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Effective Shear Strength Parameters for Stiff Fissured Clays

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SUMMARY Shear box and triaxial tests have been used to investigate the effective shear strength of a stiff fissured clay of constant mineralogy but variable plasticity. Different residual shearing mechanisms were recognised in the shear box tests with significantly different values of residual strength. The fully softened strength parameters appropriate for the analysis of first-time slides were investigated by both triaxial and shear box tests. The lower plasticity samples had a higher strength than the higher plasticity samples. For the soil tested both the residual and fully softened effective friction angles showed a pattern of dependence on the plasticity. It may be possible to establish similar correlations for other soils if the results reflect different shearing mechanisms caused by grading variations within a soil of constant clay mineralogy.

1 INTRODUCTION

Stiff fissured clays commonly occur in the more populated areas of Northern Tasmania. In Launceston and the Tamar Valley the clays are lake sediments of Tertiary age. Along the north-west coast, a red-brown clay soil has developed on basalt of Tertiary age. Landslips are common in both areas.

The analysis of the long term stability of a natural slope, or the design of permanent cuttings in stiff fissured clays, require the knowledge of the appropriate effective shear strength parameters. These parameters have been investigated at a landslip in basalt soils near Devonport on the north-west coast of Tasmania. Multi-stage direct shear tests and consolidated undrained triaxial tests were used to determine the laboratory strength of undisturbed and remoulded samples of the soil.

Moon (1983) has reported the results of the investigation of residual strength by direct shear tests. He showed that the recognition of the different residual shearing mechanisms in the natural soil enabled a relationship between plasticity index and residual strength to be established. Residual shearing mechanisms are described in detail by Lupini, Skinner and Vaughan (1981) who worked with artificial soil mixtures.

In this paper the investigation of residual strength by direct shear tests is described in more detail. The definition of fully softened shear strength parameters which are appropriate for the analysis of first-time slides is considered and the relationship between laboratory determined parameters and those applicable to the field is discussed. The investigation of fully softened strength by both triaxial and direct shear tests is described. The paper presents the results of all of the strength tests and discusses the relationship between shear strength parameters and plasticity index for a soil of constant clay mineralogy but variable grading and plasticity.

2 DESCRIPTION OF SOIL

All of the samples tested were obtained from test pits and boreholes within the landslip. Field observations and laboratory tests indicate that the slip occurs within one soil unit of constant clay mineralogy. The soil has a continuous variation in plasticity due to variations in clay content. The soil consists of red-brown silty clay with minor rock fragments. Soil properties are summarised in Table I.

TABLE I

SOIL PROPERTIES

Liquid Limit:	46 to 124%
Plastic Limit:	28 to 44%
Plasticity Index:	17 to 84%
Clay Fraction:	30 to 65%
Activity:	0.53 to 1.28
Clay Mineralogy:	Montmorillonite and kaolinite

3 STRENGTH PARAMETERS REQUIRED

If a landslip already exists, or there are pre-existing shear surfaces, residual strength parameters are required (Skempton, 1964).

If there has been no previous failure the possibility of a 'first time' slide must be considered. Skempton (1970) suggested that the field strength of stiff fissured clay at first failure corresponded to the 'fully softened' condition which is reached when further deformation at constant stress fails to cause any further increase in water content. The fully softened condition may be taken as a practical approximation of the critical state. The peak strength of normally consolidated remoulded clay is also the theoretical limiting strength of a stiff fissured clay which has undergone complete softening.

In a review of the slope stability of cuttings in Brown London Clay, Skempton (1977) reports that the fully softened angle of friction is equivalent to the peak angle of friction determined by laboratory tests on undisturbed samples. However, values of cohesion determined in the laboratory generally overestimate fully softened cohesion (c'). Chandler and Skempton (1973) discuss the cohesion intercept obtained by back analysis, and argue that although the field cohesion at the time of first failure is small, it cannot be zero. They point out that the c' = 0 assumption leads to the conclusion that the limiting slope of a cut would be, contrary to practical experience, independent of depth. They suggest c' values of between 1 and 2 kPa for London Clay and Upper Lias Clay. These values are similar to the residual cohesion determined by laboratory tests.

In light of the above discussion the effective shear strength parameters appropriate for the analysis of first time slides are referred to in this paper as the fully softened parameters. The fully softened angle of friction (ϕ') is assumed to be equal to the peak angle of friction determined by laboratory tests while the fully softened cohesion (c') is assumed to be equal to the cohesion obtained in residual strength tests.

4 RESIDUAL SHEAR STRENGTH

4.1 Test Methods and Procedures

The results presented in this paper were obtained using a reversing shear box. It cannot be assumed that ring shear tests would give similar results.

Multi-stage tests were used as described by Cullen and Donald (1971) and Chowdhury and Bertoldi (1977). Shear strength was recorded during the forward travel of the shear box which was reversed by hand at the end of each run. Each sample was tested under four different normal pressures ranging from 30 to 150 kPa. Test procedures varied slightly but most samples were tested at least twice at each normal pressure. After each change of normal pressure the sample was left overnight to expand or consolidate before testing continued. The tests were carried out with a box drive rate of 0.02 mm min $^{-1}$.

4.2 Load Displacement Curves

The form of the load displacement curve depended on the mechanism of residual failure (Lupini, Skinner and Vaughan, 1981). Moon (1983) has shown that the samples with a plasticity index below 40% failed by turbulent shear and did not develop shear planes, while samples with a plasticity index above 55% failed by sliding shear and developed continuous shear surfaces. Samples which failed by turbulent shear had a higher residual strength and produced different load displacement curves to samples which failed by sliding shear. Typical load displacement curves for the two types of failure are shown in Figure 1. The peak values were only obtained on the first run for an undisturbed sample (Section 5.3.1.).

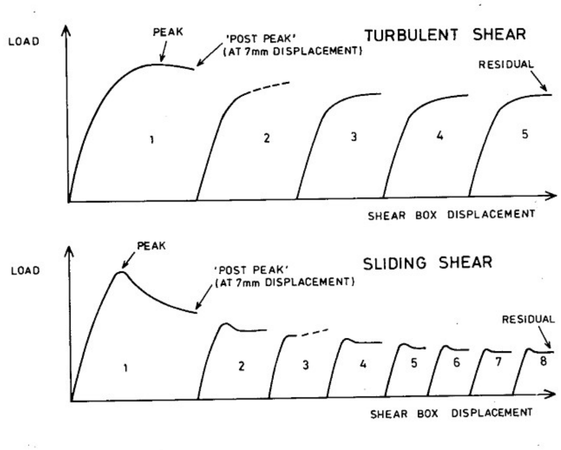

Figure 1 Typical load displacement curves

A number of forward runs were required to establish the residual strength at each normal pressure. There was a tendency for the load to drop a little from run to run until the residual state was reached. However, the load usually remained approximately constant (flat curve) during each run. After some experimentation it was decided to discontinue each run once the curve was flat and not to continue to an arbitrary displacement. This had the effect of increasing the number of runs that could be achieved each day and reducing the total testing time. In samples failing by sliding shear some of the later runs could be completed after less than 1 mm displacement.

4.3 Residual Shear Strength Results

Residual strength results for fifteen different samples are given in Table II. Values of effective residual cohesion (c'_r) and effective residual friction angle (ϕ'_r) were obtained by linear regression analyses. The assumption that the failure envelopes are linear in the range tested is justified by the high values of R^2. Residual cohesion varied but there was no significant difference between the values for the different shearing mechanisms.

TABLE II

RESIDUAL SHEAR STRENGTH RESULTS

Shearing mechanism	Plasticity index	Residual cohesion in kPa	Residual friction angle	R^2 %
Turbulent	25	0.5	28.2	99.96
(plasticity	32	3.5	28.3	99.79
index	27	3.2	28.1	99.92
<40)	39	7.3	27.8	99.96
	26	3.7	29.0	99.97
Transitional	46	5.1	15.4	99.99
	50	4.7	15.0	99.77
Sliding	59	4.2	12.0	99.99
(plasticity	61	3.1	12.0	99.91
index	-	2.6	7.7	99.88
>55)	67	2.8	9.6	99.99
	79	4.1	10.8	99.88
	-	3.1	8.4	99.68
	67	4.4	10.4	99.97
	61	4.9	8.8	99.11

R^2 is a measure of the proportion of variation of the data which is explained by the assumption that the regression equation is linear.

5 FULLY SOFTENED STRENGTH

5.1 Test Methods

Fully softened strength parameters were investigated by consolidated undrained triaxial tests and by direct shear tests. As discussed earlier (Section 3) laboratory strength testing on undisturbed samples may be expected to provide an estimate of the fully softened angle of friction (ϕ') but will generally overestimate the fully softened cohesion (c'). The five different methods used to determine ϕ' are shown in Table III.

Tests on undisturbed samples were preferred to tests on remoulded samples because remoulding destroys any diagenetic bonds or preferred particle orientation which may occur in natural soils.

TABLE III

METHODS USED TO DETERMINE FULLY SOFTENED STRENGTH

Apparatus	Sample Type	Failure Definition
Triaxial	Undisturbed	maximum ratio of principal stresses
Triaxial	Undisturbed	maximum difference of principal stress
Shear box	Undisturbed	peak strength
Shear box	Undisturbed	post peak strength (at 7 mm displacement)
Shear box	Remoulded	peak strength of normally consolidated sample

5.2 Triaxial Tests

5.2.1 Procedures

Consolidated undrained triaxial tests with pore pressure measurements were carried out and the results plotted on p-q stress path diagrams (Figure 2). The cell pressures were chosen to obtain strength parameters in the effective normal pressure range from about 20 to 200 kPa. A back pressure was applied to all of the samples and checks on the value of pore pressure parameter B indicated that the samples were fully saturated. The strain rate used was about 0.003% min^{-1}. The effects on the failure envelope of the restraint imposed by the filter paper drains and the rubber membrane were considered but appeared to have a negligible effect on ϕ'.

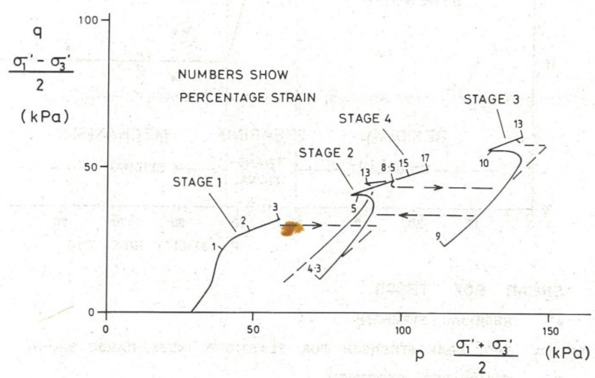

Figure 2 P-Q diagram for staged triaxial test

5.2.2 Definition of failure

Two definitions of failure were used. The first, the maximum ratio of principal stresses occurred at a low strain whereas the second, the maximum difference of principal stresses (deviator stress) occurred when the strain was significantly higher. The stress path between the two points follows the 'Coulomb line' and the sample may be regarded as being in a 'stabilised state of failure' (Kezdi, 1980). The different definitions of failure result in different values of c' and ϕ' (Table V).

5.2.3 Staged tests

Most of the consolidated undrained tests were staged with each sample being tested at four different cell pressures. Figure 2 shows that the stress path followed the Coulomb line over a large strain (1% to about 17%). In each test the cell pressure for the final stage was chosen to allow the stress path to cover the same range as in an earlier stage. In every case the Coulomb line from the final stage closely overlapped an earlier stage. Thus the Coulomb lines from each stage could be connected to form a single straight failure envelope.

5.3 Direct Shear Tests

5.3.1 Peak and post peak strength of undisturbed samples

For the first forward run of each shear box test the peak strength and the 'post peak' strength have been recorded (Figure 1). The post peak strength has been defined as the strength at the end of the first run which was standardised at a shear box displacement of 7 mm. The box drive rate used for these tests was about 0.005 mm min^{-1}. The post peak strength results are given in Table IV.

TABLE IV

POST PEAK STRENGTH RESULTS

Normal effective stress in kPa	Plasticity index %	Post peak strength in kPa	Plasticity index %	Post peak strength in kPa
30.0	25	22.7	60	21.2
30.0	27	21.7	61	18.3
57.2	27	36.0	59	31.1
57.2	33	31.9	67	26.0
57.2	39	39.7		
98.1	25	63.4	59	46.0
98.1	26	70.5	64	40.1
98.1	27	49.1	79	48.3
98.1	32	52.8		
152.6	25	92.5	59	68.0
152.6	26	101.5	79	63.1
152.6	27	86.4		

It was considered that the failure envelopes defined by the post peak strength would provide a better estimate of the fully softened friction angle. Many of the samples, which were collected in summer, may not have been fully saturated at the start of testing and scatter in the peak strength results could be due to variable increases in effective strength due to negative pore pressures. By the end of the first run (post peak strength), the soil in the failure zone would be likely to be closer to full saturation and negative pore pressures would be less. The results support this argument as the post peak strengths fit linear failure envelopes more closely than the peak strength results (R^2 in Table V).

5.3.2 Peak strengths of remoulded samples

A series of shear box tests was carried out on remoulded normally consolidated samples. Remoulded soil with a consistency close to the liquid limit was placed in the shear box and allowed to consolidate overnight before being tested. This process was repeated with consolidation and testing being carried out at four different normal pressures in

TABLE V

RESULTS OF TESTS USED TO INVESTIGATE FULLY SOFTENED STRENGTH

Test Method	Plasticity index less than 40%				Plasticity index 50% or greater			
STAGED TRIAXIAL	cohesion in kPa	friction angle	R^2 %	number of samples	cohesion in kPa	friction angle	R^2 %	number of samples
maximum ratio of principal stresses	14.4	30.8	99.95	1	8.2	22.0	98.72 to 99.60	3
maximum difference of principal stresses	20.0	28.4	99.89	1	9.4	20.5	97.53 to 99.93	3
SHEAR BOX								
peak	6.5	30.6	99.26	12	15.7	22.9	95.06	9
post peak	2.8	30.4	99.76	12	7.8	20.7	99.91	9
remoulded	-	-	-	-	6.5	19.6	99.38	1

R^2 is a measure of the proportion of variation in the data which is explained by the assumption that the regression equation is linear.

the range from 30 to 150 kPa. The peak angle of friction has been taken as an estimate of ϕ' (Table V). The relatively low value of R^2 is caused by the slightly curved failure envelope which often results from tests on 'young' (i.e. remoulded) soils. This curvature of the failure envelope results in a lower estimate of ϕ' than that obtained from tests on undisturbed samples.

5.4 Fully Softened Shear Strength Results

The results of the investigation of fully softened strength parameters by triaxial and shear box testing are summarised in Table V. Soils with a plasticity index of less than 40% had a higher strength than soils with a plasticity index of 50% or greater. Thus the results were divided into two groups and analysed separately. The fact that the different methods of estimating ϕ' gave similar results increases confidence in the parameters obtained.

6 RELATIONSHIP BETWEEN SHEAR STRENGTH PARAMETERS AND PLASTICITY INDEX

The relationship between angle of friction (ϕ') and plasticity index (PI) for the soil tested is shown in Figure 3. The post peak results were obtained by analysing groups of samples with similar plasticity. Group A represents ϕ' obtained by linear regression analysis of test results obtained on eleven samples whose PI ranged from 25 to 33%. Group B represents the analysis of seven samples whose PI ranged from 59 to 67%. All the other results on Figure 3 represent single samples where multi-stage tests have resulted in the definition of separate failure envelopes for each sample.

The solid lines show the general pattern of results. The correlation between the residual angle of friction (ϕ'_r) and plasticity index has been explained by differences in residual shearing mechanism caused by variations in clay content (Moon, 1983).

The solid line indicating the relationship between the fully softened angle of friction (ϕ') and the plasticity index is less well established but can be justified on the following grounds. Up to a PI of 39% the test results indicate a ϕ' only slightly higher than ϕ'_r. Between a PI of 39% and 59% the only information is one remoulded test result which

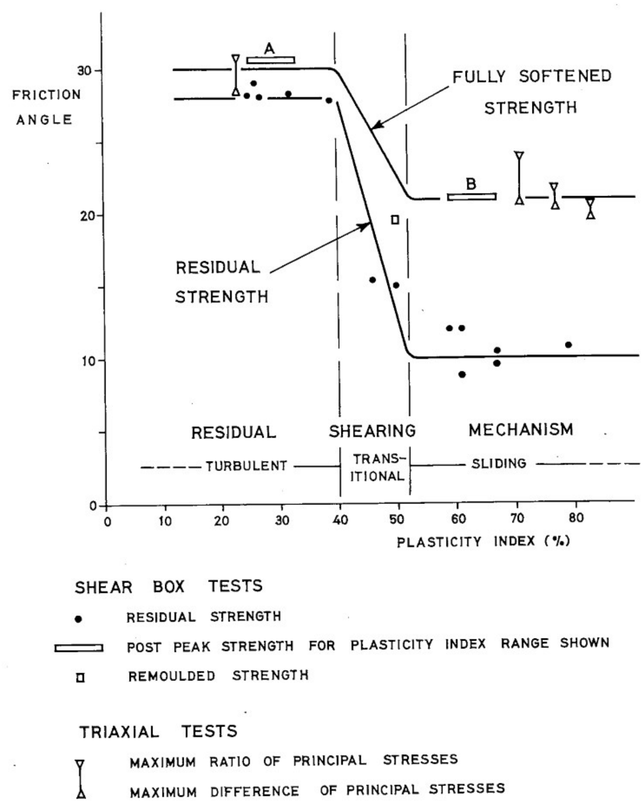

Figure 3 Relation between strength and plasticity

is likely to give a low estimate of ϕ' because of the curved failure envelope (Section 5.3.2). For a PI of 59% and above the three triaxial tests could be interpreted as giving a sloping curve. However, the sample which gave the highest strength was tested at lower cell pressures than the other two samples and this may explain the slightly different results. The post peak shear box tests indicate a consistent strength over the range tested (Table IV). Lupini, Skinner and Vaughan (1981) tested sand-bentonite mixtures in a ring shear apparatus and found little variation in peak strength for clay fractions between 50 and 90%.

The cohesion (of about 3 kPa) obtained in the residual strength tests did not appear to be dependent on the residual shearing mechanism or the PI (Table II). The fully softened cohesion parameter is assumed to be similar to the residual cohesion (Section 3) and therefore also independent of the plasticity.

A summary of the relationship established between effective shear strength parameters and plasticity index is given in Table VI.

TABLE VI

SHEAR STRENGTH PARAMETERS AND PLASTICITY INDEX

	Plasticity index range (%)					
	Below 40		40 to 52		Above 52	
Parameter	c' kPa	ϕ' deg	c' kPa	ϕ' deg	c' kPa	ϕ' deg
Fully softened	3	30	3	21-30	3	21
Residual	3	28	3	10-28	3	10

The best estimate of the boundary between the middle and upper plasticity range is 52% (Table VI and Figure 3). The position of this boundary is not well defined and may lie anywhere between 50 and 60%.

7 CONCLUSIONS

It has been shown that the fully softened effective friction angle has a similar pattern of dependence on plasticity as previously demonstrated for the residual friction angle (Lupini, Skinner and Vaughan, 1981; Moon, 1983). Establishing the correlation between plasticity and strength depended primarily on the recognition of different residual shearing mechanisms. If the soil fails by turbulent shear, the fully softened strength will be slightly higher than the residual strength whereas if the soil fails by sliding shear the fully softened strength is likely to be much greater than the residual strength. For soils falling in the transitional zone both strength parameters will be sensitive to small changes in plasticity.

Effective strength testing is time consuming and expensive. The work of Lupini et al. (1981), Moon (1983) and the results presented here indicate how effective strength parameters may be determined with the minimum amount of such testing. Initial work should be aimed at establishing clay mineralogy, grading, and plasticity variations. Residual strength testing with shear box or ring shear apparatus should then be used to determine residual shearing mechanisms and residual shear strength parameters. Once the residual shearing mechanism is established the fully softened parameters may be investigated by either direct shear or triaxial testing.

Geological formations of stiff fissured clay, although varying in grading and plasticity, often have characteristic clay mineralogies. Using the approach suggested above it may be possible to determine a relationship between effective shear strength parameters and plasticity index which will be applicable for a whole region. Investigations of specific cuttings or slopes in such a region need only concentrate on recognising the appropriate shearing mechanism.

8 ACKNOWLEDGEMENTS

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