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State of the Practice: Geotechnical Laboratory Testing

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RESUMEN

Laboratory measurements are used to obtain mechanical and physical properties of geotechnical materials for analysis and design. This paper examines the role of laboratory testing in today’s geotechnical practice, reviews the advantages and problems with automated testing systems, and discusses the future role of geotechnical laboratories in geotechnical practice.

INTRODUCTION

Engineers are in the business of producing designs based on numbers. Laboratory measurements give us the means to obtain realistic and meaningful numbers. Laboratory testing has provided the lifeblood for advances in modern geotechnical engineering. Karl Terzaghi writing in 1936 said, “I came to the United States and hoped to discover the philosopher’s stone by accumulating and coordinating geological information.... It took me two years of strenuous work to discover that geological information must be supplemented by numerical data which can only be obtained by physical tests carried out in a laboratory.”

Table 1 shows my biased characterization of the development of modern geotechnical engineering by decade. The table attempts to capture the central role of laboratory testing to every decade of progress in our field. It ends on a disturbing observation though - my perception that in geotechnical engineering today, there is a significant trend away from using measurements of hard data for the specific site. Testing seems to have fallen out of favor over the past 20 years. Why is this? From my own experience and discussions with engineers across the United States, there are several reasons. These are summarized in Table 2. In the decades of the 70s and 80s, the cost of lab testing increased relatively rapidly. Some of this increase was driven by the demands of the nuclear power industry. During this time, it was also typical practice to take several weeks to complete testing projects. As pressures mounted to complete jobs more quickly, many project engineers found themselves receiving lab data after they had completed their designs. The quality of testing also seemed to deteriorate compared to that of the 50s and 60s. Research developments of the 50s and 60s lead to relatively

Table 1: Role of Lab Testing in Development of Geotechnical Engineering

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

straightforward and simple equipment that most engineering firms could afford. However, research of the late 60s and 70s produced much more complicated and sophisticated equipment that required specialists to operate and maintain. Devices like cyclic triaxial machines and constant strain rate consolidometers required expensive electronics and frequent calibration. Data processing remained expensive and time consuming.

These conditions lead many designers to look for ways to minimize or avoid reliance on lab testing. They resorted to "conservative" estimates of soil parameters for design based on published values or prior experience. Some looked to field testing with cones, vanes,

Table 2: Reasons for Decline in Laboratory Testing

- Price became relatively high
- Turnaround time was too slow to meet industry needs
- Quality began to suffer
- Low barriers to entry for basic testing introduced heavy competition
- New equipment from research was too complex or of little practical value
- Use of “conservative” or assumed data in design
- Switch to field testing where possible
- Decline of the big earthwork projects
- Diminished role of labotratory and hard data in educational programs.

pressuremeters and dilatometers to replace the laboratory. Competitive pressures of the past decade further reduced the demand for lab testing as engineers sought ways to win projects by reducing costs.

ROLE OF LABORATORY TESTING

What is the role that laboratory testing can or should take in today’s geotechnical practice? There are a number of advantages that laboratory testing offers. We can see the sample and the failure modes. This may help us understand anomalies and explain variations in the test results. We can perform index tests on the same specimens. We can control the stresses and match them to the actual stress path for our design. We can control the drainage conditions. We can measure stress, strain and pore pressure from low strains to failure. We can overcome most of the effects of sample disturbance.

There are some drawbacks to laboratory testing. We must have representative samples to test. These may be difficult or expensive to obtain. All samples are disturbed to some degree, which affects their strength and stiffness. Structure and fabric of specimens prepared in the laboratory may substantially differ from that attained in the field. Lab testing is generally limited to a few tests at specific points where we have samples, so we may miss layers, seams or strata that will dominate performance. A good quality laboratory requires a variety of specialized equipment and personnel with the training and skills to properly use that equipment.

Despite these drawbacks, there are an increasing number of ways that laboratory testing can contribute to geotechnical practice. These are identified and discussed below.

<u>Establish baseline site conditions</u> – Laboratory tests are used to characterize site conditions so engineers know what to design and contractors know what to bid. For larger underground projects, geotechnical baseline reports are increasingly used to

establish a reference for helping to resolve future disagreements. Generally, well-defined baseline conditions reduce the risk and uncertainty that designers and contractors incur.

Improve quality of analysis – Engineers use analysis to predict performance and cost. Today’s numerical methods give the engineer very powerful analytical methods but those methods are only as good as the parameters they use. Appropriate lab tests provide these parameters.

Develop more cost effective design – Geotechnical design depends on strength, stiffness, and permeability. Using estimated or “conservative” parameters for design inherently increases the cost of construction. Realistic parameters obtained from appropriate laboratory testing can reduce the cost from such conservatism.

Determine feasible ways to improve existing conditions – Lab testing provides a way to test ideas to improve the soils at a site before mobilizing expensive equipment. Bench scale tests to measure the effects of improvement options on strength, stiffness or permeability can be performed relatively inexpensively.

Develop mix formulations – Additives such as cement, lime, fly ash, and chemical stabilizers can alter the mechanical and chemical properties of soils, but the degree of alteration is very difficult to predict. Each soil condition responds to additives in different ways. Lab testing is used to develop the best combinations to achieve a desired result.

Show compliance with regulations – Some regulations require specific tests. Regulations governing construction of liner and cover systems for landfills require specific values of permeability for different components. Lab tests of permeability are used to demonstrate that the regulations are met. Some states such as California and Colorado require specific tests be performed to measure soil strength for the foundations of homes placed on hillsides.

Provide manufacturing quality control and quality assurance – Geotechnical engineers increasingly use manufactured products to enhance or replace geologic materials. Significant businesses have developed to produce a wide variety of geosynthetic materials for geotechnical separation, filtration, and isolation. Lab tests are used to ensure that the physical and mechanical properties of these manufactured materials comply with their technical specifications.

Provide construction quality control and quality assurance – Testing is used to determine whether a contractor is meeting the specifications. A significant amount of the geotechnical testing performed today is to screen the contractor’s source materials and to check on the finished conditions of his work.

Troubleshoot construction problems – When problems do occur, lab testing of the materials involved can provide valuable insight to what is causing the problem and how to fix it. Unfortunately, too many construction problems in earthwork are addressed with the equivalent of band-aids and aspirin rather than the sound diagnostics that good testing can help provide.

<u>Determine cause of unacceptable performance</u> – Unacceptable performance may occur after the engineer and contractor have finished and left the job. Lab testing can play a crucial role in determining what caused the unacceptable performance and how to fix or adjust to the problem.

<u>Minimize risk from failure, surprises, damages and delays</u> – Engineering and construction companies spend considerable high-level management time with risk management. Increasingly, the risks associated with damages to third parties and delays to project completion may exceed the building risks. These risks inherently result from the unknown. Data from good quality lab testing help reduce these unknowns.

<u>Assist with claims and litigation</u> – When things go different than expected on a project, claims for extra money can develop. If these proceed to litigation, the costs can greatly exceed the entire design cost. A frequent occurrence in underground construction is the claim of a Differing Site Condition by the contractor. Solid data from a good baseline study can help resolve the issues in an equitable way. Even testing performed during the claim and/or litigation phase can be very effective at countering theories based on "expert opinion."

<u>Develop new materials</u> – Laboratory testing fills an important role in the development of new construction materials. Geosynthetic materials and flowable fills are examples of materials whose development and refinement occurred largely by laboratory testing.

<u>Develop new methods</u> – Many ideas for new methods of earthwork construction are initially explored in a laboratory setting. For example, we are currently engaged in a study of grouting materials that we can use to replace sand filters and bentonite seals around electrical piezometers so that several units can be placed in the same borehole and thereby reduce the cost of their installation.

<u>Improve our understanding of material behavior</u> – Testing gives us great insight to a material's behavior. As quoted in the opening to this paper, Terzaghi relied heavily on detailed laboratory testing to develop and confirm his concepts of fundamental soil behavior. While we have a much broader and deeper understanding of fundamental geotechnical material behavior today, like every human, each soil exhibits its own behavioral characteristics, which we can only best characterize with appropriate tests.

<u>Save time and money</u> – All of the potential roles of laboratory testing described above have one element in common. We are striving to save time and money by reducing the cost of construction, reducing the risk of failure and damage, and avoiding delays as much as possible. A properly conceived and executed laboratory testing program can pay for itself many times over through reduced costs for construction, damage, delays, and

claims. This statement is perhaps truer than ever as the costs from damages, delays and claims become increasingly significant in earthwork construction.

EQUIPMENT TO MEASURE GEOTECHNICAL PROPERTIES

Today, we have an amazing choice of devices with which to equip our laboratories. In general, this equipment is more reliable, accurate, durable and capable than its predecessors. The primary change in geotechnical laboratories in the last 30 years has been the introduction and use of electronics to run tests, collect data and produce reports. Figure 1 shows a universal testing system that we use for consolidation, strength and permeability testing in our laboratory. By changing the test cell and the software, this equipment can run most of the more sophisticated tests we perform on soils and weak rocks.

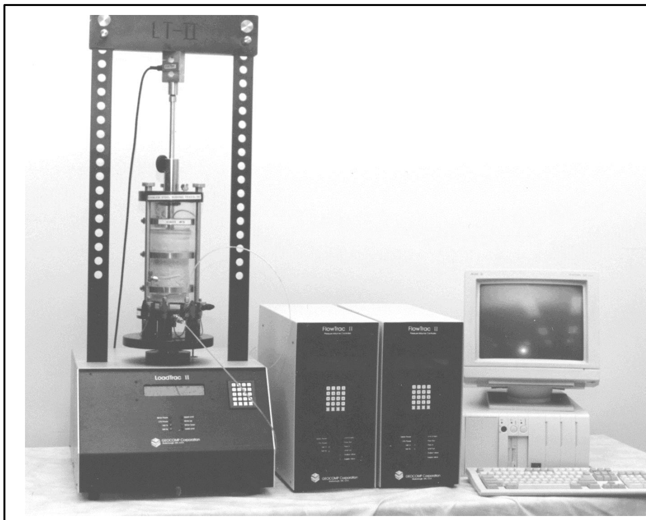


Figure 1: Universal Triaxial System

Figure 2 shows this system configured for incremental consolidation testing. By having the computer determine when primary consolidation is over and automatically proceeding to the next load step, this system can complete an entire incremental consolidation test without human intervention. The automated system runs the equipment, logs the test data, provides the technician with real-time data, and shuts down the equipment when the test is complete. Load is maintained to within 1 kPa (0.01 tsf). Vertical displacement is read and maintained to within 0.001 mm (0.00005 inch). In this system, the computer determines when primary consolidation is completed in each load step and automatically proceeds to the next load step. This is done using Taylor’s square root of time fitting method (Lambe and Whitman, 1969) to compute t_{100}. A minimum time is input by the user for each step to avoid the step being ended too quickly due to unreasonable values of t_{100} that can result from poorly fitting consolidation test data.

Options for each step allow one to control how and when the step is terminated. Load for a new step is added as rapidly as possible. In this system, 90% of the added load for the new load increment is placed within 1 second. The test data are reduced and reports produced with software provided with the system. With this system, we typically complete an incremental consolidation test on Boston Blue Clay consisting of 12-17 load steps in 30-48 hours. This is a major reduction in time compared to the traditional approach where a new load is

Figure 2: Automated Consolidation Device

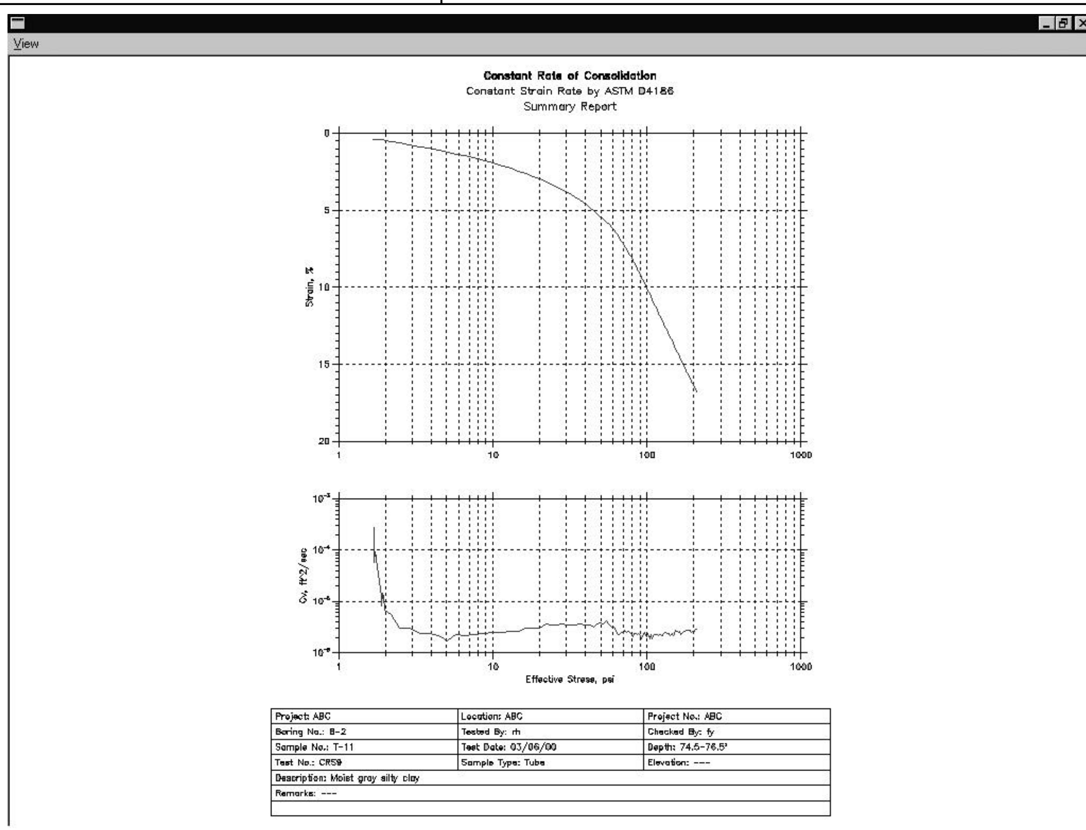


Figure 3: Constant Rate of Strain Consolidation Test

Table 3: Labor savings from automated consolidation testing (Marr et al, 1998)

Soil Type	Conventional Manual		Conventional with Data Acquisition		Automated System	
	Elapsed Time, days	Labor, hours	Elapsed Time, days	Labor, hours	Elapsed Time, days	Labor, hours
Silty fine sand	16-18	4-12	12-16	3-5	0.5-1	1
Silty clay	16-18	8-16	12-16	3-5	1-2	1
Plastic clay	16-18	12-32	12-16	3-6	2-3	1

applied every 24 hours, five days a week and requires 2-3 weeks to complete the test. Likewise, there is a significant reduction in man time required for the test with most tests completed and the report prepared with less than one man-hour. Table 3 summarizes our typical experience with time savings provided by different degrees of automation for incremental consolidation tests. The values in Table 3 are based on a consolidation test that includes 12 load increments with one log cycle of secondary compression each. Time includes the effort to prepare the test specimen, run the test and report preliminary data. Times for conventional methods assumes the standard practice of holding each load increment for 24 hours. Automation will pay for itself within a relatively short time if one has sufficient work to keep the equipment in use.

By changing the consolidation cell and control software, this same system can run constant rate of strain consolidation, constant rate of loading, constant gradient and constant pore pressure ratio consolidation tests. Figure 3 illustrates results for a constant rate of strain consolidation test obtained with one man-hour of labor, of which 60% was required to prepare the specimen, set up the test, and tear down the test. Note the continuous stress-strain curve provided by this test. With a Rowe cell, the system can also measure consolidation with radial drainage, thereby giving us a measure of horizontal coefficient of consolidation under vertical loading.

Figure 1 showed the universal triaxial system configured for triaxial testing. Computer controlled flow pumps are used to control cell pressure and back pressure. A flow pump is a cylindrical chamber with a piston that is moved in and out of the chamber under computer control. A pressure transducer provides feedback for the computer to make the flow pump produce the desired pressure. The flow pumps can resolve volume changes as small as 0.001 ml and maintain pressures to within 0.05 kPa (0.005 psi or 0.1 inch of water head) over a pressure range of 300 psi. The only external input to this system is a power source, e.g. no air compressor and no mercury pots.

With the load frame controlling the vertical force on the sample, one flow pump controlling the chamber pressure, and the other flow pump controlling the backpressure, this system provides complete control over the stresses in a triaxial cell. This system can run unconsolidated undrained, consolidated undrained, K_o consolidated undrained, consolidated drained and stress path triaxial tests. In fact, it can run any stress path that can be produced in a triaxial cell.

For a triaxial test, all phases of the test can be programmed at the beginning and the entire test run without intervention by the technician. This includes backpressure-saturation, consolidation, and the shear phases of the test. Automation of all phases permits the system to complete triaxial tests much faster than conventional equipment allows. For many materials, we set up the equipment in the morning, backpressure-saturate during the day, start consolidation near the end of the day, and shear the sample overnight. Much of our triaxial testing is completed within 24 hours from the start. Longer testing times are used for tests on highly plastic materials with long consolidation times and for special tests. We try to schedule tests with longer times for weekends to get the best utilization of equipment and labor. We evacuate samples during setup to remove air, use filter strips, and employ high backpressures to speed up saturation and consolidation. Figure 4 illustrates a set of triaxial tests obtained with a total of five hours of labor, of which 75% was required to prepare the specimens and set up the tests.

Backpressure saturation is performed automatically by increasing the cell pressure by a constant amount and measuring the resulting change in pore pressure. If the measured B after a specified time is less than the required B, the pore pressure is raised so that the change equals the change in cell pressure. This condition is maintained for a specified time to allow pore pressure equalization within the sample. Then the entire step is repeated. As the cell pressure increases, the sample becomes more saturated and B increases. If the required B is not obtained at some preset maximum cell pressure, the process is stopped and the sample maintained until an operator can instruct the system what to do. K_o consolidation is performed by constantly monitoring axial strain and volumetric strain and adjusting the horizontal stress so that the computed radial strain is zero (axial strain equals volumetric strain). The sampling effective stress can be measured with the system and backpressure/saturation performed at this effective stress. However we usually backpressure/saturate around some nominal effective confining stress between 10 and 50 kPa (2 and 10 psi), depending on the final effective stresses used for shearing the specimen. Table 4 summarizes our experience with typical testing times and labor required for different degrees of automation of triaxial testing.

Table 4: Labor savings from automated triaxial testing (Marr et al, 1998)

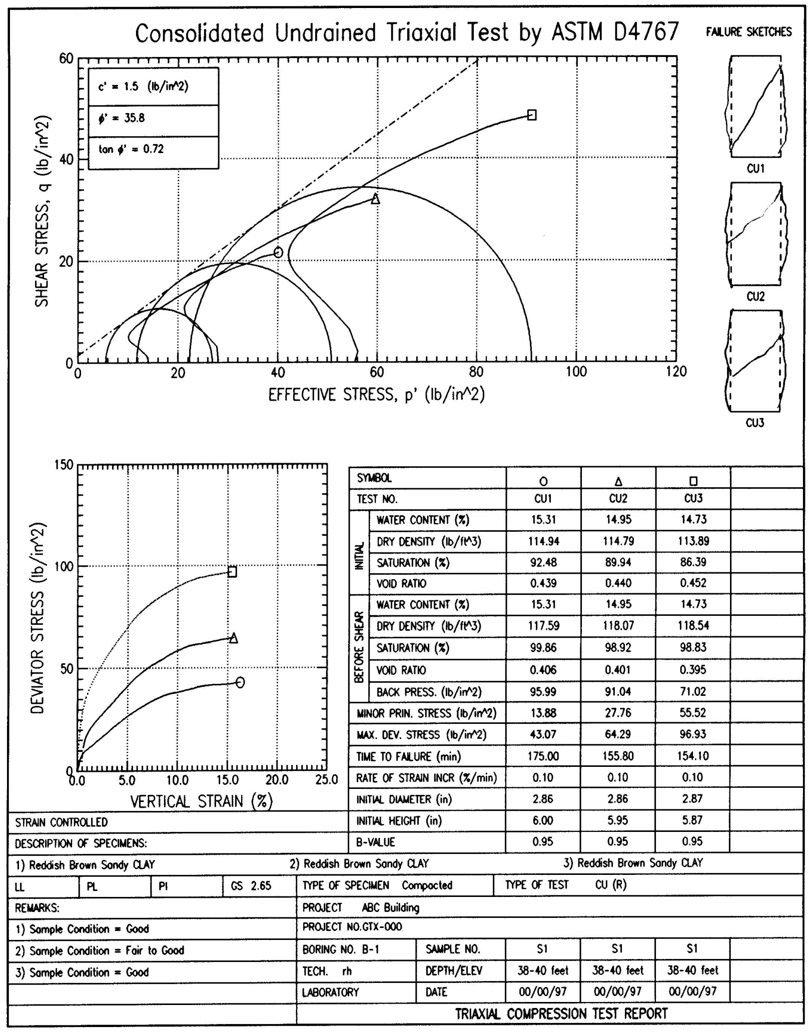
Soil Type	Conventional Manual		Conventional with Data Acquisition		Automated System	
	Elapsed Time, days	Labor, hours	Elapsed Time, days	Labor, hours	Elapsed Time, days	Labor, hours
Silty fine sand	1	6-8	1	5-6	0.5	2
Silty clay	2	10-16	2	8-14	1	2
Plastic clay	5	12-24	4	10-20	2	2

Table 5 summarizes the tests that can be performed with this Universal Triaxial System. It’s remarkable that one basic system can provide essentially all of the more sophisticated tests done today to measure soil properties in a laboratory. Having one test station capable of performing all of the tests in Table 5 permits us to obtain a high utilization rate for the equipment and minimize the lab space required to perform the tests.

Table 5: Test Types Performed by Universal Triaxial System

Unconfined Compression (UC)
California Bearing Ratio (CBR)
Incremental Consolidation
Consolidation with measurement of K_0
Constant Rate of Strain Consolidation
Constant Rate of Loading Consolidation
Constant Gradient Consolidation
Constant Pore Pressure Ratio Consolidation
Rowe cell consolidation
Consolidated Undrained Triaxial (CU)
Consolidated Drained Triaxial (CD)
Anisotropically Consolidated Undrained Loading, $CK_0U(L)$
Anisotropically Consolidated Undrained Unloading, $CK_0U(U)$
Anisotropically Consolidated Drained Loading, $CK_0D(L)$
Anisotropically Consolidated Drained Loading, $CK_0D(U)$
Triaxial stress path
Cyclic Triaxial
Resilient Modulus
Constant gradient permeability
Constant flow permeability

Figure 5 shows a Universal Shear System designed to measure strength of soils. As shown in the figure, the unit runs a direct simple shear (DSS) test of the type developed by NGI. Ladd (1991) showed that the DSS test gives a very good measurement of the average field strength for undrained construction on and in clays. Unfortunately, use of this device in the past was severely limited because the equipment was expensive and the test required a lot of labor. This device has been redesigned and modernized to use the same approaches as described above for triaxial test equipment. The same device can also be used to run direct shear tests, incremental consolidation tests and constant rate of strain consolidation tests by changing the test cell and the control software. Thus with one device we can obtain the drained and undrained strength and consolidation characteristics of soils.



SYMBOL		O	Δ	□	
TEST NO.		CU1	CU2	CU3	
INITIAL	WATER CONTENT (%)	15.31	14.95	14.73	
	DRY DENSITY (lb/ft^3)	114.94	114.79	113.89	
	SATURATION (%)	92.48	89.94	86.39	
	VOID RATIO	0.439	0.440	0.452	
BEFORE SHEAR	WATER CONTENT (%)	15.31	14.95	14.73	
	DRY DENSITY (lb/ft^3)	117.59	118.07	118.54	
	SATURATION (%)	99.86	98.92	98.83	
	VOID RATIO	0.406	0.401	0.395	
	BACK PRESS. (lb/in^2)	95.99	91.04	71.02	
MINOR PRIN. STRESS (lb/in^2)		13.88	27.76	55.52	
MAX. DEV. STRESS (lb/in^2)		43.07	64.29	96.93	
TIME TO FAILURE (min)		175.00	155.80	154.10	
RATE OF STRAIN INCR (%/min)		0.10	0.10	0.10	
INITIAL DIAMETER (in)		2.86	2.86	2.87	
INITIAL HEIGHT (in)		6.00	5.95	5.87	
B-VALUE		0.95	0.95	0.95	

STRAIN CONTROLLED

DESCRIPTION OF SPECIMENS:

1) Reddish Brown Sandy CLAY 2) Reddish Brown Sandy CLAY 3) Reddish Brown Sandy CLAY

LL	PL	PI	GS 2.65	TYPE OF SPECIMEN Compacted	TYPE OF TEST CU (R)

REMARKS:
1) Sample Condition = Good
2) Sample Condition = Fair to Good
3) Sample Condition = Good

PROJECT ABC Building
PROJECT NO.GTX-000

BORING NO. B-1	SAMPLE NO.	S1	S1	S1	
TECH. rh	DEPTH/ELEV	38-40 feet	38-40 feet	38-40 feet	
LABORATORY	DATE	00/00/97	00/00/97	00/00/97	

TRIAXIAL COMPRESSION TEST REPORT

Figure 4: Typical Result of Triaxial Test Series

Some geotechnical laboratories had added specialized equipment to measure the mechanical properties of geosynthetic materials and their interaction with each other and with soils. Figure 6 shows a large shear box that can test a specimen size up to 12 by 12 inches (300 x 300 mm). This device is used to measure the interface strength between geotextiles and geomembranes, geomembranes and geosynthetic clay liners, and geosynthetics and soils. It is also used to measure the internal strength of geosynthetic clay liners, geocomposites and soils. By using inserts, we can also measure the shear strength of rock cores. Figure 7 illustrates the wide variation in strength behavior of these materials. Many exhibit a curved strength envelope, a loss of strength after reaching a peak, and internal failure at high normal loads. Their properties also change with small changes in the manufacturing processes and with different hydration conditions. Generally, project specific tests should be run using the actual materials for the site and test conditions that represent conditions at the site.

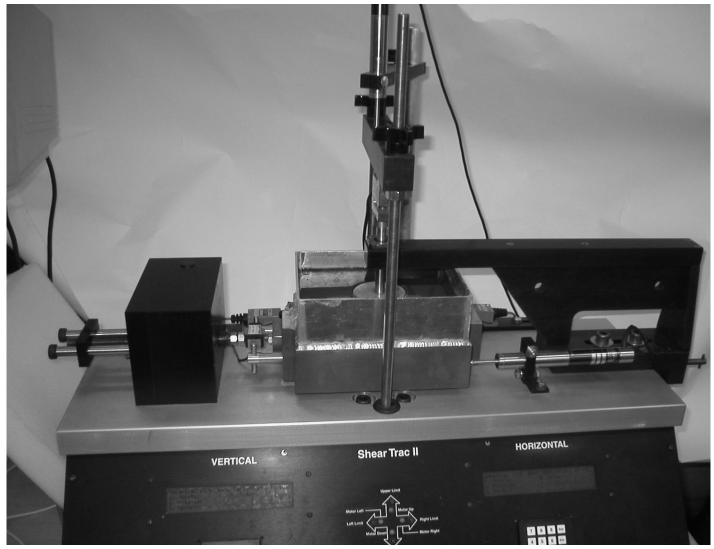


Figure 5: Universal Shear System

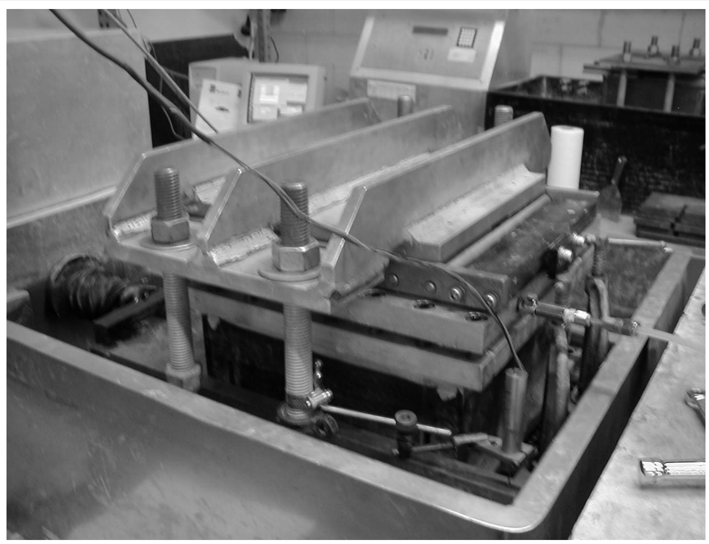


Figure 6: Large Shear Box

The preceding discussion focused on automated equipment. More powerful electronics at lower costs and reliable sensors with higher sensitivity and stability have made this automation possible. Simultaneous developments in mechanical materials and components have made laboratory equipment more durable and reliable. New valve designs are amazingly reliable and less expensive. Our lab has valves that have sustained 10 years of heavy use without leaking. Reliable quick-connect connectors, stainless steel components, low friction bearings, and stiff plastic tubing are a few examples of new materials that simplify and improve lab equipment. Today's triaxial cells are comparatively simple and reliable compared to designs of 20-30 years ago.

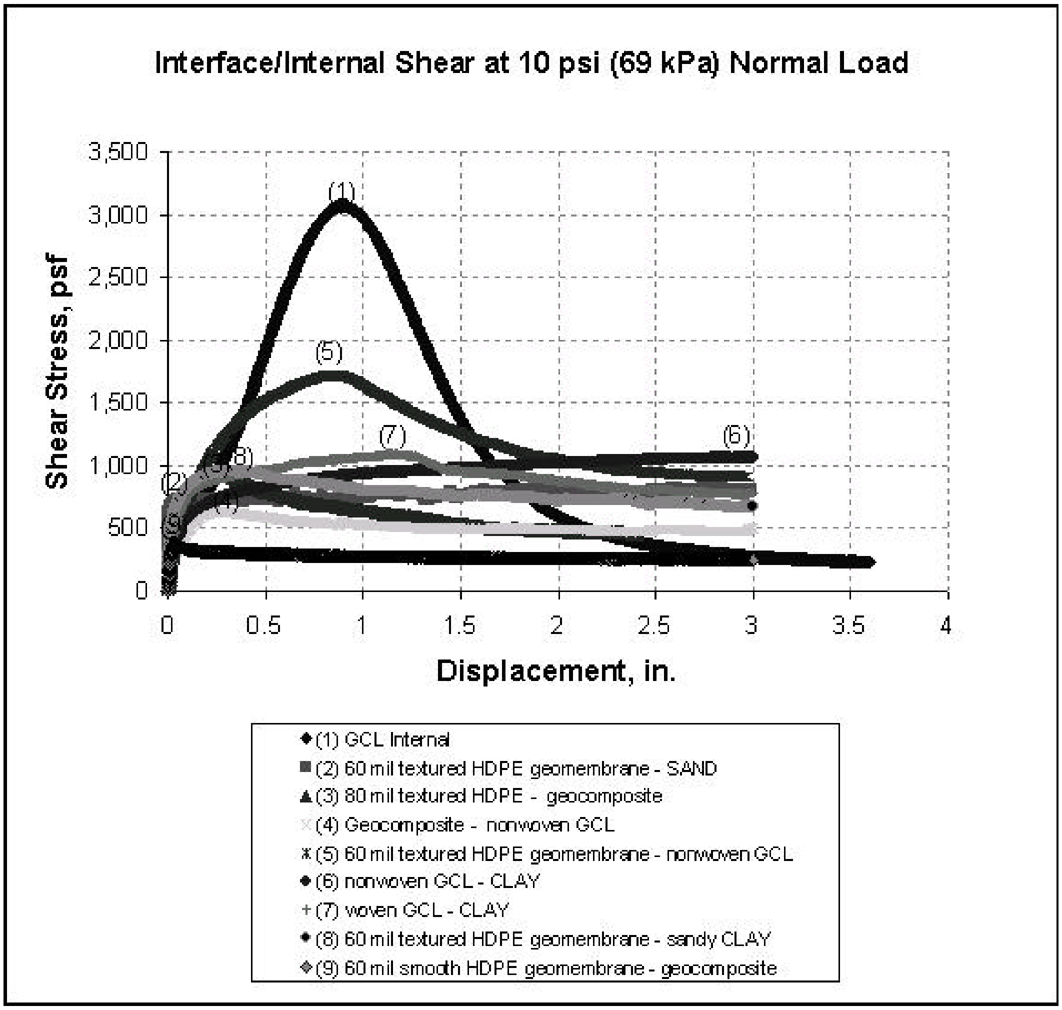


Figure 7: Interface and Internal Shear Strength of Various Geo-Materials

A modern, well-equipped geotechnical laboratory is an impressive display of computers, electronic gadgets and test chambers. With a trained staff, it can produce remarkable data on the physical properties of subsurface materials, quickly and at a reasonable cost. Table 6 summarizes some of the benefits we have enjoyed from automating our laboratory. Automation provides many more benefits than the obvious one of saving man time and reducing costs.

Automated equipment has also improved the sensitivity with which we can obtain measurements. Typical equipment can now measure pressure to 0.005 psi (0.1 inch of water, or 0.3 kPa). Force can be measured to 0.05 lb (0.22 N) and displacement to 0.00005 in ($2*10^{-6}$ mm). Volume change can be measured to 0.001 cc. For special applications, these resolutions can be divided by 10, provided temperature is precisely

Table 6: Benefits of Laboratory Automation (adapted from Marr, et al, 1998)

- 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 and Prospective Employees

controlled. These resolutions greatly improve our ability to look at parametric variations and perform specialized tests.

We have experienced some drawbacks associated with using automated test equipment in the laboratory. Automated equipment tends to have higher up-front cost for the equipment. Startup costs may be higher due to the longer time to shake down the equipment and train new users. Automation generally requires a higher knowledge level of the technician. This can produce efficiency problems if staff turnover is high. Repairs can be time consuming. Calibrations should be performed more frequently. Power brownouts or blackouts have destroyed complete tests, but we have overcome this problem by placing every system on an uninterruptible power supply. We also find that our technicians begin to rely too much on the computer to run the test and produce the test report. It's difficult to get them to observe key parts of the test and examine the test results carefully.

There are several external factors which I believe reflect a retreat by our profession from quality laboratory work. We see a shortage of people with interest in lab work and with hands-on knowledge of soil behavior. I also perceive a decreased appreciation by practitioners of the importance of soil behavior to good design. As some degree of proof of this point, I offer our own experience. Aside from tests done for our own projects and work for Prof. T. W. Lambe, over the past five years we have had very few requests to perform CK_0U triaxial tests, constant rate of consolidation tests, and no requests for stress path tests. There appears to be a gross imbalance between what we teach in universities and write papers about and what is actually done in practice. This imbalance is made even worst by the recent trend to treat geotechnical testing as a commodity service, i.e., a situation where all labs are considered qualified to do the work so use the one offering the best price.

INFORMATION MANAGEMENT

A major task for any laboratory is to keep track of all activities within the lab. Knowing what samples are in the lab, the status of a particular test, which technician is to do what, and what the resource utilization is are all constant questions with constantly changing answers in any busy laboratory. We developed a computer based information management system to track this information. From the time a quotation is prepared until the report is released to the client, we use one system to track the progress of work.

In developing this system, we divided the laboratory operations into discrete steps: making quotes, tracking projects, logging samples, defining tests, reducing data, preparing reports, and producing an invoice for the services. Figure 8 shows a sample screen for entering information about a project. It includes information that is specific to the project. Because we handle contaminated samples and foreign soils, we also use this screen to log and track how samples from the project are to be disposed of.

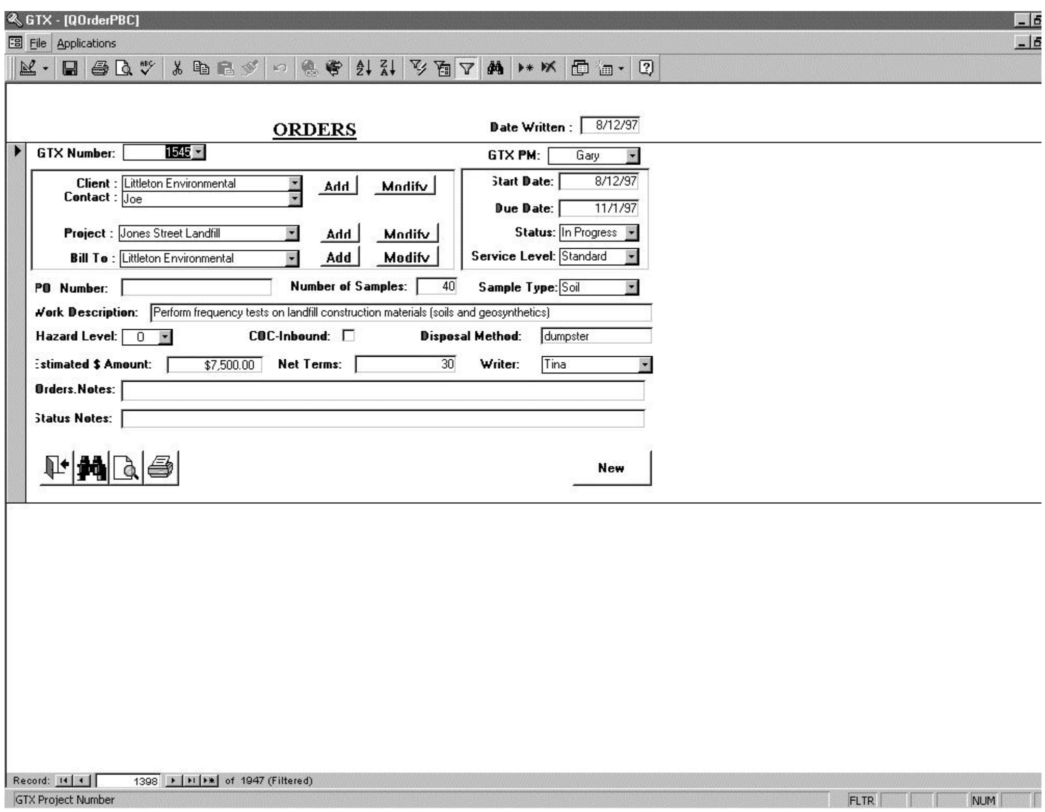


Figure 8: Order Entry Screen

We used Microsoft Access™ to develop this system. It permits one to lay out input screens and produce reports without having to do low level programming. Data in the Access database can be accessed by different users for whatever specific purpose they require. Access also runs in a networked environment so several users can be working with the system at the same time. This capability is especially important in a busy laboratory.

Figure 9 illustrates the screen for logging in samples. Every sample coming into the lab is assigned a unique sample number in the database. As soon as the sample is logged into the database, a unique label is printed and placed on the sample container. This operation is essential to minimizing the chance of mixing up samples within the laboratory.

Different tests or multiple tests may be performed on the same sample. Therefore, a separate screen is used to specify the tests to be run on each sample. Figure 10 illustrates the screen used to enter specific tests. Test type to be performed is selected from a programmed list of tests that the laboratory is qualified to run. A technician is assigned to perform the test from a list of technicians qualified to run that test. Any special instructions for the test are also entered. This approach centralizes all information about the client’s specifications for the test. It gets the test requirements off scraps of paper and out of people’s minds into a central place.

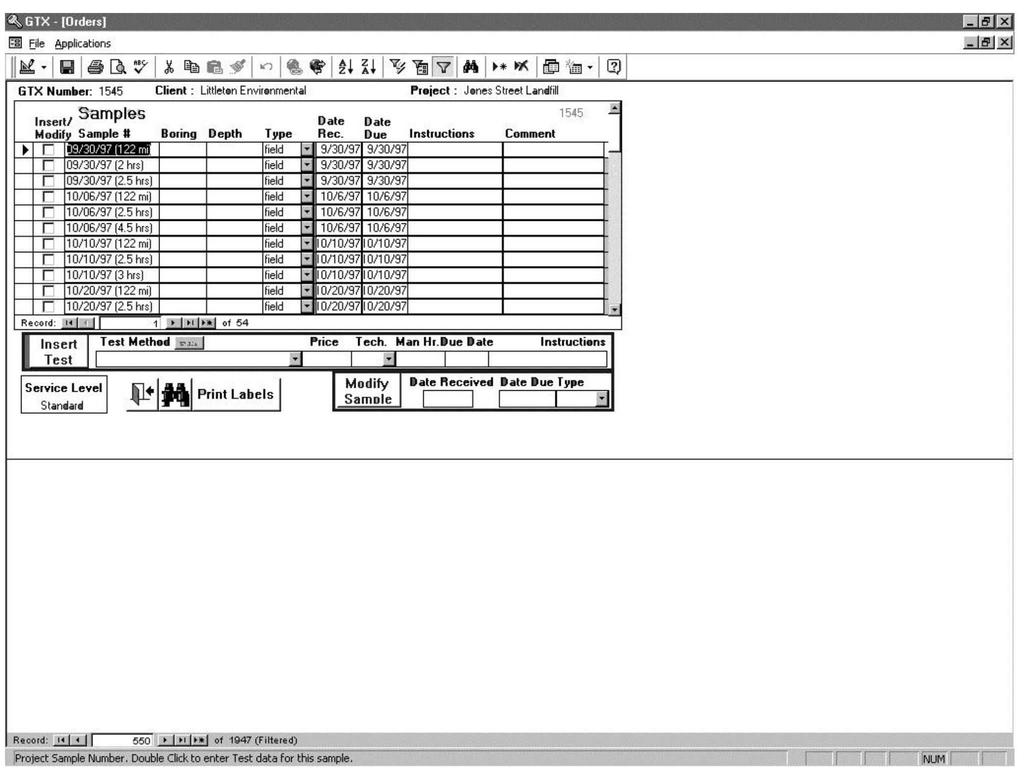


Figure 9: Sample Entry Screen

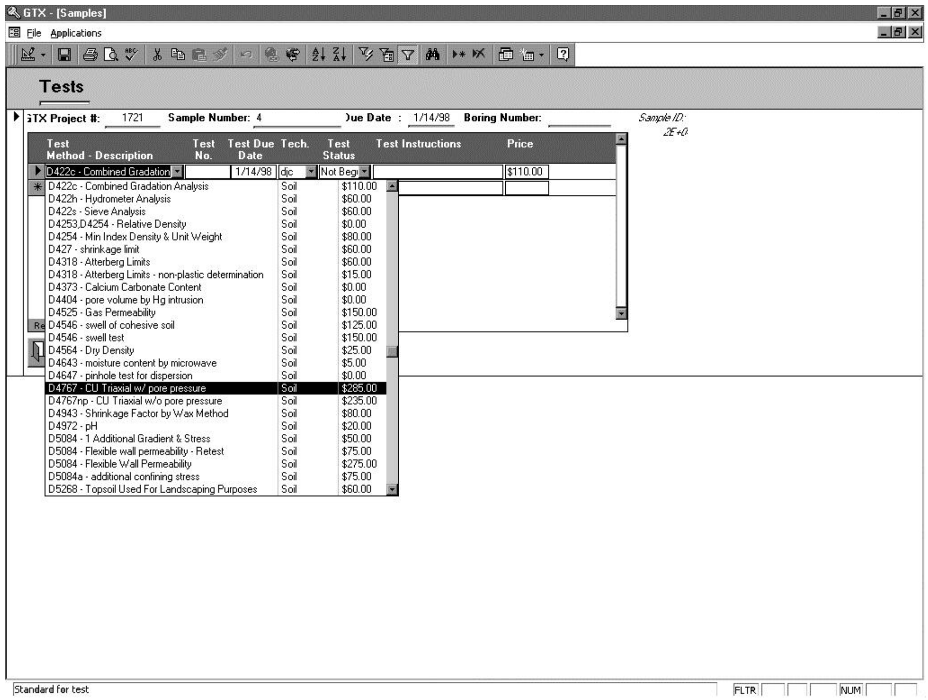


Figure 10: Test Setup Screen

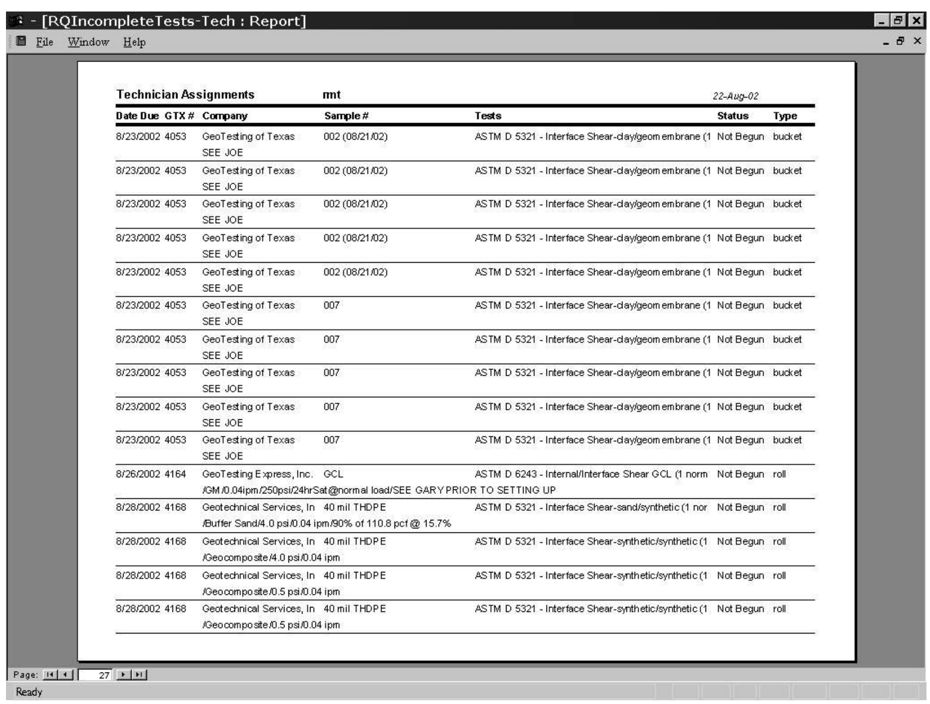


Figure 11: Technician Work Sheet

Once information on projects, samples and tests has been entered into the system, it is used to produce daily work sheets for individual technicians. Figure 11 shows a typical worksheet. Each technician receives a sheet at the beginning of the day. During the day, the technician marks off completed work and adds remarks to the sheet. This information is then entered into the system at the end of the day. We originally thought that each technician would make entries into the system. However, the nature of their work does not make it convenient for them to do so, i.e., gloves and dirty hands make it impractical to enter data into a computer. Entry of test data into this system remains a challenge. We continue to collect some data by manually writing it on paper and later entering it into the database system. Manual readings introduce to much opportunity for error. The technician writes the data incorrectly, or it isn't legible, or it is keyed into the database incorrectly. We are now experimenting with hand held computers such as the one shown in Figure 12 to reduce these errors and reduce the use of paper. This unit can accept data from the keyboard, from an infrared scan and from a serial connection to another device. It can wirelessly transmit the data immediately into our database. In the near future, we expect each of our lab technicians to have one of these devices to track their work and report test data.

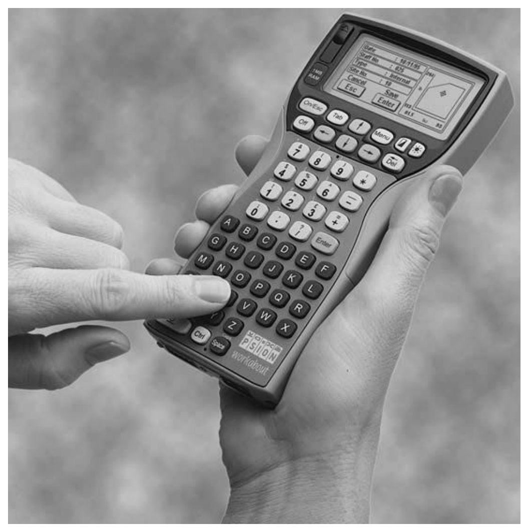


Figure 12: Handheld data input device.

Separate software modules are used to reduce and prepare test reports. These modules convert the raw data into final test quantities using ASTM procedures. They provide tabulated test results and, where appropriate, graphs. Using software for this step has several advantages. It greatly improves quality control. The calculations are done by software that only has to be verified once instead of verifying each hand calculation. Thereafter, it is only a matter of checking that the input data are accurate. Our software also permits us to plot the results of several tests together. Best-fit curved lines can be used to interpolate between data points. (However, computer generated curved lines can sometimes give unreasonable relationships, such as a portion of a gradation curve with a reverse slope. The final plots must be reviewed carefully for reasonableness.) The capability to plot several tests together gives considerable added value to clients.

Table 7: Status Indicators for Lab Tests

On Hold	Insufficient information available to start work
Not Begun	Test conditions are known but work hasn’t started
In Progress	Test is underway
Completed	Test work is complete but not reported
Reported	Test has been reported to client
Invoiced	Test has been invoiced to client
Paid	Client has paid for the work

One of the most valuable benefits of our information management system is its ability to help us track the progress of work within the laboratory. When designing the system, we looked at the different operations within a laboratory that create bottlenecks. We then designed the system to track work passing through these bottlenecks. We use the descriptions given in Table 7 to define the status of each test in the database. Once a test has been requested and the test conditions defined by a client, it is assigned a status. The status of every test is updated daily.
With this information, two important reports are produced daily. One is a listing of all tests in the “Not Begun” and “In Progress” categories with the listing ordered by due date. This listing immediately tells lab management how much backlog is in the laboratory and what work is behind schedule. It is used to reassign test schedules and estimate upcoming labor needs.

The second report is a graph showing the dollar amount of work in each category for a specific time. The report is typically run for the current month to identify where problems and bottlenecks exist. For example, if the graph shows an abnormal dollar volume in the “Completed” category but little in the “Reported” category, management knows that work is falling behind in getting reports processed. From our past experience, we know that many labs have the tendency to let samples lie around for days before starting work, to complete the test work but not the report, and to complete the work but not prepare an invoice. This single graph helps us identify these problems so they may be corrected quickly.

After eight years of experience using this information management system, we have come to the opinion that it is essential to the successful operation of our facility. Without it, we would have to increase our manpower by 10-20% to manually deal with the information. We would also suffer delays and errors in completing our work. There are commercial software packages available that do some of the information management work described above, but none to my knowledge fully integrate the equipment in a geotechnical laboratory with a complete database and reporting system. Most laboratories have, or can obtain, sufficient hardware to provide this integration, but the software remains disjointed pieces. Many labs resort to manual readings or simple data acquisition systems and use spreadsheets to perform the calculations and produce test reports.

Testing of soils to determine gradation, classification, index properties and compaction hasn’t changed much in the past 30 years. Data reduction and reporting for these tests are now done by computer but most of the work remains labor intensive. Most smaller labs limit their services to these tests and do not have the automated equipment described above.

FUTURE DIRECTIONS

There is one basic tenet of soil mechanics - that stress-strain behavior and flow characteristics of soil are dependent on the past, present and future effective stresses. Determining behavior for past, present and future effective stresses cannot be done without testing the specific soils. Ideally, tests to measure stress-strain, strength and flow properties of geo-materials should be made with the same stress path that the soil has and will experience in the field. Automated equipment permits us to do this today with a high degree of capability and at relatively low cost. We can run a stress path test for about the same cost as a high quality triaxial test was run 20 years ago.

Automated testing gives us much more capability for production work than we ever had in the past. We can do a better job, faster and more economically than we ever could. To make automation pay, however, requires a first class facility with a highly trained staff. The lab needs to receive enough work to keep it gainfully employed.

What do we do with all of this capability? Without a demand for these services, this capability will go unused. I am amazed to see how many projects are designed and built with little to no testing of the geo-materials. Talking with engineers, I get some idea of why this happens. In their experience, test results were slow to come, results were many times confusing and contradictory to their experience, and testing was expensive. I think many engineers altered their practices to avoid testing. They convinced themselves that they could estimate material properties or make “conservative” assumptions in their design, thereby avoiding testing and the associated problems. I believe this is a false premise. Many of the problems and failures in construction can be linked to problems in understanding and characterizing the materials involved. Many of these problems and failures could have been recognized and perhaps avoided had more attention been given to determining the appropriate material properties.

External factors that may affect the future demand for lab testing are briefly considered next.

Client demands for rapid results to meet project schedules – The push to fast-track design and construction places big pressures on laboratories to complete work as quickly as possible. Automation helps meets this demand by working day and night, seven days a week and transmitting results to the client within minutes of completing a crucial test.

Clients' demands for higher performance at lower cost – Clients in today's competitive environment constantly demand more – more innovation, more service, more of everything. Companies who cannot keep up with these escalating demands will be abandoned. This pressure will force many laboratories to modernize or close.

Parameter input for more detailed models – Numerical models, such as PLAXIS, are becoming easier to use and more directly applicable to design. These models allow increasing sophistication in the characterization of soil. Laboratory testing should experience more demand for high end testing as these models become a part of routine practice.

Answering public's demand for minimal negative impact from construction – Increasingly, the public demands little to no adverse impact from earthwork construction. This requires use to do a much better job of predicting how our designs will perform. That will require more and better information on subsurface parameters from laboratory testing.

Protecting against claims and legal action – Claims management is becoming a significant part of any major earthwork project. Good, reliable data on subsurface conditions provides a very cost effective way to reduce and manage claims for changed site conditions. When dealing with claims, I often think of US Navy Admiral Grace Hooper's remark about the value of data, "One accurate measurement is worth a thousand opinions."

De-emphasis of lab experience and lab research in the universities – Too many educators see the civil engineering laboratory as an outdated, expensive tool that can be replaced with virtual reality simulator. In my opinion, there is no substitute for hands on work with soils and the insight into fundamental soil behavior that comes from figuring out whether a particular test result is meaningful or not. Rather that replace our laboratories with computers that simulate a lab experience, I think we should be equipping our labs with automated devices that take the tedium out of testing and let the students concentrate on the geotechnical issues involved with the test.

Pricing and competition in testing business – Like most businesses today, laboratories face constant pressure to keep prices low. This is a difficult task to do and maintain a high level of quality and service at the same time. Unfortunately, many labs sacrifice quality and service to offer a lower price. I urge engineers to use the same quality based procurement practices to procure laboratory services that they ask their clients to use in obtaining engineering services.

Certification – Laboratory certification is one effective way to establish a threshold of quality that labs must strive to exceed. Certification provides one yardstick of quality work. Certification raises the barriers to entry for marginal operations that do poor quality work. Unfortunately, certification is not widely required today and there are too many certifying organizations with different requirements. We need to move towards national and international certification and we need more engineers to require testing be done by certified laboratories.

Improved quality – There is a widespread move internationally to improve quality of all work. ISO standards established for manufacturing operations are being extended to engineering design. It seems only a matter of time before geotechnical laboratories will have to adhere to ISO standards. This will be an expensive step for many laboratories and an impossible one for others.

Regulations – The demand for lab testing can be greatly affected by new regulations. Many geotechnical laboratories in the US obtain a lot of their current work from landfill closures and expansions because regulations require measurement of the permeability of the materials. It is difficult to predict the future impact of regulations, except to extend a guess that they will become more pervasive and perhaps increase demand for laboratory services.

Crises and disasters – Crises and disasters, both natural and manmade, can exert a big influence on the demand for testing services. They usually lead governments to allocate money in new and generous ways that can place large demands on the existing service base. These events are difficult to predict but their impact can be enormous. The development of the Interstate Highway System in the United States had a huge impact on materials testing laboratories. The decision to abandon further development of nuclear power had a huge negative impact on geotechnical labs.

New materials and processes – New materials and processes can open entire new lines of testing for laboratories and replace existing work. Testing of geosynthetics has become a new business line for many geotechnical laboratories. Likewise, quality control testing for soil improvement projects, such as soil mixing, brings new business. I look for more of this specialized work to occur in the coming years as engineers produce designs that are more daring and depend greatly on the strength and stiffness of the new materials used by those designs.

Engineers' attitudes towards testing – Will we see a continued trend towards using "conservative estimates" for design parameters in place of specific values from testing? Will we see engineers ordering up multiple tests to protect themselves against litigation much as medical doctors do for protection against malpractice suits? How will recent engineering graduates with little to no lab experience conduct their practice? The answers to these questions will have a major impact on the future of geotechnical testing.

Reputation of laboratories – Laboratories need to improve their image. Too much poor work has been produced in the past thirty years. Many designers distrust test results and seek to avoid laboratory testing. The testing industry needs to promote ways to improve overall quality and performance of its members.

Technology – The rapid pace of innovation in all areas is bound to produce new materials to test, new equipment to perform tests, and new ways to work with customers.

Changes in the design-construction industry - It is not clear how the trend to design-build will affect the demand for testing services. One could argue that more testing should be done to improve the quality of designs and save construction costs; however, I fear that that opposite may happen as management presses for reduced design time.

Effect of consolidation of engineering firms – Parts of the world are experiencing substantial consolidation of geotechnical engineering services into big, global engineering service firms. It is not clear how these firms will look at lab testing. Will they outsource testing services to save money or will they expand their in–house services? Will they become more general service firms and downplay geotechnical work or will they do more work internally to minimize their risk exposure? I don't know the answer to these questions.

Globalization – The Internet provides the possibility to exchange information anywhere in the world. Software standards permit people to share and exchange work. Some design firms routinely have portions of designs done in developing nations at reduced costs. Are we likely to see soil samples shipped around the world to the lowest cost provider with results returned electronically? Today's courier services provide 2-3 day delivery services to almost anywhere at affordable costs. It's possible to ship samples from anywhere in the world to our lab, we complete the testing and provide the final report electronically in less time than typical practice. However, I doubt that this will happen to any significant degree. Many people still prefer to have their testing work done locally. We have difficulty getting people to ship samples across the US, much less around the world.

These external factors make the future of geotechnical laboratory testing uncertain. I think laboratories will have to automate to provide high quality results quickly to remain competitive. Engineers will be expected to design more complex things, to reduce the cost of underground work, and to reduce the negative impact from underground work. I hope that engineers will recognize that high quality lab work can help them address these challenges and provide their clients with more value.

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