Role of Modern Fully Automated Geotechnical Laboratory Testing Equipment in Academia and Industry

Rachid Hankour
Geocomp Corporation, Acton, MA, USA

Allen Marr
Geocomp Corporation, Acton, MA, USA

ABSTRACT: This paper presents the role of modern automated geotechnical testing equipment in academia and industry. The latest innovative technologies in sensors, data acquisition, automated controls, remote monitoring and control in geotechnical testing are highlighted in terms of the quality, reliability, repeatability, accuracy, and confidence in geotechnical test results. A particular emphasis is given to the time savings achieved by using fully automated computer-controlled testing systems for performing consolidation, triaxial and direct shear laboratory tests. Benefits and limitations of modern equipment are discussed as they pertain to collaborative research, training, remote-evaluation and diagnostics around the world.

An illustrative example of consolidation testing (incremental – ASTM D 2435 methods A and B and constant-rate-of-consolidation – ASTM D 4186) is presented which compares manual and fully automated test equipment. These tests were run on Boston Blue Clay and show significant time savings when using fully automated equipment.

Keywords: Full automation; Consolidation testing; Geotechnical testing, Laboratory Soil Testing Equipment, Remote Control.

1 INTRODUCTION

Commercial and academic laboratories for soil testing traditionally required time to manually apply loads and pressures, adjust valves and regulators and record data. Each of these steps is prone to human error and operator’s subjectivity. New and established technologies are now available to assist geotechnical engineers, teachers, and researchers with viable, economical, and accurate modern laboratory geotechnical testing systems. In academia these systems are used for teaching both at the undergraduate and graduate level as well as for doing research. Students are increasingly able to spend valuable time concentrating on soil behaviour, understanding basic principles of geotechnical engineering, and learning more about the application of sensor technology, electronics and software rather than spending hours reading dials and adjusting loads and pressures. These technologies are applied to geotechnical engineering to accurately determine consolidation, permeability, shear strength, and dynamic properties of soils. Students can now confidently run multiple tests in the same traditional amount of time to more comprehensively test the theories learned in the classroom. Conversely, in industry modern emphasis is on reliability of test results according to testing standards and fast turnaround. The application of automation to geotechnical laboratory testing equipment has opened many opportunities in research as well as design optimization and risk management in construction (Marr et al, 1998).

2 HISTORY OF ROLE OF LAB TESTING

A brief history of the role of lab testing and primary advances in geotechnical engineering is summarized in Table 1 (Marr A. 2002). It shows the Marr's characterization of the development of modern geotechnical engineering by decade.

Table1. Role of laboratory testing per decade since 1920 (After Marr, 2002).

Decade	**Primary Advances**	**Role of Lab Testing**
1920's	Development of fundamental concepts of modern soil mechanics.	Lab tests confirm and help extend theoretical concepts.
1930's	Application of fundamental developments to engineering practice.	Meticulous field observations explained with data from new laboratory tests.
1940's	Extrapolation of experience to more daring projects.	Use of laboratory tests to expand envelope of practice and to help interpret field measurements.
1950's	Major advances in concepts of shear strength culminating in ASCE Boulder Conference	Laboratory is center of geotechnical research.
1960's	Larger scale projects (massive dams) undertaken	Field measurements of deformation and pore pressure become a key part of geotechnical engineering
1970's	Focus on behavior and measuring properties in situ. New lab devices are more complex.	Variety of devices developed to measure physical properties in situ.
1980's	Era of advanced modeling-risk, probability, constitutive relations.	Models require more data and more sophisticated data but demand for lab testing declines.
1990's	Specialized materials and methods like geosynthetics, reinforced soils, flowable fills. Era of the computer-compute and display	Laboratory measurements help make use of these new materials and methods possible
2000's	Automation	Faster testing with less human error
2010's	Reliability and risk management	Establishing bias and variance.

Traditional test equipment and methods relied on the operator to be on duty, remain alert, transfer manually recorded data to a spread sheet program, process, evaluate, and generate reports with plots and tables during a working week as illustrated in Figure 1 a). As The price of labor increased in the '80s laboratories hired technicians that cost less but had much reduced skill sets. Test quality and turnaround became poor. Simultaneously, pressure to complete more work in less time increased and clients began to view engineering and testing as commodity services. The consequences were lower quality test results delivered too late in the design process. Many designers and design manuals fell back to presumptive values for soil parameters and by passed most testing, except classification, all together.

With the introduction of modern equipment as shown in Figure 1 b), test results of higher quality has become available much faster. Growing demand for rapid test results as well as more complex designs requiring more detailed models and input parameters are increasing demand for fast quality, fast results. Reliable and on time data also plays an important role in protecting against claims, legal action, and answering public's demand for minimum negative impact from construction. In academia there still seems to be a gross imbalance between what is taught in classes, written in papers and what is actually done in practice. However this perception is changing with the introduction of modern test equipment.

Recent advances in geotechnical test equipment automation make it possible for complete computer control of most tests. Today there exists fully automated geotechnical testing equipment that integrate the latest sensor technology, highly precise micro-stepper and servo-motors, electronic valves, high speed data acquisition and controls, and computer networking to provide up to the second test results of high quality with much reduced labor (Marr et al. 2003, Dasenbrock and Hankour 2005 and 2006). One modern testing station can replace up to three traditional testing stations in terms of production. Remote access to real time test data from any point on the internet is becoming more possible and reliable.

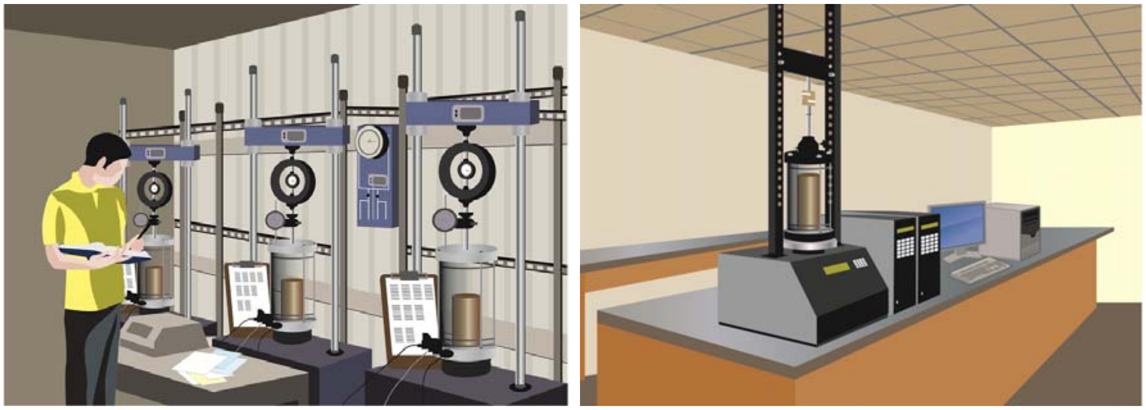
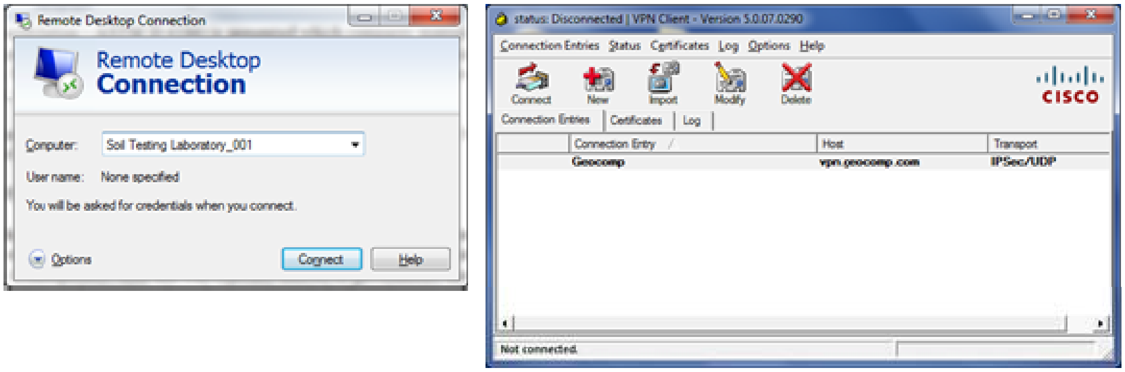


Figure1. a) Traditional Method (3 manual test stations) b) Modern Method (one automated station replaces 3 manual stations)

3 REMOTE CONTROL IN MODERN GEOTECHNICAL TESTING

The need for a fast, secure and reliable way to share information across computer networks has resulted in the emergence of software programs that allow users to view and fully interact with one computer from another computer anywhere on the internet by means of already built-in desktop remote access in the latest Microsoft Windows® and Virtual Private Network (VPN) type programs. Additionally there are ‘open source’ computer software versions of VPN that have been available since 1998 such as VNC (Virtual Network Computing). VNC-type programs have been extensively used in a multitude of applications throughout research centres, universities, and government institutions. Figure 2 shows a remote desktop access standard window pulled from Microsoft Windows® Version 7 Accessories program. It is extremely easy and convenient for anyone with the PC password to communicate with a networked PC controlled geotechnical testing system.



Remote Desktop Connection

Computer: Soil Testing Laboratory_001

User name: None specified

You will be asked for credentials when you connect.

status: Disconnected | VPN Client - Version 5.0.07.0290

Connection Entry	Host	Transport
Geocomp	vpn.geocomp.com	IPSec/UDP

Not connected.

Figure 2. Open dialogue boxes of remote desktop connection access and standard VPN user interface.

This combination of desktop remote access software program from Microsoft Windows® and a computer controlled geotechnical testing equipment provides a clear advantage for inherently time consuming geotechnical tests which require test parameter adjustments in real time. Such tests include multi-phase and multi-step tests such as triaxial, consolidation, and direct shear. For example the shear rate of a direct shear or a triaxial test is dependent on the consolidation properties which require entry of an appropriate shear rate while a test is running to meet test standards requirement. Figure 3 shows the real time determination of the end of primary consolidation during a triaxial test. This determination is based on square root of time Taylor's graphical construction. Similarly adjustments may be required for an incremental consolidation test to insert an unloading reloading loop or to better define and capture the preconsolidation pressure value. Being able to monitor results in real-time and control the equipment remotely opens all kinds of testing flexibility and helps improve test quality.

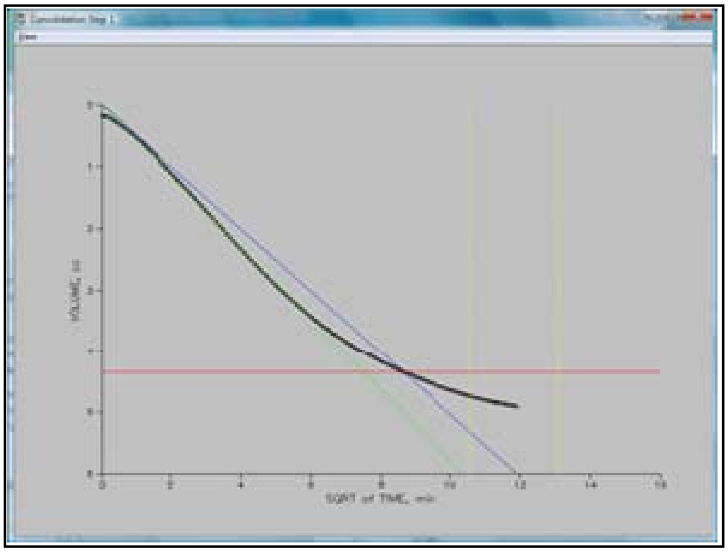


Figure 3. Real time determination of end of primary consolidation phase during a fully automated consolidated undrained (CU) triaxial test.

With internet connectivity, the end user is no longer required to be physically present in the lab in front of the testing station to monitor test progress and make any necessary adjustments when required. This can now be all performed remotely. Not only does it save time and make lab testing more efficient, it creates distance learning and fosters research among universities regardless of their geographical location. A great advantage to the industry is the fact that the client can now be involved with the testing, with real time updates of test progress including access to test results. The software programs have security features to stop unauthorized use.

4 CONSOLIDATION TESTING PROGRAM ON BOSTON BLUE CLAY (BBC) USING THREE DIFFERENT METHODS

4.1 *Introduction*

To illustrate some of the benefits of automated testing we consider consolidation testing a Boston Blue Clay (BBC). Three consolidation tests were carried out on undisturbed samples of BBC. The material tested was from a Shelby tube obtained from a depth of 5.5 to 6.7 meters. Initial water content was 34%, and void ratio was 0.80. Two tests were run according to ASTM Standard D 2435 “Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading”. The first test followed Method A whereby each pressure increment was held for 24 hours. The second test followed Method B whereby each pressure increment was terminated once end of primary consolidation was achieved. During this later test the consolidation cell was fitted with a pressure sensor to measure excess pore water pressures during each pressure increment. A set-up of the testing systems is shown in Figure 5. A total of 18 pressure increments were applied for both Methods A and B.

A third consolidation test was run according to ASTM Standard D 4186 “Standard Test Method for One-Dimensional Consolidation Properties of Saturated Cohesive Soils Using Controlled-Strain Loading”.

4.2 *Consolidation Method A and B with Excess Pore Water Measurements*

Both consolidation ASTM D2435 Methods A and B were performed using the same automated equipment shown in Figure 5. Pore water pressure at the base of the specimen can be measured in both methods. Therefore the process of primary consolidation can be precisely determined by observing the dissipation of excess pore water pressure. Theoretically, the primary consolidation ends when this excess pore water pressure is completely dissipated. The excess pore water pressures were measured at the bottom of the sample resulting in one-way top drainage condition for Method B. Figure 4 shows an example of excess pore water pressure dissipation during a pressure increment.

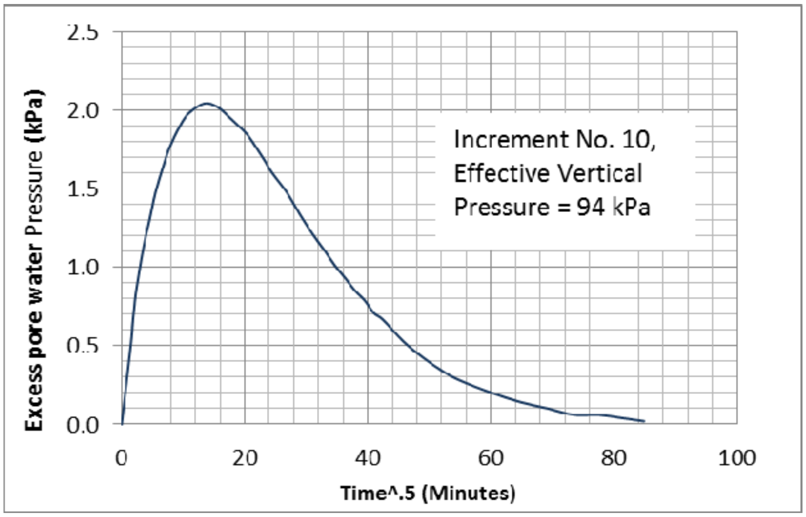


Figure 4. Example of excess pore water pressure dissipation during a pressure increment

Figure 5. Front view of a fully automated constant rate of consolidation system.

4.3 *Constant Rate of Strain Consolidation (CRSC)*

A third test was run using constant rate of consolidation method. A picture of fully automated equipment is shown in Figure 5. Following its development in the ‘60s this method was considered to be the fastest method in performing a consolidation. Since measurements of total vertical stress and excess pore pressure can be measured continuously, the consolidation curve can be determined as a continuous relationship rather than discrete points as obtained in ASTM D2435. This allows more accurate determination of the maximum past pressure and a continuous curve between coefficient of consolidation and vertical effective stress.

4.4 Summary of test results

Table 2 compares time to reach end of primary consolidation based on Casagrande logarithmic method, Taylor's square root of time method, and excess pore water pressure dissipation method. Figure 6 shows summary plots of all three tests using the aforementioned three methods. All three methods yield consistent consolidation test results as show on Table 3.

The consolidation method B is a more advanced method that makes use of computer automation as compared to the consolidation method A, although method A is more widely used. Pore water pressure can be measured in both methods. Therefore the process of primary consolidation can be precisely determined by observing the dissipation of excess pore water pressure. Theoretically, the primary consolidation ends when this excess pore water pressure is completely dissipated. The excess pore water pressures are measured at the bottom of the sample resulting in one-way top drainage condition.

It should be noted that the soil sample used when running Method B was slightly disturbed which may explain the excessive straining at higher stresses.

		Time to End of Primary Consolidation				
Method A: 24 hr per increment				**Method B: End of Primary**		**Excess Pore Water Dissipation Method**
Step	Vertical Effective Stress	Log Time Method	Square Root Time Method	Log Time Method	Square Root Time Method	
	(KPa)	(min)	(min)	(min)	(min)	(min)
1	10	40	38	30	37	34
2	22	40	42	52	60	39
3	46	40	37	34	35	48
4	94	52	55	45	47	54
5	190	26	25	26	30	67
6 (U)	94	20	20	14	18	120
7 (U)	46	25	22	32	36	110
8 (U)	22	60	54	27	29	105
9	46	50	58	44	51	88
10	94	20	19	22	22	60
11	190	50	43	22	24	63
12	381	56	59	42	49	69
13	764	40	39	40	37	75
14	1530	24	25	30	33	46
15	3062	40	41	29	31	21
16 (U)	764	50	48	12	16	>120
17 (U)	190	15	15	20	24	>120
18 (U)	46	36	39	38	35	>120

Table 2. Comparative table of time to end of primary for the consolidation tests.

Method	CC	CR	σ'p kPa
CRCS	0.14	0.0042	460
Method A &B	0.16	0.0050	565

Table 3. Consolidation parameters test results

According to Holtz and Kovacs (1981), and Ladd and DeGroot (2003) the value of CC for Boston Blue Clay ranges from 0.17 to 2.8. Hence the CC = 0.14 obtained from this test was reasonable. The overall results three methods as well the shape of the summary curves compare very well.

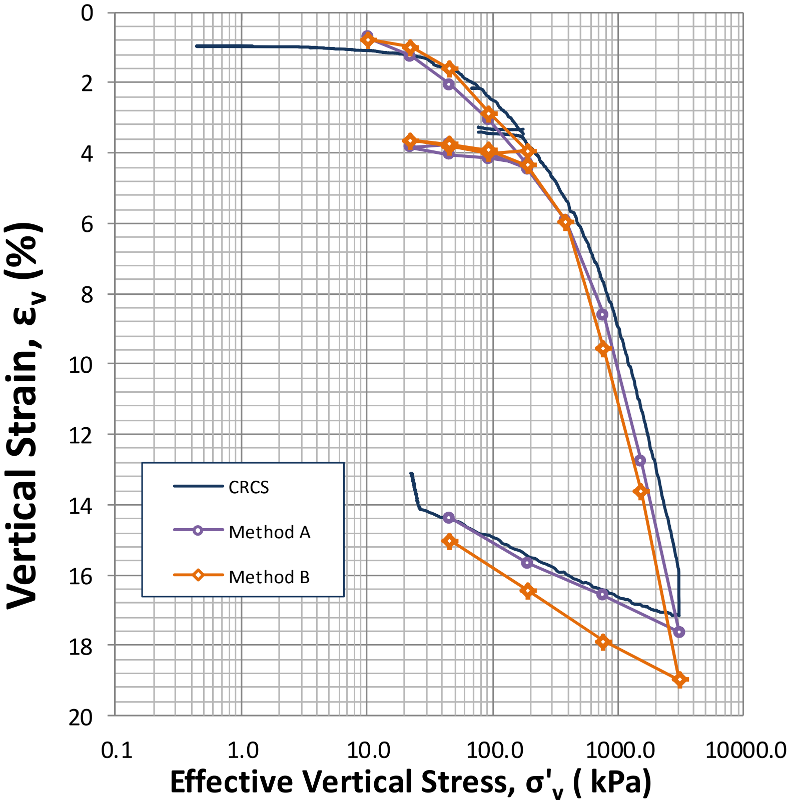


Figure 6. Plot comparing summary curves of the three consolidation methods

5. SUMMARY OF ROLE OF MODERN GEOTECHNICAL LABORATORY TESTING

A major advantage of automated laboratory testing is the substantial reduction in both labor and testing time required to run tests. Some tests such as cyclic triaxial, direct simple shear (DSS) , resonant column and torsional shear (RCTS) can only be run with a computer controlled system . Tables 4 to 6 show the considerable amount of time saving for common triaxial, consolidation, and direct shear tests. Other advantages are listed as follows (Marr 2002):

- Reduce risk by providing more reliable test data
- Maintain and manage information flow
- Finish tests faster
- Provide consistency in test procedures and results
- Give more data on all phases of test
- Permit more detailed analysis of test
- Make more specialized tests possible
- Utilize facilities better
- Improve quality
- Present data to meet specific client needs
- Electronically submit results
- Make lab work more interesting for the technician
- Improve image of lab to clients
- Remotely monitor tests 24x7
- Save money by running several testing stations from one computer

The disadvantages are listed below:

- Automated equipment tends to have higher up front cost
- Automation generally requires a higher knowledge level from the end user
- The above can produce efficiency problems in commercial labs if staff turnover is high
- Calibrations of sensors should be performed more frequently
- Power brownout or blackouts can cause damage and loss of tests results
- Over-reliance on PC, and tendency to forget to observe key parts of the test and examine test results carefully

Table 4. Labor saved with fully automated consolidation testing (after Hankour 2008).

Soil Type	**Test Time, days**			**Labor, hours**		
	Conventional	Automated	Testing Time Saving	Conventional	Automated	Labor Saving
Silty sand	16 ~18	0.5 ~ 1	94% ~ 97%	4 ~ 12	1	75% ~ 92%
Silty Clay	16 ~18	1 ~ 2	88% ~ 94%	8 ~ 16	1	88% ~ 94%
Plastic Clay	16 ~18	2 ~ 3	81% ~ 89%	12 ~ 32	1	92% ~ 97%

Includes 12 load steps with one log cycle of secondary compression. Times include preparing specimen, running test and reporting results. Times for conventional tests assume standard practice of applying each increment for 24 hrs.

Table 5. Labor saved with fully automated triaxial testing (after Hankour 2008).

Soil Type	**Test Time, days**			**Labor, hours**		
	Conventional	Automated	Testing Time Saving	Conventional	Automated	Labor Saving
Silty sand	1	0.5	50%	6 ~ 8	2	67% ~ 75%
Silty Clay	2	1	50%	10 ~16	2	80% ~ 88%
Plastic Clay	5	2	60%	12 ~ 24	2	83% ~ 92%

Times include preparing specimen, running test and reporting results.

Table 6. Labor saved with fully automated direct shear testing

Soil Type	**Test Time, days**			**Labor, hours**		
	Conventional	Automated	Testing Time Saving	Conventional	Automated	Labor Saving
Silty Sand	1~2	0.5	50%	6 ~ 8	2	67% ~ 75%
Silty Clay	2~3	1	50%	10 ~16	2	80% ~ 88%
Plastic Clay	5~7	2~3*	60%	12 ~ 24	2	83% ~ 92%

Times include preparing specimen, running test and reporting results.
*not including very fat clays

6. CONCLUSION

Modern fully automated computer-controlled geotechnical testing systems can perform the majority of geotechnical tests to measure strength, stiffness, and permeability. As more and more advanced computer programs are used in the industry for design projects, there is a growing need for the use of input test parameters that simulate as best as possible field conditions (Dasenbrock and Hankour 2006). Some of these realistic and meaningful parameters can only be determined with modern equipment. In academia, these systems are used for teaching and advanced research. They save space and, more importantly, time which allows students and faculty to run tests that require multiple points in the case of triaxial and direct shear for example in the same allotted laboratory time. An added benefit is the capability for remote access and control.

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