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Determination of Effective Stress Parameters for Clayey Silt Using a Borehole Shear Test

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ABSTRACT

The determination of shear strength parameters for use in geotechnical analysis is integral to safe and cost effective design. In general practise, shear strength parameters are frequently determined using published correlations and relationships with insitu field tests that are highly variable and are not intended to be used to develop shear strength relationships. Laboratory testing for measuring shear strength parameters is often minimal due to the inherent expense. Commercial drivers, sample quality assurance and turnaround timeframes greatly influence the quantity and quality of laboratory testing which is used to directly measure the shear strengths of soils. The Borehole Shear Test (BST) is an insitu testing apparatus that provides near instantaneous shear strength parameters, directly measured by shearing the side walls of a borehole at various normal stresses. Peak shear stresses are used to develop a Mohr Coulomb failure criterion and provide a direct measurement of shear strength. This paper summarises the results obtained from a series of Borehole Shear Tests undertaken on clayey silt in South East Queensland. Shear strengths were measured at various depths using the BST and were used to develop shear strengths parameters for the tested material. Thin walled Shelby tubes were used to recover insitu material samples which were used to determine the laboratory shear strength of the material. Consolidated Undrained Triaxial tests, Index testing and Standard Penetration Testing (SPT) were compared with the field BST results to assess relationships between the different testing methods. Results of the BST agree well with those tested in the laboratory. Results suggest that the BST could be an effective and alternative, cost efficient investigation tool which can be used to assess insitu strength parameters in conjunction with traditional laboratory testing.

Keywords: Borehole Shear Test, Effective Stress, Insitu Testing, Shear Strength

1 INTRODUCTION

Geotechnical design frequently requires the interpretation and assignment of ‘characteristic’ soil strength parameters for the various subsurface materials encountered during site investigations. Subsurface materials are generally classified using insitu exploration methods and typically involve a series of penetration tests (Standard Penetration Test and Cone Penetration Test) being undertaken to measure soil strength with depth.

Laboratory testing is undertaken on recovered disturbed samples, with a general focus on material classification and development of characteristic design parameters. Insitu Shelby tube samples collected during an investigation yield undisturbed samples that can be used to determine material shear strength; however results may be significantly altered from their insitu state by sample disturbance. Stiff to hard clay samples can be difficult to sample and require special tools to successfully obtain insitu samples. Similarly, the shear strength of granular dominated material samples is seldom determined within a laboratory due to difficulty in retaining insitu conditions when extruded. To accurately replicate the insitu conditions and determine suitable shear strength parameters using laboratory testing methods, high quality (undisturbed) sampling is required.

Laboratory testing is often seen as an excessive expense, and to people with limited geotechnical knowledge, it can be seen as an unnecessary cost burden to a project, as similar material parameters can be determined using correlations with penetration tests. Commercial drivers dictate the quantity and types of laboratory testing that can generally be accommodated on a project. The cost of site investigation generally increases significantly when laboratory shear strength testing is specified. This adversely increases the reliance on empirical relationships to determine characteristic shear strength parameters.

Common geotechnical engineering practice involves using correlations with empirical relationships of soil parameters with insitu tests; such as Standard Penetrations Tests (SPT) and Cone Penetration tests (CPT). Such empirical relationships have been derived from comparison between field and laboratory tests. These generic relationships are often deemed acceptable for use in geotechnical design, but can be highly variable and do not always account for the intrinsic nature of a specific soil. Although often universally applied, generic relationships are a direct production of the data available to the author at the time of their derivation. Accordingly, the results of the 'blind' application of such a generic relationship may be highly variable and may not account for the site specific nature of a soil (e.g. Application of a correlation upon alluvial / transported soils compared with a residual soil). Adopting empirical relationships may provide a design approach to determining material strength characteristics; however the accuracy of a geotechnical design is best defined by a direct measurement of the soil strength characteristics.

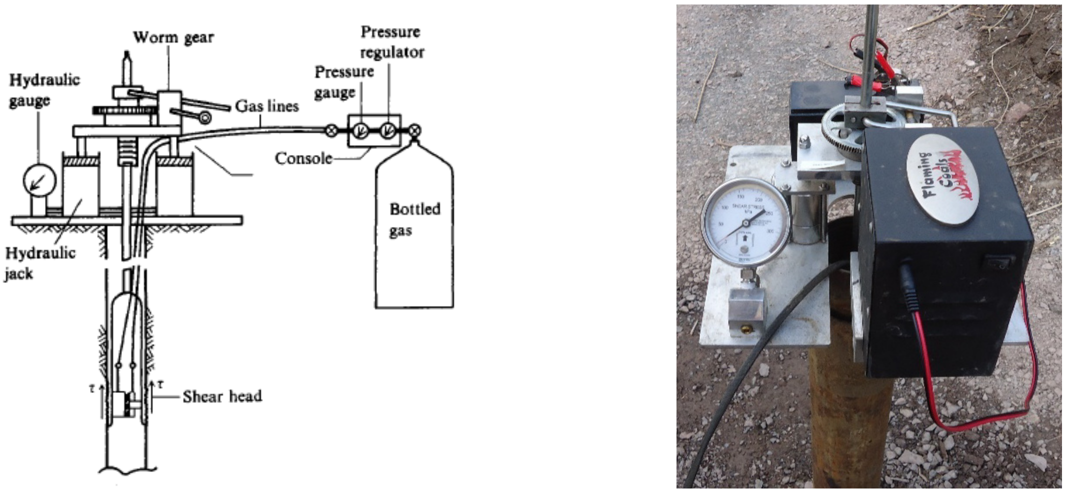
The BST is a unique tool that can be used to directly measure the shear strength of a soil within an open borehole. The BST uses a retractable shear head that can expand within a borehole to allow shearing of the encountered material on the side walls of a borehole. The BST can be used to test subsurface material at any depth below the ground surface, limited only by the number of extension rods and length of pneumatic tube used to control the shear head.

The BST presents numerous advantages when complementing a typical site investigation due to its ability to directly measure Mohr Coulomb shear strength parameters without the need for direct correlation. The test can be undertaken during borehole advancement and is intended for use within the void created from thin walled Shelby (u75) tube sampling. As the BST is undertaken insitu, it is likely to provide improved representation of actual shear strength parameters due to minimisation of sample disturbance compared with traditional laboratory sampling methods. A complete test can usually be completed within one hour with results providing instantaneous shear strength parameters. This can be advantageous for projects, providing both cost and time efficiencies.

This paper provides detail of a case study in which the BST has been used to obtain shear strength parameters. The Borehole Shear Test is an additional field investigation tool that can be used to obtain direct measurements of a soils shear strength.

2 BOREHOLE SHEAR TEST APPARATUS

The BST is undertaken by lowering a bilateral expandable shear head into a carefully drilled borehole or open cavity resulting from thin walled Shelby tube (u75) sampling. The test proceeds by expanding the shear head so that it engages the soil on the walls of the open borehole. A normal force is firstly applied to the shear head through pneumatic pressure plates that are controlled from the ground surface. The shear head is then axially pulled in the direction of the base plate with measurements of the shear force recorded at time intervals until peak failure is observed. Figure 1 shows the major components of the BST apparatus.



(a) (b)

Figure 1. (a) Typical Borehole Shear Test Apparatus (Handy, 2013); and (b) Photo of the BST with retrofitted motorised crank during a trial test in a cased borehole.

2.1 Test Methodology

The BST operation is undertaken in two phases:

- A seating / consolidation phase – A normal pressure is applied to the side wall of a borehole and then left for a duration of time to allow surrounding material to consolidate and for any excess pore water pressures to dissipate prior to commencement of the shear phase; and
- Shearing phase – A shear force is applied by rotating the crank attached to the base plate at a constant rate (typically 2 revolutions per second). The shear force is transferred along the pull rods to a dynamometer fitted with a hydraulic shear gauge. Results on the gauge are recorded until the soil material is observed to reach its peak shear strength. The peak shear strength is recorded and plotted against its corresponding normal stress.

Both testing phases are repeated for increases in normal stress. The test is typically repeated four to five times with the individual data points used to plot measurements of shear stress against normal stress. Figure 2 shows a typical BST data plot.

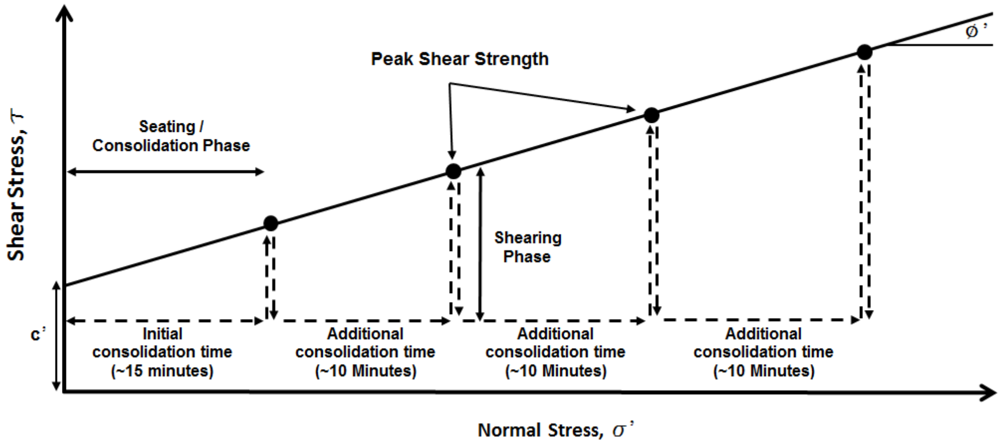


Figure 2. Typical borehole shear testing procedure for clayey silts (Bechtum, 2012)

With sufficient time allowed for consolidation and drainage, the slope of the line passing through each of the ‘peak’ shear strength points should be linear and conveniently plot a Mohr Coulomb failure plane. A line of best fit is applied to the data points with the characteristic strength parameters determined from the fitted lines slope and y-axis intercept. Consolidation times vary between material types, with granular soils typically requiring a shorter consolidation durations.

The shear head plates are equipped with grooved teeth that engage the material on the walls of the borehole and force the failure plane to occur within the surrounding soil material rather than at the shear head interface. Each repetition of the shearing phase shifts the shear surface radially outwards into virgin material and as such, consolidation and dissipation of pore water pressures are considered to be cumulative for each test (Lutenegger and Tierney, 1986). When an increase in normal stress is applied, the previously sheared material will reconsolidate and increase in strength. This causes the shear plane to move outwards into weaker undisturbed material. The radial geometry of the shear head distributes stresses away from the surface of the borehole walls such that consolidating pressures are highest in the soil closest to the shear plates. Successive shear failure readings are therefore able to be obtained without relocating the shear head or releasing the normal stress between each test interval.

The Borehole Shear Test has been well documented as a successful insitu test that can determine shear strength parameters for all soil types. Historically the BST has been compared with direct shear tests which force failure through a horizontal failure plane with results suggesting that the BST produces similar strength parameters.

3 SOUTH EAST QUEENSLAND CASE STUDY

A case study undertaken using the BST at a site in South East Queensland (SEQ) is presented to demonstrate the effectiveness of the BST. A borehole was undertaken and advanced using a 75 mm tungsten carbide tipped auger to a depth of 10m below the existing ground surface. The site comprised primarily of alluvial clayey silt extending to a depth of 9.5m below the existing ground surface.

SPT tests were undertaken at 1.0m intervals with 50mm diameter (U50) Shelby tube samples recovered at alternating 1.0m sample depths. The consistency of the soil was assessed as 'firm' (as per AS1726-1993) within the top 4.5m and improved in stiffness thereafter. Laboratory index test results for the clayey silt are provided in Table 1 and confirm the consistency of the material within the depth intervals subsequently tested by the BST.

Table 1. Laboratory Test Results

Depth (mbgl)	Sample Classification (USCS)	Moisture Content (%)	Particle Distribution			Atterberg Limits			
			Sand (%)	**Silt (%)**	**Clay (%)**	**LL (%)**	**PL (%)**	**PI (%)**	**LS (%)**
1.00–1.45	clayey silt (ML)	20.2	13	60	27	35.2	21.6	13.6	5.2
2.00–2.45	clayey silt (ML)	20.4	–	–	–	33.0	20.6	12.4	5.6

A total of six multistage BST's were undertaken at various depths within the top 2.0m of the borehole. As per Table 1, all tests were undertaken within 'firm' clayey silt. Swelling of the borehole after excavation limited the test depth to 2.0m, as the shear head could not progress further to promote testing at greater depths. The shear head of the BST was inserted to the desired test depth, with an initial normal stress of 20kPa applied to the shear head. A ten (10) minute consolidation period was allowed between each increase in normal stress test to allow for equalisation of pore pressures. An applied shearing force was standardised using a retrofitted motorised crank that rotated at a constant rate of 2 revolutions per second (0.05 mm/s). The shear stress was recorded at 15 second time intervals. Once the peak shear stress was observed, rotation of the BST crank was stopped and the shearing force reduced until the shear stress gauge returned to a zero reading. The normal stress was then increased by increments of 20kPa, with the test repeated until four successful peak shear stresses were obtained.

Three Consolidated Undrained (CU) Traixial tests were undertaken on samples extruded from the recovered Shelby tubes. The triaxial tests were undertaken at normal forces similar to those applied during the BST field investigations. A Mohr Coulomb failure envelope was developed for each triaxial test, with the results summarised in Table 2.

Table 2. Consolidated Undrained Triaxial Test Results

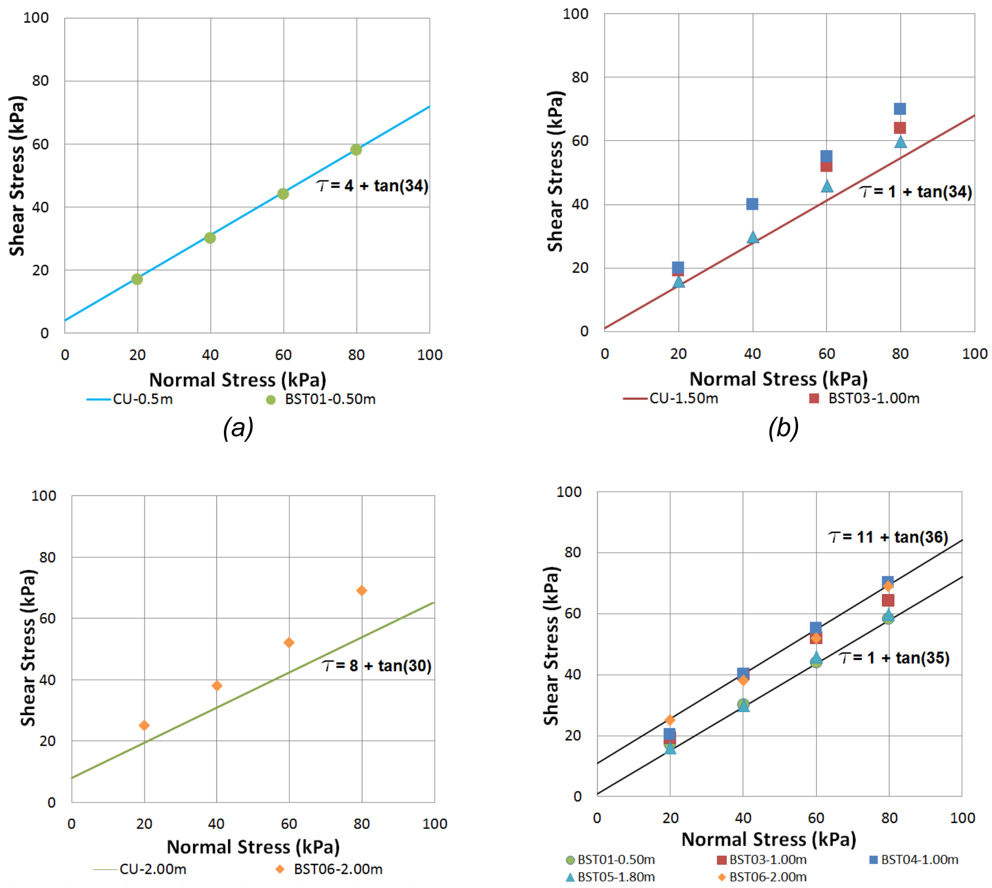
Sample ID	Depth (mbgl)	Sample Classification	Description	SPT 'N' Value	Effective Stress Parameters	
					c'	**Ø'**
CU-01	0.00 – 0.50	clayey silt (ML)	Soft - Firm	–	4	34
CU-02	1.00 – 1.50	clayey silt (ML)	Firm	5	1	34
CU-03	2.00 – 2.50	clayey silt (ML)	Firm	5	8	30

4 RESULTS

The peak shear stress and the corresponding normal stress were recorded and graphed to produce a Mohr Coulomb failure criterion. Each BST result was plotted in terms of normal and shear strength relationships and compared with the nearest CU triaxial test result. One BST results has been excluded from further analysis due to data irregularities - likely due to the over extension of the shear head during the completion of the test. Table 3 shows the peak failure shear stresses for each corresponding normal stress. Figure 3 shows the peak BST results compared with the laboratory triaxial tests undertaken on extruded samples.

Table 3. Peak Shear Results

Normal Stress (kPa)	Peak Shear Strength (kPa)				
	BST-01 (0.50mbgl)	**BST-03 (1.00mbgl)**	**BST-04 (1.00mbgl)**	**BST-05 (1.80mbgl)**	**BST-06 (2.00mbgl)**
20	17	19	20	16	25
40	30	40	40	30	38
60	44	52	55	46	52
80	58	64	70	60	69



(a) *(b)*

(c) *(d)*

Figure 3. Comparison of Individual BST data points and laboratory triaxial failure envelope – (a) Comparison of BST and CU test between 0.50m and 1.00m depth; (b) Comparison of BST and CU test between 1.00m to 1.80m depth; (c) Comparison of BST and CU test between 2.00m and 2.50m depth; and (d) All data points for Borehole Shear Tests undertaken in clayey silt.

The results of the BST compared with the effective stress parameters determined from the CU Triaxial tests are summarised in Table 4.

Table 4. Effective stress comparison between BST and CU triaxial tests

Sample ID	Depth (mbgl)	BST		Triaxial Compression	
		Effective Cohesion (kPa)	Effective Friction Angle (°)	Effective Cohesion (kPa)	Effective Friction Angle (°)
BST-01	0.50	3	34	4	34
BST-03	1.00	16	31	1	34
BST-04	1.00	10	37		
BST-05	1.80	1	37		
BST-06	2.00	11	34	8	30
Mean		8.2	34.6	–	–
Standard Deviation		6.1	2.5	–	–
COV		75%	7%	–	–

5 DISCUSSION

The BST results observed within the clayey silt material agree well with the shear strength parameters derived from laboratory triaxial test results. Comparison of the results show that the BST achieves similar friction angles compared with the CU triaxial test results, with the effective friction angle calculated to be typically within ± 3° (±10%) of the corresponding laboratory test result. The apparent cohesion determined by the interpretation of the BST was observed to be approximately equal or greater than that observed in the laboratory test results. Comparison of the shear strength failure plots suggests that the BST generally provided equal or higher shear strengths than those observed in CU triaxial tests. When comparing the results of the BST and the triaxial tests, it is important to consider the different failure paths which can occur for each test method. The BST forces failure to occur in a plane that is approximately parallel to the shear head. Conversely, a triaxial test induces a compressive force that encourages a failure plane to develop anywhere within a soil sample. It is likely that this variation in failure mechanism could contribute to variances in shear strengths between the two test methods.

Laboratory test results can be adversely impacted by sample disturbance compared with their insitu counterparts. Insitu tests typically experience less disturbance than those extruded from a Shelby tube as the sampling and extrusion process may create variances in the soils microstructure. In some cases, these processes may impact on the observed shear strength of a material. Similarly, any variance in moisture content between the insitu samples and those tested in a saturated triaxial test is likely to have an impact on the apparent cohesion for a tested material. The influence of matric suction on an unsaturated soil is not captured in a standard consolidated undrained (cu) triaxial test, and therefore such tests discount any apparent cohesion that may exist within the unsaturated zone. The strength anisotropy of a soil may also have an impact on the soil shear strength. Further research comparing the results of the BST and unsaturated triaxial test results should be considered to assess the suitability of the BST in estimating the increase in apparent cohesion due to matric suction within the unsaturated zone.

The presented results compare CU triaxial tests and BST's within close depth proximity to one another. It is possible that there is a slight variation between the tested triaxial samples and that of where the borehole shear tests were undertaken. However, due to the encountered subsurface profile and the repeatability of the triaxial test results, this is not considered to be of significant impact. As expected with geotechnical testing, some variability between test results can be expected. This is demonstrated by comparison of the laboratory triaxial test results which were undertaken on three samples considered to be of the same material unit. Due to the inherent nature of the soil, slight variations in the microstructure of the soil matrix are likely to exist between the tested samples. Phoon et al, 1999 suggested that the friction angle of clayey silt broadly has a coefficient of variation (COV) of less than 20%, typically with a measurement error between 5% and 15%. Considering this, the results of the triaxial tests appear to correlate well with one another. Similarly, it can be expected that there will be a certain degree of difference between the laboratory test results and those measured in the field due to reasons mentioned above. Analyses of the BST effective friction angles provide a COV of 7%. This is within the typical measurement error range suggested by Phoon et al (1999). Generally the results obtained from the BST appear to provide a good correlation with those calculated from laboratory CU Triaxial tests. Small variations in friction angle and apparent cohesion can be expected and attributed to measurement error, sample disturbance and matric suction.

6 CONCLUSION

The case study undertaken on clayey silt soils supports the existing literature, such that a BST can be used on clayey silts to determine effective stress parameters. The BST can provide insitu measurements for both the effective friction angle (Ø') and the apparent cohesion (c') of a soil without the need for laboratory testing. The results of the friction angle are expected to be within 10% of comparative laboratory test results, whilst the apparent cohesion appears to capture the additional strength gains associated with matric suction and insitu conditions. The BST provides an effective and alternative tool capable of determining direct insitu strength parameters in a time and cost effective manner which are comparable to CU triaxial tests.

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