Application of Automated Laboratory Tests to Minnesota D.O.T. Highway Project Site Characterization

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Abstract

In 1997 the Minnesota Department of Transportation (Mn/DOT) began operating fully automated computer controlled geotechnical testing equipment, replacing many existing systems. Existing systems required active technician oversight particularly for consolidation and triaxial testing. An increase in the number of projects requiring testing, shorter project time-lines, rapid advances in computer technologies, a decrease in the number of skilled technicians, and a desire to reduce project costs, made automated systems especially attractive. As a result of the effectiveness of the automated systems, today, the geotechnical section routinely conducts specialized tests previously available only to academic institutions and research labs. Automated laboratory testing combined with automated in-situ cone penetration testing (CPT) has dramatically improved overall site characterization quality while reducing both cost and time associated with geotechnical investigation. Test reliability, repeatability, accuracy, and confidence in the test results has improved, while decreasing subjectivity and operator error. Measurable cost savings, both in field costs and lab costs, and increases in efficiency have been realized, even after the relatively large investment cost of the new equipment.

A comprehensive suite of lab and in-situ CPT tests were performed on clay soils at a bridge site in northern Minnesota; results of this study are presented to illustrate the uses and benefits of automated systems. Lab tests included 1-D consolidation, triaxial stress path, flexible wall constant gradient permeameter tests, direct shear, and direct simple shear tests. Shear strength (s_u) and modulus values (M, G, E) were compared with in-situ CPT tests conducted at the site.

Introduction

The Minnesota DOT (Mn/DOT) Foundations Unit is responsible for the geotechnical site investigation, analysis, and forensic investigations of soil failures. Although geophysical methods, and other in-situ instrumentation may be employed, the most common methods of investigation for site characterization and design are foundation borings and CPT soundings. Typically, foundation borings involve drilling into the site soils, performing in-situ SPT testing, and recovering 'undisturbed' soil samples for laboratory analysis. Borings typically range in depth from 9 m (30 ft.) to 52 m (170 ft.), depending on the site. CPT soundings are performed where soil conditions allow and typically extend over the same depths as SPT boreholes.

In the past four years all of the geotechnical laboratory equipment has been upgraded. At the time of the proposed upgrades, new fully automated equipment was becoming available that could provide advanced fully automated test control. This equipment represented a substantial investment; however, considering the age of the existing equipment and the effort that would be needed to retrofit it, the investment was deemed necessary. A cost-benefit analysis, based on projected use, indicated the equipment would pay for itself over a relatively short investment period. Projected benefits included simplified operation, improved accuracy, expanded testing options, and reduced time and cost associated with active operator oversight. Investing in the new equipment would also provide a benefit in the event that advanced tests were required critical projects where an 'in-house' capability was necessary.

The Impact of Automation

Lab Automation. Today, Mn/DOT testing systems that perform a wide variety of traditional and advanced geotechnical tests including unconfined compression, one-dimensional consolidation, direct and residual shear, direct simple shear (DSS), Consolidated-undrained (CU) triaxial stress path (compression and extension), and flexible wall constant gradient (FWCG) permeability.

Unconfined compression testing is conducted at an improved pace with a better user interface. Consolidation and direct shear testing have both increased dramatically with the deployment of the new systems. CU triaxial stress path tests, seldom conducted due to their complexity, and overall technician time commitment, have become routine. In addition, tests that were once considered impractical due to their complexity, including the DSS and the CU triaxial stress path test are now commonly used to aide in material characterization.

Automation has significantly reduced the amount of time that technicians need to devote to test monitoring (Marr, 1998). Although there is still a need for careful and representative field sampling and lab specimen preparation, the general test function is conducted and recorded automatically, allowing the technician to use his time more effectively in the preparation of additional samples or in the analysis and reporting of the final test data to the project engineers. Despite a reduction in lab staff, there has been a significant increase in lab testing in the past five years.

Field Automation. Through the use of more thoughtful testing programs and comparison testing with CPT data for field investigations, the overall number of borings has been reduced on many projects, saving considerable time and expense outside the lab. Fully automated laboratory testing combined with automated in-situ cone penetration testing (CPT) has significantly improved the quality of site characterization while reducing both cost and investigation time. Changes in soil strata can be resolved with the CPT; samples from companion borings are then tested and the results are applied as appropriate. Lab and field cost savings, and increases in program delivery efficiency have been realized, even after the relatively large investment cost of the new equipment has been considered.

Beginning the Automation Process

Historic "Standard" Lab Tests. Standard penetration test "split-barrel" (SPT) samples and "thin walled tube" (TW) samples are routinely obtained as standard practice. In the late 1990's, specialty testing was conducted infrequently because the tests took comparatively greater effort and involvement on the part of both the engineer and the technician. Although in practice, they are also more expensive, this was not a limiting factor in this situation, more so other factors, including:

1) Effort to regain familiarity with advanced tests, as they were conducted relatively infrequently (including how to prepare samples, calibrate equipment, prepare test equipment, run the test, recover data, post-process and present the data).
2) Time required to monitor and execute the tests (particularly the consolidation and CU triaxial tests). Time required to collect the data, enter it into spreadsheets, and calculate relevant values for analysis and reporting.
3) General test operating complexity (i.e. back-pressure saturation, CU triaxial test)

Motivation for Change. The upgrade to the lab equipment was in the early 1980's when data acquisition systems were incorporated with the existing load frames. Linear variable displacement transducers (lvdts) were mounted with existing dial gages to provide electronic sensor output for data collection systems which were also acquired and installed at this time. The data acquisition systems consisted of HP™ computers, data collection and acquisition units, power supplies, and printers.

This equipment had performed well for over 20 years, without any significant problems. A growing concern was that the equipment was becoming increasingly dated, documentation was poor, and no one had a working knowledge of the systems. Care had to be taken during the 'Y2K scare' that the computer equipment in the lab was *not* replaced, as no one could determine if any of the existing equipment would be compatible with newer computers or peripheral devices. There were several additional reasons to upgrade the equipment: the existing software had outdated cumbersome interfaces, test data was not stored, and the consolidation and shear programs required that the user plot the data in a spreadsheet after collecting the series of required data points.

A number of external factors were also changing, influencing the decision to upgrade the lab equipment. The aging transportation infrastructure was receiving increased attention and the amount of lab testing was expected to increase significantly. These projects were also expected to have shorter project time-lines. Mn/DOT culture was also changing, resulting in employees changing jobs more frequently than in the past and an overall decrease in the number of skilled technicians. Finally, there was a renewed desire to reduce project costs and reduce the number of government employees. Table 1 lists the major factors in deciding to upgrade the equipment.

Table 1. Automated Lab Equipment Considerations

Reasons to Upgrade Systems	**Reasons Not to Upgrade Systems**
Aging computer software systems (Y2K)	Investment expense
Aging computer hardware/systems	Unfamiliarity with new equipment
Electronic data storage	Simplicity of Mechanical Systems
Reduced labor/monitoring	Low maintenance/repair costs
Improved user interface	Few tests currently conducted
Ability to adjust tests (change software)	Existing equipment still functional
Improved calculations/output presentation	Time to create bid specifications
Reduced data loss and operator error	
Unfamiliarity with existing software	
High cost of subcontracting tests	
Reduced overall test duration	
Projected increase in testing	
Staffing levels expected to decrease	

Based on these considerations, Mn/DOT embarked on a systematic plan to replace and automate the geotechnical lab equipment as time and available money permitted.

Equipment Upgrade Process

Automating the 1-D Consolidation Test (ASTM D 2435, Method-B). The one-dimensional consolidation test was selected to be the first test upgraded in 1998. This test was determined to have the greatest benefit based on the amount of time technicians and engineers spent performing the test, the number of tests conducted, and the importance of obtaining quality data. The CD triaxial test was seldom conducted, and existing direct shear and unconfined compression systems were still functional.

It had been clear for a time that consolidation tests consumed a good deal of the lab technicians' time and that the data acquisition system was somewhat cantankerous. The printed output was of poor quality by current standards. A new system with computer control to automatically apply and remove load increments based on a user defined time duration and the end of primary consolidation, with improved graphing and reporting functions for the determination of the degree and time rate of settlement, was highly desirable.

Shortly after the new equipment was put into service the benefits were clearly evident. The data was significantly better in terms of the number of points collected, the data presentation, automated calculations, and electronic recording of the information. Tests were now considerably easier to conduct, and there was no longer reason not to run them for fear of occupying too much of the technicians' time and attention. Now, for the first time, long-term tests to explore primary consolidation behavior on low permeability fat clays and secondary compression behavior in organic soils and peat materials were conducted.

Automating Additional Lab Tests. As the lab engineer and technicians became more familiar with the new systems there was increased interest in continuing the automation process and replacing the other test equipment with computer-controlled systems. After developing a new series of specifications, new equipment was ordered to automate the unconfined compression test and the direct and residual shear test. The lab engineer was involved heavily in the development of the equipment specifications. Table 2 shows a list of the test systems that have been automated, as well as the primary reasons for automating the tests. Consistency in the computer control systems, operator familiarity with test interfaces, and the preference for using the new systems became additional factors for continuing and expanding the automation process, in addition to the other benefits. Eventually, each of the existing systems was replaced with automated systems. One triaxial system was slowly expanded to include four complete systems, two of which are outfitted with the required components to run permeability tests. Table 2 shows the tests Mn/DOT has migrated to fully automated computer controlled systems.

Table 2. Tests, ASTM Designations and Primary Upgrade Reasons

Geotechnical Test	ASTM	Mn/DOT Upgrade Reasons
Unconfined Compression	D 2166	Y, R
1D Consolidation	D 3080	Y, S, U, E, R, I
Direct Shear	D2345 D4186	Y, U, R, I
Direct Simple Shear	D 6528	N, S, U, E, R
Triaxial Compression	D 4767	N, S, U, E, R
Constant Gradient Permeability (Flexible Wall Permeameter)	D 5084	N, U, R, I
Stress/Strain Properties of Rock	D 3148	I, U, R
Cone Penetration Testing (CPT)	D 5778	N, S, U, E, R, I

N = New; this test was not previously performed (generally due to complexity)
Y = Y2K computer software issues
S = Speed; overall test rate; computer controlled systems can increase test speed
U = Ease of Use; reduced operator time and monitoring
E = Error reduction (reduced data loss or improperly performed test)
R = Recording and archiving test data files electronically
I = Improved data collection; increased precision and accuracy

Benefits of Automated Lab Testing

The implementation of computer-controlled automated lab testing has been highly successful. The equipment has allowed consistent productivity, quality, and timely reporting of important geotechnical parameters.

Y2K Compliance. Although this issue was never perceived as a serious concern for our equipment, the ‘Y2K’ issue called attention to the aging hardware and software applications important to the daily operations of the lab. There were methods of performing the tests in the event the current data acquisition systems failed. The computer equipment, though functional, was fast becoming antiquated in the era of significant rapid advances in computing power. The desire to upgrade systems for Y2K provided an excellent opportunity to begin the changeover from computer data acquisition to computer test control and data reduction.

New Tests. Automated equipment that provided pre-programmed computer test set-up and real-time control, based on sensor feedback allowed more complicated tests to be conducted with similar ease to more common tests.

Previously, technicians would need to be available to make constant adjustments during testing to ensure that loads, pressures, deflections, and other conditions were properly maintained or adjusted for the proper functioning of the test. Great care was needed to ensure that each step was conducted with attention to the proper sequence, and tolerances. This required a significant investment of time on the part of a skilled technician to achieve good results. Automation provided an excellent method to reduce the amount of skilled technical labor; test software monitors test conditions and takes appropriate action to properly adjust the test parameters according to pre-programmed instructions. Complicated tests could now be conducted with constant attention, to a high degree of precision, thanks to closed-loop control and feedback from electronic sensors. Previously the purview of academic institutions and research facilities, direct simple shear (DSS) testing, CU triaxial stress path tests, and FWCG permeability testing are now available to a far broader group of engineering professionals. Engineers were previously forced to use approximations and relationships based on inexpensive engineering tests to estimate lab values leading to very conservative designs in most situations. Quality lab values are now cost effective, reproducible, and available to all geotechnical professionals.

Test Rate. Many of the tests can be expedited, without loss of completeness or integrity of the overall test, by the closed-loop control described above. As an example, a consolidation step may be automatically determined by the control software to be complete when no additional deflection is observed for a period of time. When the program detects this, it may advance the test to the next step. Similarly, the control software may be set to automatically go to the next step or phase of a test based on any user prescribed criterion such as a minimum or maximum test parameter value. Testing may also be accelerated by automatically proceeding to the next phase of a test after a preceding phase has been completed, regardless of what time of day, or night, this may be. During a test operated by a technician, the next phase would generally begin when the technician next checked the machine and saw that a given phase was complete. Automated testing makes far better use of evening, weekend, and holiday hours than conventional testing.

Ease of Use. The new computer controlled tests are generally simpler to run than traditional tests. The computer interface allows the technician or engineer to input the parameters at the start of the test and check for errors. In addition, template files can be created to easily repeat tests with given loading sequences. There is a minimum of manual intervention and adjustment during the test sequence, such as: valve opening, weight stacking, screw twisting, knob turning, manometer reading, and dial gage observation. With computer control, many of the most complicated lab tests have been reduced to fairly simple operations where most time is spent preparing and installing the specimen in the test frame. It is important to emphasize, however, that a skilled operator is still essential to know when something is not operating correctly or when bad data is being collected. The labor has been reduced, but not the level of operator knowledge.

Reduction in Operator Error and Bad Test Data. Automation has greatly reduced operator error. Initial files can be loaded at the beginning of the test and error checks may be performed prior to running the test. The control software also establishes the correct procedures and sequences for the ASTM tests, minimizing errors of oversight and omission. Errors caused by transposing numbers, recording data inaccurately, skipped readings, and other ‘human factor’ errors have been removed from standard test operation. As in the previous topic, it is still important to emphasize that you can still get inappropriate data if you do not perform tests properly, which can be easier to do with automated systems. The test schemes are very easy to change; inadvertent errors can easily ruin a sample or invalidate a test.

Recording and Archiving Test Files. Modern computer test control now works within the standard Microsoft Windows™ operating environment making data exchange, organization, storage, and archiving both easy and inexpensive. Files can be moved across networks, printed on remote computers and sent via the Internet across the globe. Complete test records can be recalled in seconds and reprinted as needed. In addition, the data can be exported for use in spreadsheets or for direct input into lab data management systems.

Improved Data Collection, Increased Precision, Accuracy, and Repeatability. The number of data points collected has increased greatly with the introduction of the automated equipment. The curves for all the tests are smoother and more meaningful analysis may be conducted with the improved data sets.

Though not a direct result of computer control, a benefit of automated systems is that their components afford a high degree of precision and accuracy. Computer control requires sensitive instruments to detect small variance in the observed test parameters. The use of high-resolution 22 bit A-D conversion and quality sensors, which have become more sensitive and more robust over time, has resulted in improved data quality and allowed greater confidence in reported results. The use of electronic instrumentation has decreased operator subjectivity. Tests are conducted more consistently and operator time has been minimized. Results are generally more repeatable on similar soil samples. There is increased confidence in the data and a reduced need to test several samples to prove that data is reproducible.

Test Productivity and Volume

Although there are many engineering benefits that come with automation, as described above, generally the major reason cited for considering automation is either political or fiscal in nature. Automated systems can help maintain or increase productivity with the same or reduced labor-hours. Alternately, automation can increase productivity of a given amount of labor-hours. Technicians are free to run more tests or do other tasks while automated equipment is running. Additionally, the likelihood of errors is somewhat reduced, increasing overall operator efficiency.

This increased efficiency can be applied in different ways. More tests may be conducted on a given project, better defining the character of the site, or more projects can be accomplished in the same period of time without a decrease in the level of engineering care. Our office has realized a combination of the two benefits. Some sites are more rigorously sampled and investigated to prepare more detailed engineering designs with a high degree of confidence; other projects have benefited from performing routine testing in a shorter period of time, improving our report delivery time. With the advent of fully automated lab testing, our number of tests performed increased significantly. Engineers began using actual test data, rather than estimates of parameters from charts, tables, references, and rules of thumb.

Table 3. Geotechnical Lab Test Count by Test Type and Year

	1999	**2000**	**2001**	**2002**	**2003**	**2004***
Unconfined Compression	?	243	304	405	275	39
Consolidation	4	93	90	136	55	17
Direct Shear	0	3	19	166	154	50
Direct Simple Shear	n/a	n/a	n/a	2	33	33
(CU) Triaxial	0	4	11	144	19	4
Rock (σ/ε)	0	4	91	25	12	2
Permeability	n/a	4	5	14	12	1
CPT (in-situ)	n/a	n/a	189	803	1416	726

*Data for this year is partial; test count is as of 1 June 2004.

Application of Test Data

Mn/DOT Bridge Replacement: BR 35010. A bridge replacement at the Red River of the North near St. Vincent, MN and Pembina, ND became a case study site for lab and in-situ geotechnical testing. The soils in the area are clays and silty clays that are derived predominantly from the late glacial erosion and reworking of Cretaceous shales and dispersed as suspended sediment into Lake Agassiz (Schwert, 2003). Thick deposits of soft red river clay (SPT blow counts of 2~3) were found above over-consolidated clay glacial drift deposits. Site soils consisted of gray, slickensided, fat clays, with very high moisture contents typical of the Brenna/Argusville Formations of the Lake Agassiz sediments in the region. These soils are characterized by high plasticity; slope instability in the area is a common problem. Two soil borings and a series of adjacent CPT soundings were advanced.

In an effort to expedite the investigation, it was determined that a combination of CPT tests and lab tests could be used to characterize the site. As many as 15 borings would have been traditionally taken for the bridge replacement and associated spur dike construction, seven of which may have been 55 m (180 ft.) or more deep. Instead two soil borings, one shallow and one deep, were taken with an additional 20 CPT soundings. A series of comparison tests was conducted on samples from 12.2 m (40 ft.) and 15.2 m (50 ft.) depths, including 1-D consolidation, direct shear, DSS, CU triaxial compression, permeability, and CPT dissipation tests for purposes of assessing the relationships between lab and in-situ tests. These tests and the whole test program would not have been possible without automated equipment.

Unconfined Compression Testing. Cohesion values from unconfined compression testing ranged from around 33.5 kPa (700 psf) to 62.2 kPa (1,300 psf). These values were in consistent agreement with the estimated undrained shear strength parameter, s_u, from the CPT data that ranged from 38.3 m (800 psf) to 76.6 m (1,600 psf). The remaining tests will be described with respect to the data at the 15.2 m (50 ft.) test depth.

Direct Simple Shear and CU Triaxial Testing. Two DSS tests showed peak undrained shear strengths of 81.4 kPa (1,700 psf) and 83.8 kPa (1,750 psf) at the 15.2 m (50 ft.) depth. Two triaxial test series provided cohesion values of 23.9 kPa (500 psf) and 47.9 kPa (1,000 psf) respectively. The CPT interpreted value for s_u at the test depth was 49.8 kPa (1,040 psf). The small strain shear modulus, G, was obtained from the DSS test and used in computation of estimates of the horizontal drainage parameters from the CPT dissipation tests conducted at the site. The value of G, from 3 DSS tests was 2.2 MPa (46,000 psf). Through application of radial drainage equations and the CPT dissipation data the coefficient of horizontal consolidation, C_h, was estimated at 2.6×10^{-4} cm^2/sec (4.0×10^{-5} in^2/sec).

The soil modulus, E, at small strain was estimated at 8.6 MPa (180,000 psf). This value generally decreased significantly as strain increased. An estimate from the CPT interpreted s_u data using a published method and assuming a value for highly plastic clays (as is appropriate at the site), provided a value for E of 9.6 MPa (200,000 psf).

1-D Consolidation and Permeability Testing. The one dimensional consolidation parameter, C_v, and the constrained soil modulus, M, were obtained from multiple lab tests on specimens from the 12.2 m and 15.2 m (40 and 50 ft.) test depths. Values for C_v were around $6.5x10^{-5}$ cm^2/sec ($1.0x10^{-5}$ in^2/sec). The constrained modulus, M, was found to be 48.8 kPa (1020 psi) in the load range of interest, based on lab tests; a CPT prediction of M, based on published correlations was 46.0 kPa (960 psi).

A flexible walled constant gradient permeability test recorded a vertical permeability, k_v, of $2.0x10^{-9}$ cm/sec ($5x10^{-9}$ in/sec). Computations based on the CPT dissipation test and the constrained modulus value from the 1-D consolidation test and the comparison of vertical and horizontal drainage from other consolidation tests predicted the vertical permeability to be $3.0x10^{-9}$ cm/sec ($7.6x10^{-9}$ in/sec). A set of later tests from deeper samples showed that the site soils very nearly behaved isotropically. Values for C_h were 125% greater than C_v values and the constrained modulus, M, for the vertical and horizontal consolidation tests were both nearly 70.9 kPa (1,480 psi).

CPT and Lab Data Comparison and Validation. Overall, the project data shows excellent agreement among all of the laboratory test and CPT site data for soil strength, modulus, and permeability parameters. The test data is internally consistent and correlated well with CPT data obtained in-situ. Excellent overall agreement was found among the s_u, C_v, C_h, k_v, and k_h properties of the site soil and the stiffness parameters, M, E, and G. Although these properties could have been estimated from local experience or empirical relationships with large applied safety factors, the physical investigation of the multiple soundings and extensive lab testing has provided the engineers a high degree of confidence. Automated lab testing has allowed a comprehensive set of tests to be performed in relatively little time at comparatively small expense on a standard program delivery project.

Costs and Benefits at This Site. The site was initially expected to be very consistent; it was felt that CPT soundings would accelerate the project timeline and that the information easily extrapolated with appropriate confidence. The soundings all showed similar results and the drilling duration was reduced from an expected nine weeks to two weeks. Interestingly, due to the reduced number of borings, even with the large increase in the number of tests for purposes of the correlation work, the total lab processing time was also significantly reduced as compared to a standard investigation. The timeline was advanced significantly. Additionally, the combined use of lab testing and CPT methods also resulted in a substantial projected cost savings, estimated at $30,000, associated with reduced labor and incidental costs (travel, per-diem, lodging, maintenance, traffic control, supervision, etc…)

Automation Costs and Benefits

Equipment Cost. Automated equipment is more expensive than conventional operator controlled and observed systems. The investment can be substantial, ranging from $15,000 to $50,000 for frames, software, and accessories. The life of the product can be estimated at a minimum of five years. Our earliest automated frames have not had any significant repair issues or down time since placed in regular service. The workload and billing costs must be considered when determining what to purchase and when. Where test volume is high, the cost can be amortized over more projects and distribute the up-front system cost. On a very large construction project Mn/DOT was able to show that the cost of a new test system was justified in the reduced time to perform the tests for that single project.

Reduced Field Costs. By reducing the number of borings, the field investigation timeline may be shortened and costs substantially reduced. Automated lab testing and automated CPT field testing has allowed the number of traditional labor-intensive borings to be reduced on some projects. Additional lab testing has been performed on the samples from the site borings to correlate with CPT properties and estimates made from those properties. In this manner, the scope of field investigations has increased while the time and cost has decreased. The CPT system is operated by a smaller crew than our boring crews and advances soundings at an average rate 10 times faster than drilling.

Reduced Lab Labor Cost. Our lab previously operated with two technicians and a part time engineering supervisor. Today we have one technician and one half-time lab engineer. Effective labor costs in the lab have been reduced to 80% of former annual costs while testing has increased substantially. Some tests proceed at similar rates, such as unconfined compression, while consolidation and direct shear are being conducted at an annual testing increase of more than ten times pre-automation test levels. Tests such as DSS and CU triaxial stress path, previously rarely or never performed are now routine to operate, though still not part of 'everyday' testing. Table 4 shows how annual lab costs were reduced by 20% through the use of automated laboratory equipment, while increasing test load and quality of the work.

Table 4. Annual Geotechnical Lab Labor Costs

	Staff Prior / Staff After	Estimated Costs Prior to Automation	Estimated Costs After Automation
Asst. Engineering Technician	1 / 1	$40K (100% time)	$48K (100% time)
Senior Engineering Technician	1 / 0	$50K (75% time)	n/a
Lab Engineer	1 / 1	$60K (10% time)	$58K (50% time)
Engineer Trainee	1 / 1	$30K (50% time)	$30K (10% time)
Total		$98.5K	$80K

Reduced Risk. The lab data quality is significantly improved. Engineers are no longer hesitant to run complicated tests on site samples. Today, site data is used much more than former methods: 'rules of thumb', approximations from SPT tests, published 'typical soil parameter' values. This application of field and lab data from site soils improves the design accuracy. There is also reduced liability when site data is used rather than assumed soil properties obtained from other sources or relationships that may not be relevant to the particular site or design conditions.

Conclusions

Automated laboratory and in-situ testing has dramatically improved the derivation of the mechanical properties of site soils while simultaneously reducing both labor costs and investigation time. Digital instrumentation and computer control have significantly improved test precision, accuracy, and repeatability, while decreasing subjectivity and operator error. Quantifiable annual cost savings and increases in efficiency have been realized, even considering the relatively large investment cost of the new equipment. Other benefits include ease of use and improved data storage and transmission. Advanced complex tests, once only available to academic and research institutions, can now be employed easily on routine geotechnical projects.

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