The Development of Automated Testing in Geotechnical Engineering

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1.0 Introduction

The last quarter of the 20th Century has seen an enormous development in the science of geotechnical engineering. This development corresponds to the availability of digital computers with ever increasing processing power and ever decreasing size and cost. The digital computer has not only provided the capability of quickly simulating processes using mathematical analysis, for example by using finite element analysis methods, but has also enabled sophisticated automatic data acquisition and control to be put into test equipment. The modern researcher in geotechnical engineering could not function without the support of an extensive range of computers.

2.0 Early automated testing

In the early nineteen-seventies a sophisticated triaxial testing machine with automatic data acquisition would use a loading frame with a manual mechanical gearbox, constant speed and perhaps a chart recorder to gather data on axial load and deformation. Consider the Bishop & Wesley stress path triaxial cell shown in figure 1 The cell is hydraulically actuated and the challenge was to arrange for the pressure in the lower chamber, providing axial force, and the cell pressure to be varied in concert so that a linear variation in axial stress and radial stress could occur.

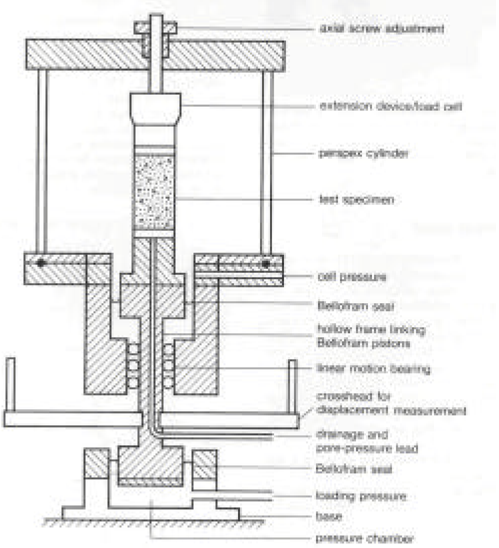

Fig. 1. Schematic diagram of Bishop & Wesley Stress Path Cell (Bishop & Wesley, 1975).

In the mid to late nineteen-seventies Dr Bruce Menzies, (the founder of Geotechnical Digital Systems Limited – later to become GDS Instruments Limited) was trying to solve this problem and used a motor driven ‘syringe-type’ pump to provide pressures and also to measure volume change. This early work resulted in the development by 1982 of the GDS pressure/volume controller (figure 2).

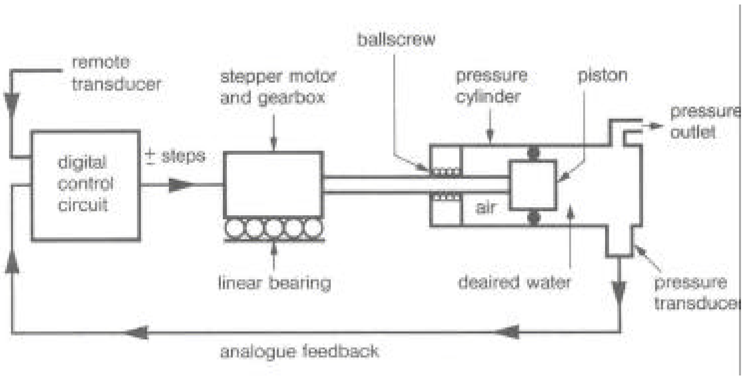

Fig. 2 Schematic Diagram of GDS Controller

In the GDS controller liquid (normally deaerated water) in a cylinder is pressurised and displaced by a piston moving in the cylinder. The piston is actuated by a ball screw turned in a captive ball nut by an electric motor and gearbox that move rectilinearly on a ball slide. Pressure is measured by an integral solid state transducer. Control algorithms are built into the onboard microprocessor to cause the controller to seek to a target pressure or step to a target volume change. Volume change is measured by counting the incremental steps of the motor. The controller can be set and read manually by an integral keyboard and display. An important provision for automated testing is the computer communications interface by which a desktop computer could direct the controller and also take readings of pressure and volume change.

At this stage the importance of the digital computer can be seen. Not only is there an early embedded digital computer in the controller but the concurrent development of desktop computers allows a number of pressure/volume devices to be controlled and data acquired by a single programmable device. The consequences of this are far reaching. With the availability of simple programming languages (for example Basic) it becomes possible to control pressure and volume change for a number of devices in concert – theoretically it was possible to consider any test trajectory that could be physically performed by the equipment. The first fully automated computer controlled stress path triaxial testing system was produced by GDS in 1982, figure 3.

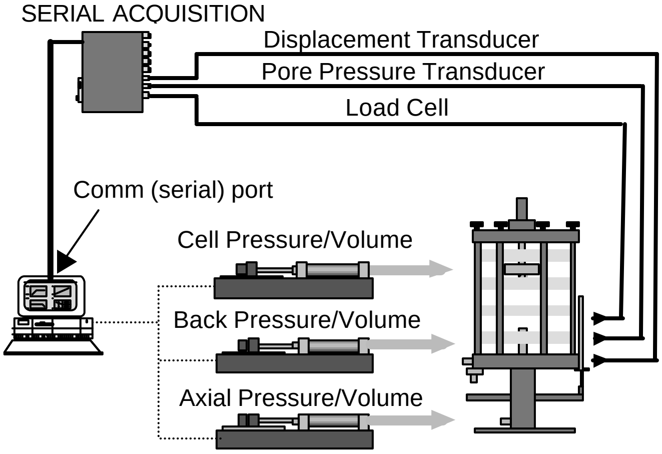

Fig. 3. Automated Triaxial System

The level of automated control gave this new triaxial testing system many novel features:-

? Automatic area correction - the system automatically used volume change and axial displacement to compute the current average area of the test specimen.

? Pore pressure was measured at the base pedestal and could be used in control calculations.

? Volume change, resolved to one cubic millimetre, was easily measured.

? All tests could be either strain or stress controlled in either compression or extension.

? The system allowed linear stress paths to be programmed in stress space. Any number of continuous linear paths could be made with/without user-intervention.

2.1 Influence on Geotechnical Research

The programmable/automated nature of this original system allowed research in soil testing to move on very quickly. The software (programme) could perform very sophisticated control to make tests such as K-zero, stress paths and cyclic loading very repeatable and routine.

The fact that stress path tests could now be carried out routinely allowed them to become a key test in predicting accurate soil deformation in critical site investigations. Pushed by the availability of equipment to carry out advanced tests routinely engineers started specifying these advanced tests for important projects.

The advantages of computer control and acquisition were quickly adopted in other areas of soil testing. By using a hydraulic consolidation cell (Figure 4.) instead of the triaxial cell the GDS automated system could be used for traditional and advanced consolidation testing. The continuous consolidation tests (constant rate of deformation, constant rate of loading, controlled hydraulic gradient) cause the pore water to flow into or out of the test specimen at a more or less steady rate. This is in direct contrast to the classic step loading test where the hydraulic gradient causing the flow is itself reduced by the flow thus giving rise to the well known exponentially decaying flow rate. Accordingly, the continuous flow tests may be carried out in a fraction of the time taken by the conventional test. Using the system, the conventional step loading test and the various continuous tests could now be compared using the same soil in the same test apparatus.

Fig. 4. Rowe & Barden Consolidation Cell

2.3 Expanding the Range

The use of fully automated control with hard soils and soft rocks required a change in mechanical capability of equipment. For normal and soft soils it is sufficient for equipment to have a pressure capability of hundreds of kPa (0 –2000) and to have a force capability of a few kilonewtons (0 –10). In contrast a step change is required for testing the range of materials from hard soils to rocks. In this range of materials accurately controlled triaxial tests can call for equipment providing pressures of 100 to 200 MPa and forces up to 1000 kN. In the higher ranges the push for systems capability came from petroleum research and led to the development of the high pressure range of triaxial testing systems.

Figure 5 shows a schematic diagram of a typical system.

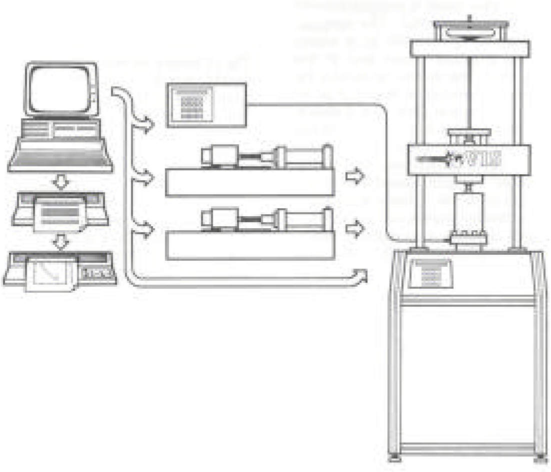

Fig. 5. High Pressure Triaxial System

In this system, in addition to the standard tests of UU, CU and CD, tests may be controlled by a generalised stress path control algorithm. Stress paths are defined in terms of the triaxial stress invariants of deviator stress q and spherical total stress p. Any number of continuous linear paths can be executed either with user intervention or automatically. In providing generalised stress path control the system allows a wide range of tests to be carried out including, for example, isotropic and anisotropic consolidation. Conventional cyclic axial loading with sinusoidal, triangular and square wave forms is also a feature of the system. The system also gives the basic functions to perform tests under manual control with general purpose platen control of displacement, axial load, pressures and volume changes. The control may be provided from the computer or by direct manual control of the loading frame and controllers. In this way, the system can be manually used for a variety of additional tests whilst the computer logs the data and plots on-line graphics. These options show the power of having not only a controlling computer but also individual devices with embedded local control.

2.4 Improving the measurements

The capability of automated control and data acquisition fuelled the requirement for higher accuracy of measurements and more representative values being obtained from test specimens. In the triaxial test this led to transducers getting closer to the test specimen. For example the internal submersible load cell is developed to remove the effects of ram friction that are seen when using external load cells and proving rings. In addition ‘on specimen’ transducers are developed to move the transducers away from the problem areas of bedding errors and end effects. Local transducers for measuring both axial and radial strain are developed along with the capability of mid-plane pore pressure measurement. Figures 6 and 7 show a selection of advanced transducers.

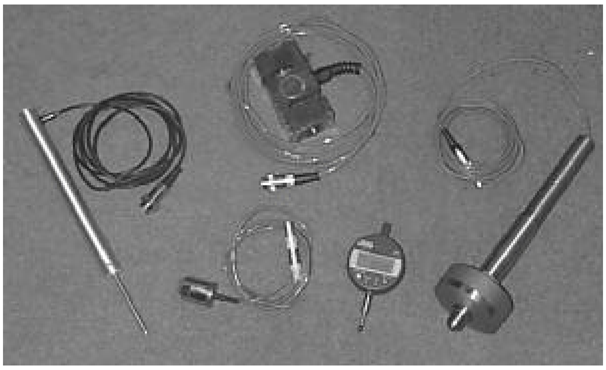

Fig. 6. Advanced Transducers

Fig. 7. Hall Effect Strain Transducers

3.0 Dynamic triaxial testing to simulate earthquake conditions

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. Existing or planned structures can be mechanically improved. 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. These requirements led to the development of accurate computer controlled dynamic triaxial testing systems to evaluate soil performance in the range static to 10 Hz. A typical set of equipment is shown in Figure 8. In this combined cell and dynamic actuator, axial force and axial deformation are applied through the base of the cell. This new cell is screw-driven from an integral base unit housing the motor drive. The cell is provided with a balanced ram to eliminate disturbance to constant cell pressure during dynamic testing. The use of electromechanical actuation allows this system to run the full range of time-based tests. From creep tests lasting several weeks to dynamic tests lasting a few seconds. The method of actuation in dynamic tests is critical to both performance and system costs and is examined in detail in Menzies et al (2002).

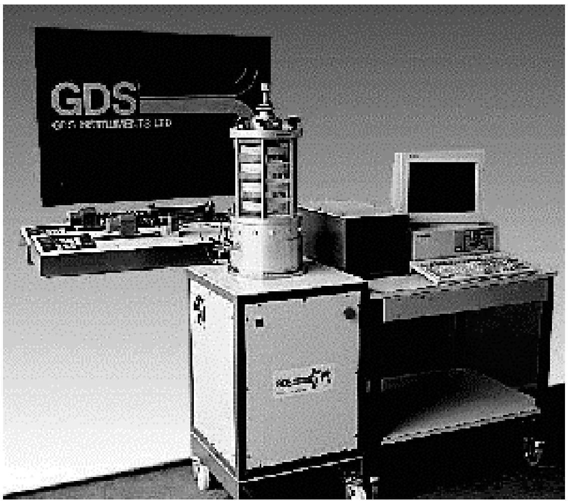

Fig. 8. Typical Dynamic System

4.0 Small Strain Stiffness Measurement

During the late 1980s and early 1990s, dynamic soil stiffness was being measured in the laboratory using small strain resonant column apparatus. Investigators were struck by the similarity of these *dynamic* moduli to *static* moduli back-analysed from movements around real static structures like retaining walls and excavations. They then realised the differences in moduli measured in the past between static tests (conventional triaxial) and dynamic tests (resonant column) were related to strain level. That is one test measured small strain moduli and the other large strain moduli - not that one test was “dynamic” and the other “static” (see Fig 9).

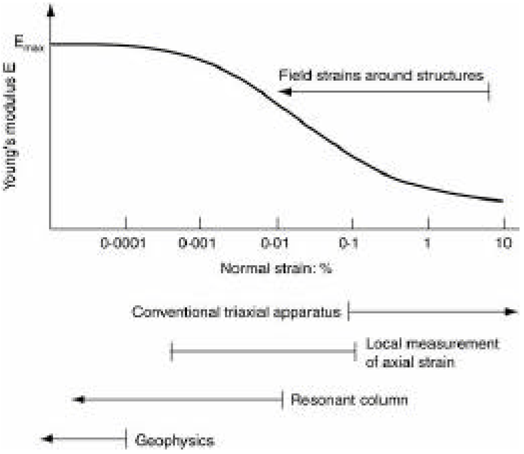

Fig. 9. Idealised stiffness-strain behaviour shown by most soils illustrating that stiffness is strain-level dependent

The value of Gmax (the value of the shear modulus at very small strains) is now treated as a fundamental soil property and is used extensively in finite element modelling. For this reason there is much current interest in the measurement of Gmax both in the laboratory and field.

In the laboratory the small strain stiffness can be measured using local measurements of axial strains either with Hall Effect local strain measurement devices (Clayton & Khatrush, 1989) or LVDT based devices. For very small strain measurements the resonant column or bender element methods can be used.

In the field seismic methods can be used for measuring the value of Gmax. 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. The field seismic methods can be divided into borehole methods and surface methods as shown in Fig 10.

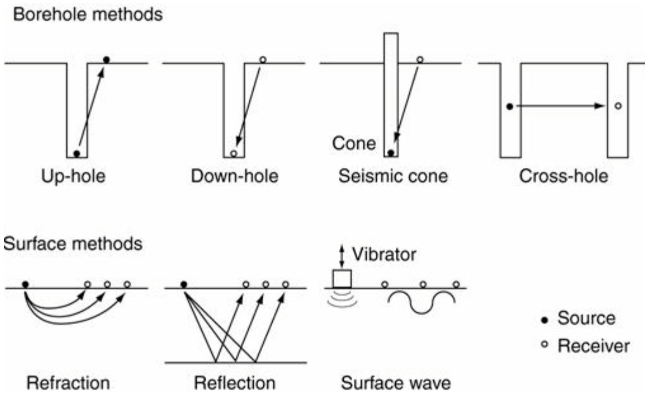

Fig. 10. Seismic Methods

4.1 Bender Elements

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 regularly 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 makes the routine measurement of Gmax, maximum shear modulus, simple. GDS Instruments Ltd have developed a cost effective bender element system. The system is available to be integrated with new systems from GDS or for fitting into existing systems (including those not manufactured by GDS).

Fig. 11. Bender Elements

4.2 Small-Strain Hollow Cylinder Apparatus

Another technique for examining soil properties at small strains is the the new GDS Small-Strain Hollow Cylinder Apparatus. This has been designed to be a high quality, low cost hollow cylinder apparatus. The apparatus has specifically been designed to be capable of testing at very small axial strains (down to 0.00004%). See Figure 12.

Fig. 12. Small Strain Hollow Cylinder

Using a Hollow Cylinder Apparatus it is possible to control the magnitude and direction of the three principal stresses. Studies can for example be made of the following:

- The anisotropy of soil samples,
- The effects of principal stress rotation,
- The effects of intermediate principal stress.

The system can apply a uniquely wide range of stress paths on the test specimen. The loading systems are computer controlled and strains can be measured directly on the test specimen. These strains can also be servo-controlled. Studies can therefore be made under the following test conditions:

- Plane strain,
- Simple shear,
- Very small shear strain.

In addition, standard and advanced triaxial tests can be carried out in the apparatus on standard solid cylindrical test specimen, including:

- K-zero consolidation and swelling,
- Continuous linear stress paths.

There are two versions of the system, dynamic and static. The dynamic version of the system has all the functionality of a dynamic hollow cylinder apparatus at a price approaching that of a standard dynamic triaxial system.

4.3 The GDS Continuous Surface Wave System (CSWS)

The CSWS system takes the measurement of Gmax out of the laboratory and into the field – see figure 13. The GDS Continuous Surface Wave System (CSWS) is used on the ground surface and makes use of Rayleigh waves which are constrained to propagate within a zone approximately one wavelength in depth. In ground where the stiffness changes with depth these elastic waves are dispersive in nature which means that they travel at a velocity which is dependent upon frequency or wavelength.

Fig. 13. CSWS in Action

The CSWS uses a frequency controlled vibrator to regulate the frequency of these surface waves thus permitting a dispersion curve (velocity against frequency or wavelength) to be readily available. By using the theory of elasticity, shear wave velocity and shear modulus G, can be determined from these velocity measurements. Thus the system enables a shear stiffness-depth profile to be determined to depths between 10m (in clays) and 30m (in some granular soils and weak rocks) without the need to provide a borehole. These profiles enable remarkably accurate geotechnical engineering predictions of surface settlement.

5.0 Software

The capability of the sets of hardware described above would not have the same impact without the ability to direct several sets of hardware in concert from a single controlling computer. It is the availability and quality of software that has enabled the power of the hardware. From the early systems based on Hewlett Packard programmable calculators, through the early days of the IBM PC with programs executing in a DOS environment we have now moved into the user friendly graphical user interface world. The reality of this is however that although the software has much greater capability it has become more difficult for the layman to access the computer power without access to generic software development products. But even these generic products require a considerable understanding of systems engineering and programming if the best is to be obtained from a multi actuator system with computations interelated between actuators.

GDS Instruments have approached this problem by developing a general purpose software package aimed at the geotechnical laboratory. This software, called GDSLAB is designed to carry out test control and data acquisition using not only GDS equipment but also other industry standard manufacturers hardware. This means that the same software can be used in a range of laboratories and that the quality of results is determined by the available hardware.

6.0 Conclusion

The science of geotechnical engineering has seen a remarkable growth in the latter part of the twentieth century. This growth has been linked directly to the availability of digital computer processing power. Companies like GDS Instruments Limited have applied the available computing power to the development of commercial testing equipment for soils and rocks and have supported the hardware with a comprehensive set of software (GDSLAB).

The computer controlled actuators and software have enabled the development of a vast range of systems for testing saturated and unsaturated soils in both the laboratory and field. These include; triaxial, consolidation, transducers, bender elements, resonant column, static, dynamic, hollow cylinder, true triaxial, shear box, CSWS, cross hole, down hole and up-hole seismics.

The availability of vast computing power has seen the development of numerical analysis methods like finite elements. The power of these analysis techniques is, however, useless without the availability of real, representative soil parameters. It is the purpose of these systems described above to enable engineers to acquire those parameters in a consistent manner.

The engineer involved in soil and rock testing now has an impressive armoury of equipment available and it is no longer necessary to carry out heroic mechanical and electrical engineering to test soils and rocks. The engineer can now devote his effort to testing the soil.

References

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