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Strength parameters and the progressive failure of hill slopes.

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Symbols used:

c' = cohesion intercept (kPa)
F = factor of safety
LL = liquid limit
m = moisture content (%)
p = effective normal load
PI = plasticity index
s = shear strength (kPa)
s_p = peak strength (kPa)
s_r = residual strength (kPa)
s_s = fully softened strength (kPa)
St = sensitivity
u = pore water pressure (kPa)
τ' = shearing stress (kPa)
ϕ' = internal fraction (°)

INTRODUCTION

Over-consolidated clays are generally brittle, that is, they have a peak strength which is greater than their residual strength. With over-consolidated plastic clays, such as those of the Tamar region, sensitivity is generally between 2 and 5 (undrained values).

$$St = \frac{s_p}{s_r}$$

When a clay becomes stressed, it resists movement according to the Coulomb equation: $s = c' + (p - u).\tan \phi'$

i.e. strength = cohesion + friction

On a stable slope only part of the available shear strength will be developed.

$$\Sigma\tau = \frac{\Sigma c' + \Sigma(p - u).\tan \phi}{F}$$

where F is the factor of safety. If F becomes less than 1 then the slope fails.

TEST METHODS

The shear box

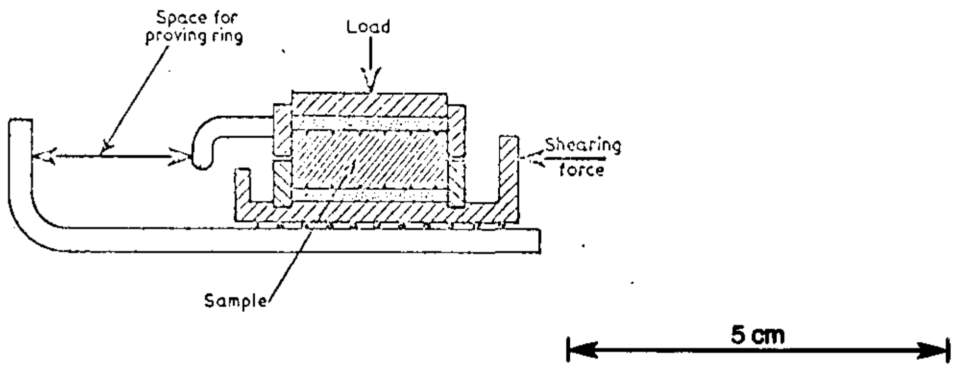


Figure 1. *Diagrammatic section of shear box.*

The clay sample is held in a split box and a normal load p is placed on the sample. The lower part of the box is slowly moved. Movement of the upper part of the box is resisted, and the force of this resistance is measured by a proving ring. Stress on the clay between the two halves of the box increases until ultimately the stress equals the peak strength, and the clay fails.

After failure the steady movement of the lower part of the clay is continued, but the resistance between the two parts of the clay is less and the remaining stress measures residual strength.

In practice, the clay sample is kept at equilibrium moisture content and movement is sufficiently slow to allow dissipation of excess pore pressure. In this way effective stresses are measured.

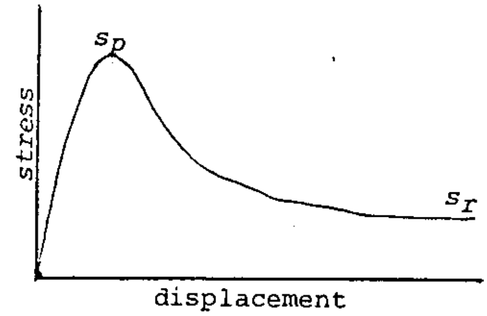


Figure 2. *Results of a shear box test; stress plotted against displacement*

Other test apparatus

Effective stress parameters can also be obtained from tests using triaxial or ring shear apparatus. The triaxial machine holds a cylindrical sample to which hydrostatic pressure (*p*) is applied. The ends of the cylinder are then loaded until failure occurs. The ring shear apparatus operates on an annular sample which is rotated slowly, and sheared under normal load (*p*). Using this apparatus a sample can be sheared indefinitely, allowing complete orientation of particles.

Cohesion and internal friction

When a series of tests have been completed, using several different normal loads, the values for *s* may be plotted against those for *p*; c' and ϕ' can then be determined.

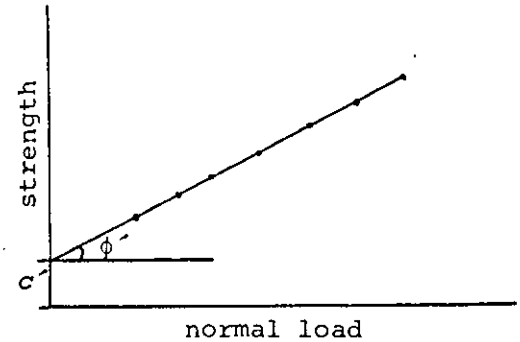


Figure 3. *Graphical determination of c' and ϕ'*

POST-PEAK STRENGTH

The importance of residual strength has been highlighted by Skempton (1964), for previously tests were often stopped once peak strength had been reached. It is now recognised that clays often fail progressively and the whole section will not reach peak strength at one time.

In long term situations strength will gradually be reduced by factors such as mechanical and chemical weathering, localised stress concentrations and fluctuations in pore pressure.

PLANES OF WEAKNESS IN OVER-CONSOLIDATED CLAYS

Clays of Tertiary age which have been consolidated under great thicknesses of overburden have reached their equilibrium water content under these loads. Most of this consolidation is due to water loss, but some is reversible due to the elastic properties of the clay. A rebound thus occurs during unloading and is greatest in the case of highly plastic clays (Bjerrum, 1967).

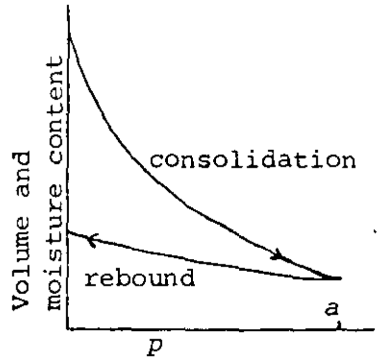


Figure 4. *Changes in volume and moisture content in an over-consolidated clay*

As the overburden is eroded, weakly bonded clays rebound. As vertical strain energy is released there is a corresponding increase in water content; often there is uneven swelling and stresses are released through localised failures. Horizontal strain energy can be released by valley erosion or cuttings and gives rise to lateral expansion and further possibility of failures. The failures show as joints and small fissures in the clay.

Towards the surface, clays are further weakened by uneven mechanical and chemical weathering. In the case of clays which were strongly bonded as a result of diagenesis, the bonds will tend to break down.

PROGRESSIVE FAILURE

Over-consolidated clays are generally sensitive, *i.e.* there is a considerable drop in their strength once they have failed.

Plastic over-consolidated clays are generally fissured and contain planes, or micro-shears where the clays have already been stressed beyond their peak strength.

Fissures allow the passage of water, causing softening of the clays.

Stresses in a hillside or cutting become concentrated in existing weaknesses, especially near the base of the slope. Once there has been localised failure, greater stress is passed to adjacent material, which in turn may fail. This process continues until there is insufficient resistance to shear forces and the slope fails.

Immediately preceding failure, different parts of the failure plane will be at pre-peak, peak and post-peak conditions.

The time taken for progressive failure will vary enormously with factors of composition and environment. As an example three cuttings in weathered

London Clay failed after 19, 29 and 49 years respectively (Skempton, 1964).

A gently sloping hillside may take hundreds of years to fail progressively.

Stages of shearing

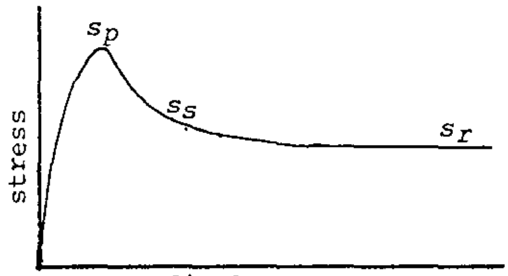


Figure 5. *Changes in shear strength with displacement*

Strength reduction in over-consolidated clays during displacement is caused by the following processes:

(1) Breaking of cementation bonds.
(2) Dilation due to over-riding of particles, causing an increase in moisture content.
(3) Reorientation and aligning of particles.

Shearing can be reduced to the following stages:

(1) Peak strength is reached after minimal displacement when shear stress reaches the maximum the clay can withstand.
(2) The fully softened condition occurs when the clay is sheared beyond peak strength, and there is small displacement. Cementation bonds have been broken, and dilation has caused an increase in moisture content so that c' tends to zero. There is some particle alignment and therefore a lowering of the ϕ value.
(3) Residual strength is lower than softened strength and can only occur after considerable displacement has caused complete alignment of particles.

Where fully softened strength is reached there are minor disconnected surfaces called Riedel shears, but not a continuous, polished shear plane. This state can theoretically be equated with the peak strength of normally consolidated, or remoulded clay. For practical testing this may be said to occur when the critical state of volume is reached. By definition, critical state means that in drained conditions any further displacement will not cause changes in moisture content (Roscoe *et al.*, 1958; Skempton, 1970).

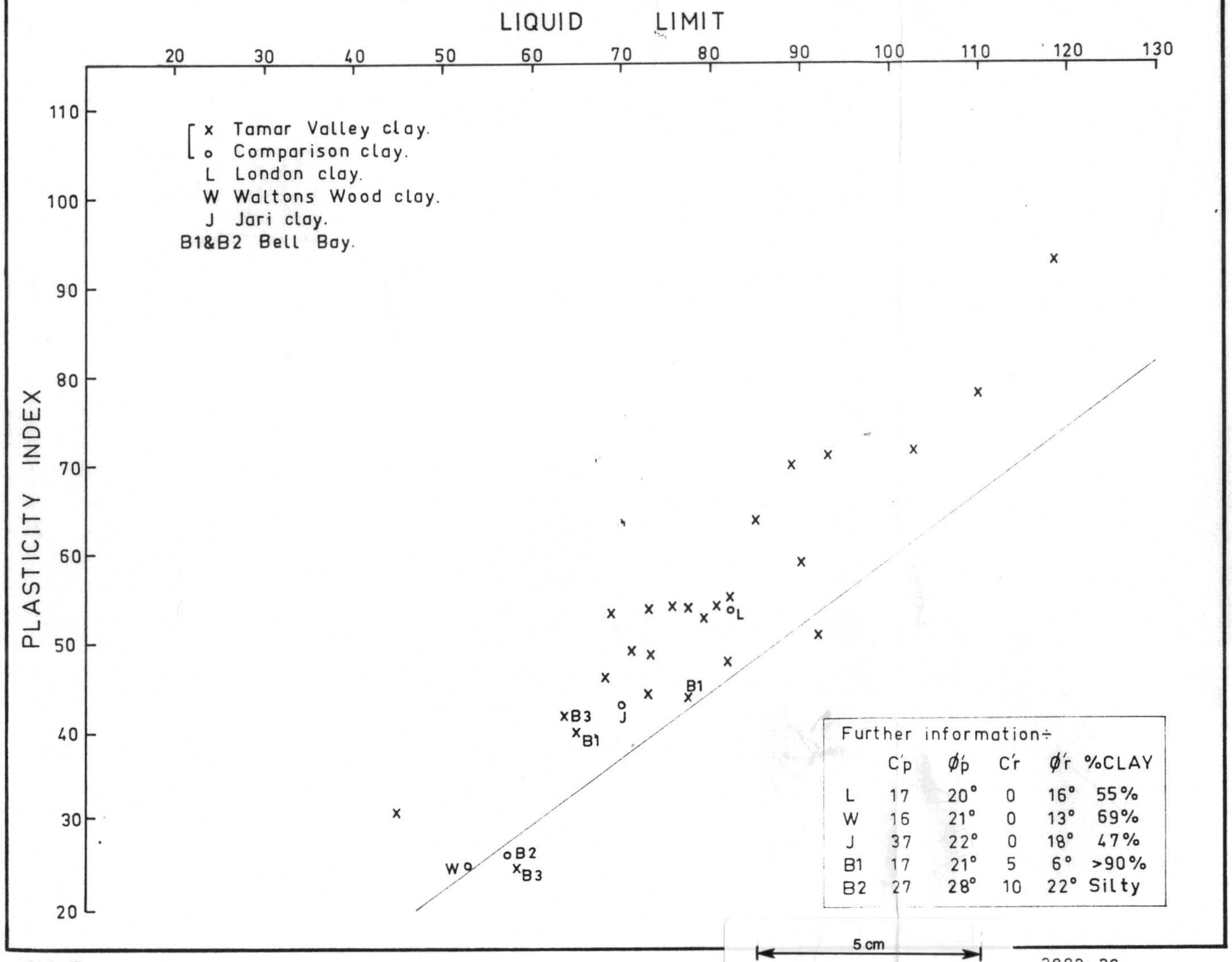
STRENGTH PARAMETERS AND NATURAL SLOPES

There is considerable evidence from slope stability analysis that natural slopes fail at some strength between the s_p and s_r values. Skempton (1964) defines a residual factor R

$$R = \frac{s_p - s}{s_p - s_r}$$

Where s = strength at failure
If $s = s_r$ at failure then $R = 1$

PLOT OF ATTERBERG LIMITS, GENERAL.



Further information÷

	C'p	Ø'p	C'r	Ø'r	%CLAY
L	17	20°	0	16°	55%
W	16	21°	0	13°	69%
J	37	22°	0	18°	47%
B1	17	21°	5	6°	>90%
B2	27	28°	10	22°	Silty

FIG 7.

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Later work by the same author (1970) considers the ultimate stability of an unfailed slope to be controlled by s_s and not s_r.

No method has been devised to calculate the stage of softening of slope has reached, or the rate at which progressive failure develops. Therefore an analysis based on s_s may be conservative.

Once a slope has failed the parameter for analysis of further slipping would be s_r.

Testing techniques

There are a variety of different testing techniques for determining different strength parameters, with differing significance in nature. Only effective stress parameters are considered.

Strength parameter	*Test apparatus*
Peak undisturbed	Shearbox or triaxial test
Peak remoulded	Shearbox or triaxial test
Residual undisturbed	Shear box
Residual remoulded	Shear box
Ultimate residual	Ring shear

For the analysis of unfailed slopes in non-plastic soils peak strength soil parameters can be used with caution.

For analysis of unfailed slopes in over-consolidated plastic clays the long term stability is controlled by s_s, the values of which can be taken from tests on either remoulded or undisturbed samples, when the critical state has been reached.

For analysis of failure on existing slip planes s_r values should be used. These can be obtained from several reversals of the shear box. However there is evidence that a shear box will never allow a full slip plane to develop and that full reorientation of particles can only occur after 1.5 to 2.5 m of movement. This ultimate s_r value can only be measured by using a ring shear apparatus (Bishop *et al*, 1971); the ϕ_r values obtained by the use of this method are extremely low.

Tamar Valley clays

The Launceston Beds are over-consolidated sediments and many of the clays are highly plastic and fissured. Figure 7 is a Casagrande diagram in which random samples of Tamar clay are compared for plasticity with other clays which have been investigated in the literature of progressive failure.

In some cases the sediments in an area are easily separable into plastic clays, low plasticity clays and possibly, sands. This situation occurs in a landslide area near St Leonards where the succession is:

Blue grey plastic clay with fissures and oxidation patches.
Red-brown sandy clay, 10 m.
Blue grey, plastic, stiff fissured clay.

The lower and upper grey clays have similar properties.

LL = 92-110   PI = 68-88   % clay = 65-75

The properties of the red-brown clay are:

LL = 85-95 PI = 65-75 % clay = 42-58

s_S taken from remoulded samples:

Blue grey clay c'_S = 0 kPa ϕ'_S = 15°
Red brown clay c'_S = 8 kPa ϕ'_S = 22.50°

However, to take s_S values for the brown clay would be too conservative.

Where highly plastic clays are present on a hill slope it is likely to suffer progressive failure so that regardless of c'_S and ϕ'_S values the plastic clays must be treated with the greatest caution.

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