mark of good test systems. There are also some other general considerations that the user needs to understand in their evaluation of equipment before purchase. These now follow.

3.2 Servo controlled systems

Hydraulic control and pneumatic control are inherently pressure control. A flow control valve is used to vary pressure to control some associated parameter – position, pressure, force or torque. Controlling the pressure in the hydraulic actuator is straightforward. Real closed loop control of torque or force via torque and force transducers becomes more difficult due to non-linearity in the test specimen and friction in various seals. Accurate displacement control using hydraulic or pneumatic systems is much more difficult because:

- compressibility of the controlling medium (air or oil) combined with slipstick in the actuation system causes nonlinearity in the control response, and

- digital closed loop control systems typically use 12 bit data acquisition in the control path and therefore resolution is only 1 in 2^{12} or about 4,000.

In contrast, an electromechanical solution typically uses brushless dc servomotors with digital control of position or speed using feedback from a remote transducer (load, torque or pressure). With regard to load, torque or pressure, electromechanical control is similar to that of a hydraulic system where a transducer is used in the primary control loop (load, torque or pressure) that is not perfectly related to the parameter being controlled by the motor (velocity or position) because of the combined non-linearity of the machine, soil and friction.

When it comes to position control, however, the motors are ideal because they have high resolution shaft encoders (8000 counts per revolution) and fixed gearing. This means that the axial displacement and rotation is known to a very high resolution of control that is better than a displacement transducer mounted externally to the test specimen being read by a 16 bit data acquisition system (i.e. with a resolution of 1 in 2^{16} or about 64,000). The control response to the feedback transducer output is therefore at very high precision giving good position control in both static and dynamic modes of operation.

3.3 Dynamic control

Hydraulic or pneumatic machines out perform in terms of speed (and are much cheaper than) electromechanical control at frequencies above 10Hz. The drawback is that there is a lack of precise control at these higher frequencies and users must accept the measurements are within about 5 percent of what is actually happening to the test specimen. In the 1-10Hz range, however, hydraulic and electromechanical control means are equally good (apart from accuracy of displacement and rotation control as described above). Below 1Hz the electromechanical systems are much better because they are able to maintain very accurate loads and positions over extended periods of time as well as having good dynamic performance.

In summary, above 10Hz choose hydraulic control, between 1 and 10Hz it is a matter of the user's preference. Below 1 Hz choose electromechanical control means. As the typical soil mechanics system will only spend less than 1% of its operational life being used above 1 Hz and 99% below 1 Hz (static soil testing is very slow!) the case for electromechanical control is also strong in the 1-10Hz range.

In GDS systems that have both static and dynamic capability (e.g. 2Hz and 10Hz triaxial, 1Hz and 5Hz hollow cylinder apparatus), however, only electromechanical control can give the range of precision of testing control from static to dynamic performance.

3.4. Stepper motor controlled systems (a static form of electromechanical control)

Stepper motor controlled systems are only suitable for static and very low frequency cyclic systems. They have the advantage of extremely stable short and long-term control of load, stress, displacement, pressure and volume change. They are also very economical when compared to servo controlled systems. This makes the stepper motor controlled devices ideal for the majority of typical non-dynamic geotechnical testing systems e.g. GDS pressure/volume controllers, load frames and force-displacement actuators.

4 Choice of systems

At GDS we advise using electromechanical control for the following applications:

- for static and dynamic soil/rock testing applications at frequencies less than 10Hz and loads less than 20kN (using brushless dc servo motors)
- for static and dynamic soil/rock testing applications at frequencies less than 2Hz and load less than 50kN (using brushless dc servo motors)
- for static loading applications for loads up to 250kN (using stepper motors).

We also recommend hydraulic control for the following applications:

- Dynamic applications above 10Hz
- Testing requiring the application of large numbers of cycles, for example routinely applying more than 1000 cycles to test specimens – such as resilient modulus tests
- High load static applications above 250kN
- High load Dynamic applications above 2Hz and 50kN

Pneumatic control can be used in the following applications (but remember that the low cost comes with a different kind of price: low precision):

- Low cost stress control at very low forces (<5kN) e.g. using Bellofram actuators
- Applications requiring low precision repeated loading such as low load resilient modulus tests.
- Simple dynamic load control at low forces (<10kN)
- Low cost pressure control at pressures up to 1000kPa using either open loop manual control valves or closed loop computer controlled valves (like the GDS 2 channel Airvalve).

5 Triaxial systems: overview

- Below 1Hz use electromechanical control systems.
- In the range 1Hz-10Hz (i.e. earthquake range) use electromechanical or hydraulic (or pneumatic but with low precision) control systems.
- Above 10Hz use hydraulic (or pneumatic but with low precision) control systems.
- For *both* static and 1-10Hz dynamic (like the GDS 2Hz and 10Hz triaxial systems and 1Hz and 5Hz hollow cylinder apparatus') use electromechanical control systems.

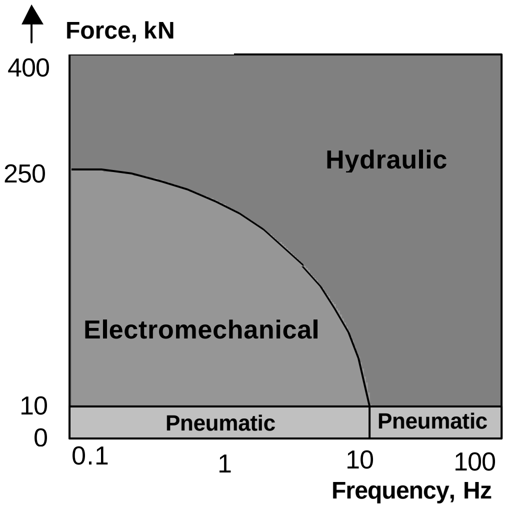


Fig 7: recommended control systems overview

6 The GDS family of triaxial systems

The above approach has resulted in a family of GDS triaxial and hollow cylinder apparatus systems as follows:

- 10kN/2Hz electromechanical triaxial compression/extension apparatus.
- 16kN/2Hz electromechanical triaxial compression/extension apparatus.
- 40kN/2Hz electromechanical triaxial compression/extension apparatus.
- 20kN 10Hz electromechanical triaxial compression/extension apparatus with dynamic cell pressure control.
- 100kN/10Hz hydraulic triaxial compression/extension apparatus with dynamic cell pressure control
- 5kN/70Hz pneumatic triaxial compression/extension apparatus.
- 25kN/ 70Hz hydraulic triaxial compression/extension apparatus.
- 10kN/100N-m 1Hz electromechanical hollow cylinder apparatus.
- 10kN/100N-m 2Hz electromechanical hollow cylinder apparatus.
- 10kN/100N-m 5Hz electromechanical hollow cylinder apparatus.

It should be noted that GDS hollow cylinder apparatus' can also operate as solid cylinder apparatus' i.e. as “normal” GDS triaxial systems with the usual options of test method such as stress path, K_0, unsaturated testing, etc.

7. Seismic methods in the laboratory

7.1. The non-linear strain behaviour of soil

During the late 1980s and early 1990s, soil stiffness was being measured in the laboratory using small strain dynamic resonant column apparatus. Investigators were struck by the similarity of these *dynamic* moduli to *static* moduli back-analyzed from movements around real static structures like retaining walls and excavations. They then realized the differences in moduli measured in the past between static tests like the conventional triaxial and dynamic tests like the resonant column were related to strain level i.e. one test measured small strain moduli and the other large strain moduli, not that one test was “dynamic” and the other “static” (see Fig 8).

Somewhat unexpectedly the seismic-like resonant column *dynamic* test measured stiffnesses close to the field *static* operational values – but this is because they both present small strain behaviour. This encouraged researchers to look again at seismic methods for measuring soil and rock stiffnesses insitu. This has given rise to the commercial development of a range of seismic tests in the field including the seismic cone penetration test (SCPT), cross-hole and down-hole shear wave velocity measurement, and the surface wave (Rayleigh wave) methods of SASW (Spectral Analysis of Surface Waves) that uses a hammer as the seismic source and CSW (Continuous Surface Wave) that uses a frequency-controlled vibrator as the seismic source (Fig. 9).

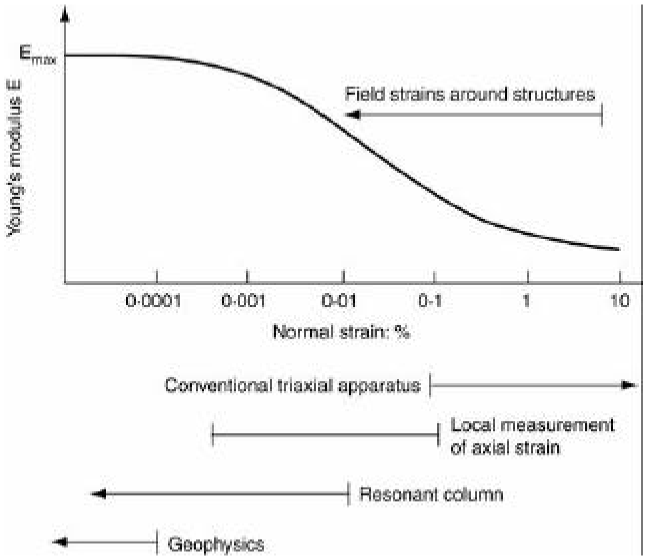


Fig.8 Idealised stiffness-strain behaviour shown by most soils illustrating that stiffness is strain-level dependent

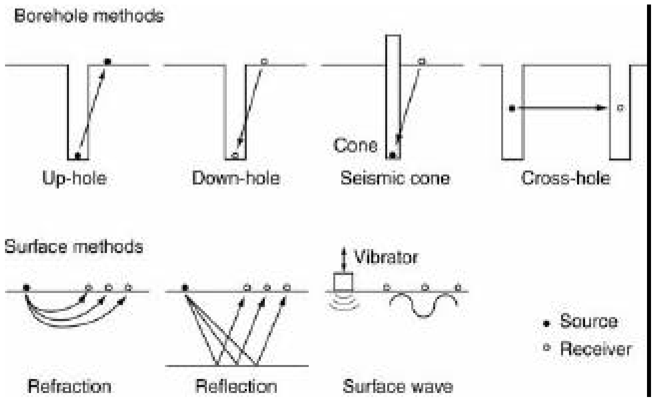


Fig.9 Surface and subsurface seismic methods for determining ground stiffness

8. Bender element measurements of shear modulus

8.1. Introduction

Measurement of soil stiffness at very small strains in the laboratory is difficult owing to insufficient resolution and accuracy of load and displacement measuring devices. The capability exists to routinely carry out measurements of small strain stiffness in the triaxial apparatus using local strain transducers, but this can be expensive and is generally confined to research projects. The addition of Bender Elements to a triaxial testing system, however, simplifies greatly the routine measurement of G_{max}, the maximum shear modulus.

8.2. The GDS bender element system

In conjunction with GeoDelft of the Netherlands, we have developed a bender element system that is PC-based and uses the PC screen in place of an oscilloscope to display wave forms. The system is available to be integrated with new systems from GDS or for fitting into existing systems (including those not manufactured by GDS).

Three different types of element pairs are available:

- S-Wave only
- P-Wave only (high power)
- Combined S + P wave.

Each set of element pairs comprises a source and a receiver element.

All bender elements are encapsulated and then mounted into inserts which are fixed into either a pedestal or top cap as shown in Fig. 10. The pedestal and top cap are then used in the triaxial cell as normal. While all supplied elements are manufactured to the highest standards, by their nature bender elements are delicate instruments. Occasionally elements may need to be replaced. Replacement of elements is then made simple by removing the insert and replacing it with another one. The system of inserts makes the system cheap to buy and maintain as well as reducing the "down-time" in a system to replace a damaged element.

8.3. Source control

The software is presented in a "wizard" format that simply and quickly configures the bender element test.

To cater for the many different approaches to bender element testing that have been developed around the world, the GDS Bender Element software allows the following source signal types to be used:

- Sine wave
- Square wave
- User defined

For each test the above wave types can be used on a single shot basis or automatically repeated to build a “stack” of data. For the S-wave elements the shot can be reversed to simplify picking by the reversal method.

The standard wave types (sinusoid and square) can be controlled using the following parameters:

- Amplitude
- Period
- Repeat Time (0 seconds (continuous) to 60 seconds)
- Offset (Positive or negative accentuated)

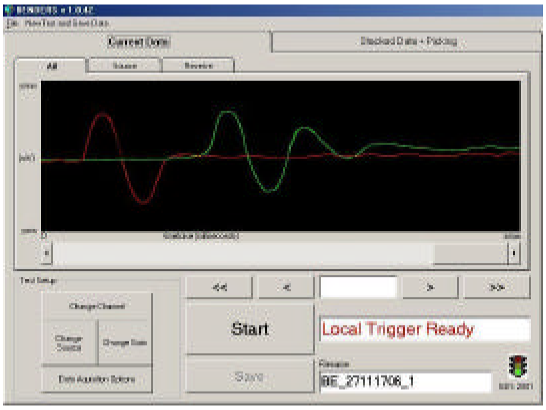
The User Defined wave type option allows the user to test using non-standard waveforms. A digitised waveform, in an ASCII text file, can be read by the software and used as the waveform for the source element.

Fig.10 GDS Bender Element inserts within top-cap and base pedestal

8.4. Receiver control

Where a full GDS bender element system is being used the software will switch input gain levels (of the received signal), set the level of the output signal voltage and control switching between the P and S wave modes for the combined wave type elements. The software will select an appropriate sampling rate but the user may override this if required.

The acquired data is presented to the user for picking of both the source (feedback) signal and the received signals. Picking of the source signal gives an absolute zero to the calculation of travel time and does not rely on trigger detection. A typical window is shown in Fig. 11.



Local Trigger Ready

BE_27111706_1

Fig.11 GDS Bender Element System software (GDSBES)

The Bender Elements are encapsulated and mounted in inserts that can be fixed in either to the cap or the base pedestal (Fig. 12). The inserts that are designed for the top cap are made of titanium to give high axial rigidity combined with low weight to minimize the imposed axial load. The titanium top cap insert is approximately half the weight of the stainless steel insert for the pedestal.

Fig.12 GDS Bender Element Insert.

Appendix

Short Course Notes: Triaxial Test

These notes are reproduced from “A short course in geotechnical site investigation” by Noel Simons, Bruce Menzies and Marcus Matthews by permission of the publisher, Thomas Telford Ltd.

Bibliography

Fredlund, D.G. (1997). From theory to practice in unsaturated soil mechanics. *Proc. 3rd Brazilian Symp. on Unsaturated Soils*. Rio de Janeiro, Brazil.

Heymann, G. (1998). *The Stiffness of Soils and Weak Rocks at Very Small Strains*. PhD Thesis, Department of Civil Engineering, University of Surrey.

Heymann, G., Clayton, C.R.I. and Reed, G.T. (1997). Laser interferometry to evaluate the performance of local displacement transducers. *Géotechnique* **47**, No.3, 399-405.

Jovicic, V. and Coop, M.R. (1997). Stiffness of coarse-grained soils at small strains. *Géotechnique,* **47,** No. 3, 545-562.

Jovièiæ, V., Coop, M.R., and Simiæ, M. (1996). Objective criteria for determining $G_{\max}$ from bender element tests. *Géotechnique* **46**, No. 2, 357-362.

Matthews, M.C. and Clayton, C.R.I (1993). Influence of intact porosity on the engineering properties of a weak rock. *Geotechnical Engineering of Hard Soils - Soft Rock* (A. Anagnostopoulos, F. Schlosser, N. Kalteziotis and R. Frank, Eds), Vol. 1, Balkema, Rotterdam, 693-702.

Matthews, M.C., Clayton, C.R.I. and Rigby-Jones, J. (2000). Locating dissolution features in the Chalk. *Quarterly Journal of Engineering Geology and Hydrogeology,* **33**(2), 125-140.

Matthews, M.C., Clayton, C.R.I., and Own, Y. (2000). The use of field geophysical techniques to determine geotechnical stiffness parameters. *Proc. Instn Civ. Engrs Geotech. Engng*. January, pp. 31-42.

Matthews, M.C., Hope, V.S. and Clayton, C.R.I. (1996) The use of surface waves in the determination of ground stiffness profiles. *Proc. Instn. Civ. Engrs. Geotech. Engng* **119**, April, 84-95.

Ray, R.P. and Morris, K.B. (1995). Automated laboratory testing for soil/water characteristic curves. *Unsaturated Soils*, Alonso & Delage (eds). A.A. Balkema, Rotterdam, 547-552.

Simons, N.E. and Menzies, B.K. (2000). *A short course in foundation engineering.* Thomas Telford, London, 244p.

Simons, N.E., Menzies, B.K. and Matthews, M.C. (2001). *A short course in soil and rock slope engineering.* Thomas Telford, London, 432p.

Simons, N.E., Menzies, B.K. and Matthews, M.C. (2002). *A short course in geotechnical site investigation.* Thomas Telford, London, 300p.

Souto, A., Hartikainin, J. and Özüdoðru, K. (1994). Measurement of dynamic parameters of road pavement materials by the bender element and resonant column tests. *Géotechnique* **44**, No. 3, 519-526.

Tou J.H., Leong, E.C., Rahardjo, H. and Cheong, H.K. (2001). Determination of $G_{\max}$ of residual soils using bender elements. *Proc. 14th Southeast Asian Geotech Conf.*, Hong Kong, Vol. **1**, pp. 581-586.

Viggiani, G. and Atkinson, J.H. (1995). Interpretation of bender element tests. *Géotechnique* **45**, No. 1, 149-154.