Improved Soil Property Classification Through Automated Triaxial Stress Path Testing

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Abstract

Economical automated geotechnical testing systems are now available, allowing laboratory tests to accurately represent any given series of loading or unloading conditions from the environment such as slow, rapid, staged, drained, and undrained conditions. High quality path-dependant behaviors may now be investigated with comparative ease. Triaxial stress path tests can now be performed where specimens are subjected to states of stress that closely mimic the in-situ stress states with modest effort and cost. These techniques deserve wider deployment and regular use to significantly improve the quality of soil property assessments and hence geotechnical design.

Introduction

Significant advances in computer test control software and automation capabilities have been made in the past 15 years. The first case, as reported by James Denning 1992, was the automation of the US-COE soil lab. Combined with advances in highly precise micro-stepper and servo-motors, sensors, data acquisition systems, adaptive controller and computer networking, geotechnical testing systems, once limited by price and complexity to government and university research centers, are now available for a fraction of the cost, and with greatly simplified operation. Due to wider application and mass production, load, displacement, and pressure sensors have significantly improved in accuracy, precision, and longevity. Digital interfaces have removed the need for complicated analog signal conditioning. Today, a personal computer has sufficient processing power to simultaneously control the testing functions of several independent test stations, continuously monitoring test parameters in real time and recording data for evaluation and reporting. Although these advances have resulted in significant improvements in the ability to operate a number of geotechnical lab tests, perhaps the greatest benefit is in the automation of the multiple phases of the triaxial stress path test. Computer test control and automation has resulted in a number of significant overall improvements as compared to traditional manual testing. Potential for operator error is minimized, the test function can be performed without operator oversight or intervention during testing, allowing tests to be performed continuously, and complicated procedures such as back-pressure-saturation and K_0 consolidation can be controlled and monitored by the test software. Traditionally, geotechnical practitioners have relied on in-situ tests and either unconsolidated-undrained (UU) triaxial compression tests or more expensive consolidated undrained (CU) tests for obtaining shear strength estimates for clayey soils. Relatively recent advances in geotechnical software and systems integration now allows complex K_0 consolidated triaxial tests, along any stress path, to be run as easily as UU or CU triaxial tests. These tests can be described by complicated stress paths modeling in-situ variations in stress state through multiple construction or failure stages. Advances in digital test automation, simple user interfaces, and progressive reductions in cost have made stress path tests available to nearly all laboratories who are interested in the investment and operation of these, still somewhat specialized, tests.

Laboratory Triaxial Stress Path Testing

A number of methods exist to evaluate the shear properties of soil in the laboratory environment and in-situ. The capabilities of several types of common lab equipment are reviewed by Jamiolkowski et al. (1985). In the authors' experience, the most common types of laboratory shear testing, are the unconfined compression test (ASTM D2166), the direct shear test (ASTM D3080), and the triaxial compression test (ASTM D2850 and D4767). These tests are usually supplemented with information from index tests and field tests to make representative assessments of the shear properties of the soil. The triaxial test is regarded as the laboratory shear test method with the most versatility and greatest ability to model the in-situ soil stress state. There are three common methods to run the test, the unconsolidated undrained (UU) compression test, the consolidated isotropically undrained (CU) compression test, and the isotropically consolidated drained (CD) test. Stress path tests are still far from, routine, and are usually conducted only by research institutions and specialized geotechnical testing agencies and companies.

Unconsolidated Undrained Compression (UU)

Unconsolidated undrained compression tests are commonly used as they are quick to complete, hence sometimes referred to as 'quick tests' or 'Q tests', to obtain design values for the undrained shear strength (s_u) of soils. These tests rely on the fortuitous cancellation of three errors to provide estimates of s_u. The fast rate of shearing causes an increase in s_u while shearing in triaxial compression, ignoring anisotropy, and sample disturbance both tend to decrease the apparent value of s_u (Ladd and DeGroot, 2003). Depending on sample quality, the predictions of the shear strength can be either conservative or non-conservative. The UU test is simple but it can be misleading; it is also of limited use, as no additional information is gained from saturated clay specimens (Day 1999), it has been popular as it does not require complicated saturation and consolidation processes necessary for more rigorous triaxial testing methods. Ladd (Ladd 2003) recommends abandoning this test.

Isotropically Consolidated Undrained Compression (CU)

Again, due to the relative complexity of both equipment and methods, consolidated undrained testing has been, and continues to be, far less common than UU triaxial tests. Overall the test is useful as measuring of pore water pressures during the test allows the estimation of both total and effective test parameters. A draw back of the test is that the isotropic consolidation, where vertical and horizontal effective stresses are equal (K=1), often performed because of its simplicity, is not representative of any field conditions. Ignoring anisotropy also overestimates s_u, which can lead to unsafe designs in clays with low overconsolidation ratios (Ladd and DeGroot, 2003).

K_0 Consolidated Undrained Compression (CK_0UC)

Specimens consolidated to as near the in-situ stress state as possible, and subsequently sheared, as in the CK_0UC triaxial test, are regarded as high quality tests on which reliable estimations of shear strength properties can be made. These tests and triaxial testing in general are described by Terzaghi et al.(1996). The simplest form of this test, and probably the most common in general engineering practice, is where the specimen is saturated, K_0 consolidated, and sheared in compression, although extension tests can also be performed. Multi-stage tests are also possible.

Triaxial Stress Path Tests

The next step in the evolving improvement of the test is to model the lab conditions to the anticipated field conditions, including all appropriate stages of stress application or release. A stress path is a collection of points that represent a series of stress states. Rather than drawing a series of Mohr's circles to represent the changes in stress during the triaxial test shear phase, a stress path can be drawn where the peak point of each Mohr's circle is plotted on a *p-q* plot (Day 1999). Both effective stress and total stress paths can be plotted; different characteristics can be immediately observed; different stress paths illustrate different types of soil behavior such as dilative vs. contractive soils (negative vs. positive excess pore water pressure during shear phase) and overconsolidated vs. normally consolidated soils (effective stress paths that bends to the right vs. effective stress paths that bend to the left).

Computer Controlled Automated Triaxial Stress Path Testing

Commercially available automated triaxial systems consist of a load frame for controlling vertical stress and strain, two flow pumps for controlling cell and sample volume and pressure, and a computer with a communication card for test control and data acquisition. One particular type of system is discussed here although a variety of systems are available on the market with some differences in the types of load and displacement application mechanisms, sensors, and transducers used in each proprietary system.

The load frame, used to hold the test chamber and apply the deviator stress, utilizes a high speed, precision micro stepper motor to apply the vertical load to the soil specimen. An embedded control board with a dedicated CPU takes readings from the force and displacement transducers to control the micro stepper motor.

Each of the two flow pumps utilizes a high speed, precision micro stepper motor to regulate pressure and volume to the cell or specimen. A built-in microprocessor controls the micro stepper motor, which drives a piston in and out of a sealed cylinder. A pressure transducer on the end of the cylinder provides the feedback for control of pressure. The number of steps of the motor times the cross-sectional area of the piston is used to compute volume changes.

Two two-way electronic valves are used to control the direction of flow to the cell or sample (output valve), and the manual fill/drain operation (supply valve). The flow pump is capable of maintaining the desired pressure within 0.35 kPa (0.05 psi) while monitoring volume changes within 1 mm^3. Pressure increments may increase and decrease in any pattern by any amount (without exceeding the system's limits) as specified by the user. The automated process makes real-time adjustments using a Proportional-Integral-Derivative (PID) controller to change control parameters.

Fully Automated Triaxial Stress Path Capabilities

This system allows specification of all steps required to perform a triaxial test along any stress path possible in a triaxial cell, including the ability to specify changes in both horizontal and vertical stress and sample pore pressure. This automated system can, for example, model the stress path for an element in the upstream slope of a dam as pore water pressure increases to a steady state seepage value. In this case the total stresses stay constant but pore pressure is increased over time. Figure 1 shows nine possible stress paths that can conceivably occur in the field. To ensure that path-dependent behavior is considered, lab tests should model anticipated field conditions as closely as possible. Expected stress changes can be duplicated in the lab for improved modeling of the mechanical behavior of site soils. This can be of particular importance in soft soils, sensitive soils, and anisotropic materials.

The system requires no special skills to operate other than those used in conventional geotechnical specimen preparation, cell set-up, and testing. A person familiar with soil testing can learn to use the system confidently within a few days. Experience with a computer and MS-Windows® can reduce the software learning time to about one day, understanding of all the applicable theories of the testing itself, of course, takes considerably longer.

Minnesota DOT Case Study

The Minnesota Department of Transportation (Mn/DOT) conducted a series of triaxial stress path tests on samples of clay from a completed project near Fargo, ND along the Red River of the North. This material was selected to test the system due to its consistency and homogeneity. The total-stress stress path test results are shown in Figure 4.

Two of the four tests were compression tests, the other two were extension tests. All tests were consolidated anisotropically with a K value = 0.67 then sheared along a total stress path to represent the following field cases: Foundation loading (case 3); Active wall (case 5); Excavation unloading (case 7); Jack reaction of an earth support system (case 9). Each of these stress paths is shown in Figure 1 and noted by arrows corresponding to cases 3 [typical], 5, 7, and 9 as noted in the diagram legend.

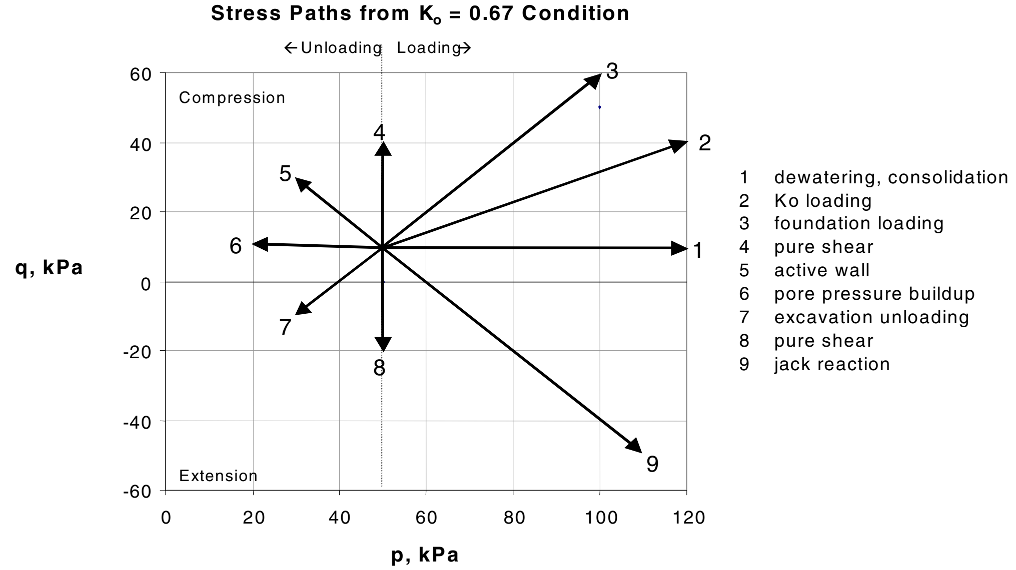
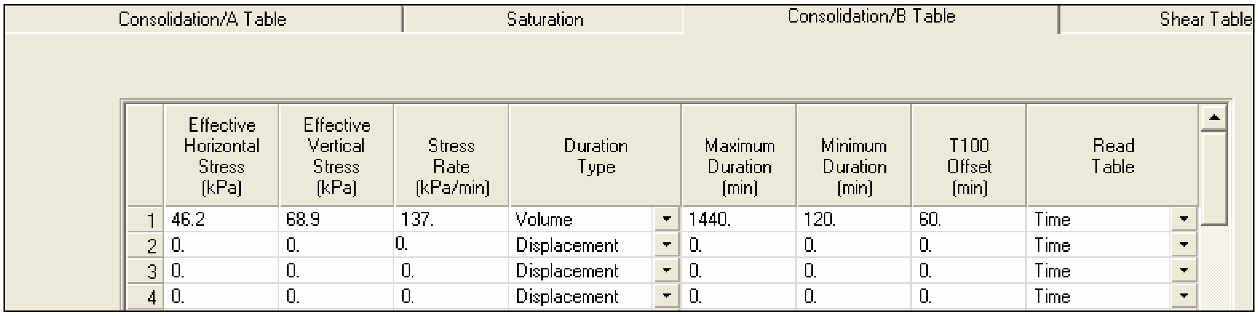


Figure 1. Possible stress path assignments and associated field conditions

All of Mn/DOT's previous testing had been isotropically consolidated CU compression testing. The main differences between a triaxial stress path test and a standard CU test are:

1. *Consolidation phases*: the ratio of the effective horizontal stress to the effective vertical stress was set at 0.67, the software program allow the user to either apply the effective stresses in steps up to 32 steps, or in one step with stress rate control along a resultant vector so that both the horizontal and vertical target stresses are reached at the same time keeping their ratio constant. The user interface for entering these control parameters is presented in Figure 2.



	Effective Horizontal Stress (kPa)	Effective Vertical Stress (kPa)	Stress Rate (kPa/min)	Duration Type	Maximum Duration (min)	Minimum Duration (min)	T100 Offset (min)	Read Table
1	46.2	68.9	137.	Volume	1440.	120.	60.	Time
2	0.	0.	0.	Displacement	0.	0.	0.	Time
3	0.	0.	0.	Displacement	0.	0.	0.	Time
4	0.	0.	0.	Displacement	0.	0.	0.	Time

Figure 2. Anisotropic consolidation test parameters table

2. *Shear phases*: The different test parameters in the shear phase are shown in Table1. In the first test the vertical stress was increased while the horizontal stress was held constant (compression), in the second test the vertical stress was decreased (extension) while the horizontal stress remained constant, in the third test the horizontal stress [confining pressure] was increased while the vertical stress was held constant (extension), and in the fourth test the horizontal stress was decreased (compression) while the vertical stress remained constant. Extension tests required that the cells be bolted to the platen, a fixed connection piston be used, and a fixed load cell coupler to connect the piston to the load cell.

Each of the four shear tests was performed automatically by the test system after the desired procedures were established in the consolidation and shear phase portions of the control software. Representative values for the different test control modes are shown in Table 1.

Table 1. Stress path shear phase test parameters table for four different cases

Case No.	Horz. Stress (kPa)	Vert. Stress (kPa)	Stress Type	Pore Pressure Change (kPa)	Shear Step Type	Shear Step Control	Rate (/min)	Max Strain (%)	Maintain Time (min)	Read Table
3. Foundation Loading	0	10000	Relative	0	Undrained	Strain	0.002	20	0	Time
5. Active Wall	-10000	0	Relative	0	Undrained	Stress	3.5	20	0	Time
7. Excavation Unloading	0	-1000	Relative	0	Undrained	Strain	-0.002	-20	0	Time
9. Jack Reaction	10000	0	Relative	0	Undrained	Stress	3.5	-20	0	Time

In the *Horizontal Stress* and *Vertical Stress* columns, values are entered which the program uses to reach a target stress condition on the specimen. Similarly, the value entered in the *Pore Pressure Change* column as an increment to be added to the value at the beginning of the step, or as the actual target value, depending on the *Shear Step Type*. In an *Undrained* step, stresses or strain (depending on the control parameter) will be applied with no specimen volume change permitted. In a *Drained* step, stresses or strain (depending on the control parameter chosen in the *Shear Step Control* column) will be applied and the pore pressure changed by the amount specified in the *Pore Pressure Change* field. A shear step can proceed either under *Strain* control or *Stress* control. If *Strain* control is chosen, the entry in the *Rate* column is taken to be the rate of change for axial strain in percent strain per unit time. For a positive value, the specimen will be compressed at the specified rate of strain, the vertical stress will be monitored, and the horizontal stress will be adjusted as necessary to maintain the stress path which has been defined from the entries in the *Horizontal Stress* and *Vertical Stress* columns. If there is a non-zero entry in the *Pore Pressure Change* column, the pore pressure will be adjusted so that its target value is reached at the same time as the target value for the horizontal and vertical stresses. For a negative value the specimen will be extended at the specified rate of strain; horizontal stress and pore pressure will be adjusted as necessary to match the measured vertical stress. If *Stress* control is chosen, the entry in the *Rate* column is taken to be the rate of change for stress. This rate together with a combination of the change in both vertical and horizontal stress (determined from entries in the *Horizontal Stress* and *Vertical Stress* columns) is used to calculate a time to reach the target values.

The rate at which the program changes the horizontal and vertical stresses in order to traverse the stress path is calculated using the entries from the *Horizontal Stress* and *Vertical Stress* columns and this time. The length of time to maintain stresses once the target values have been reached (or the maximum strain is attained) is specified in the *Maintain Time* column. The Read Table column is used to select the parameter, which the program uses to read and store data as the test proceeds. The possible parameters are *Time, Strain, Displacement* or *Volume*.

Case Study Observations

Figure 3 and Figure 4 present test results from a series of four triaxial tests. Despite the small number of tests and possible differences in sample consistency, the test results for both extension tests are fairly similar. The compression tests show that the foundation loading strength appears higher than the active wall case; no immediate conclusions can be drawn from this, as there may have been differences in sample properties or specimen quality (local weak zones are common in the clay samples used for these tests); additional tests should be carried out to thoroughly investigate the strength behavior and failure mode dependency.

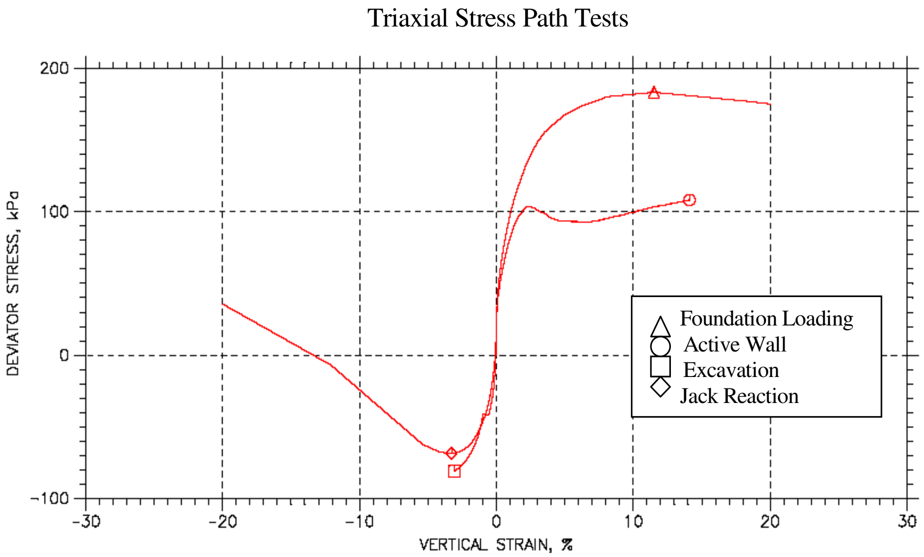


Figure 3. Combined plot of deviator stress vs. vertical strain showing each of the four stress path responses

An important observation was made during the test session. The stress controlled mode must be used when stress path tests are conducted where the horizontal stress is not constant during the shear phase. Although the lateral confining pressure is controlled by the flow pump, there is no sensor to provide direct feedback control based on horizontal specimen deflections. The rate should also be sufficiently slow to allow for the automated system to adjust test parameters and react to changes in measured stresses, strains, and pressures in real time.

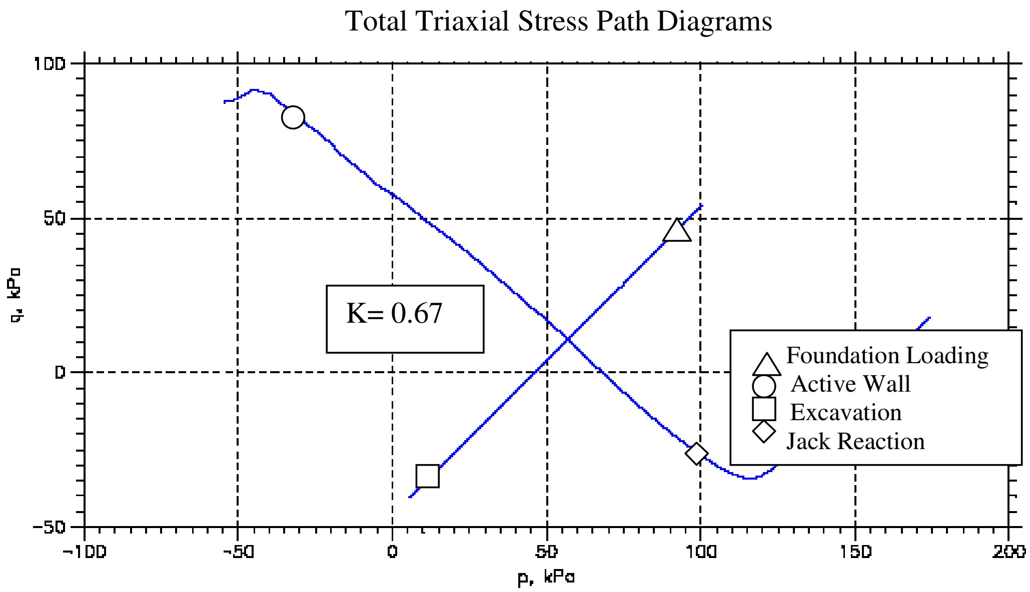


Figure 4. Combined *p-q* plot of total stress paths for the four case study tests

Conclusions

Triaxial stress path tests can now be performed without any more specimen preparation effort than UU triaxial tests; overall test design requires some additional effort to ensure the proper test parameters are established to appropriately represent the engineering problem being modeled. Overall the operation of automated stress path systems is both significantly less labor intensive and less complicated as compared to manual systems. High quality path-dependant behaviors may now be investigated with comparative ease at a reasonable price.

Triaxial stress path testing techniques, particularly when operated with meaningful consolidation parameters and relevant shear steps, can effectively model anticipated in-situ conditions. These methods deserve wider deployment and regular use to significantly improve the quality of soil property assessments for improved design analysis.

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