SOIL STRENGTH AND MICROCLIMATE IN THE DISTRIBUTION OF SHALLOW LANDSLIDES

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ABSTRACT

During the winter of 1977 the Wairarapa hill country experienced a prolonged period of wet conditions which resulted in an episode of widespread and severe landslide erosion. The areal distribution of the landslides has previously been shown to be closely related to hillslope aspect. In this work regolith strength is shown to be low and correlated with aspect. When the soils are saturated, the liquid limit water content of the sunny aspect subsoils is exceeded while that of the shady aspect subsoils is not.

INTRODUCTION

During the winter of 1977 the hill country and plains of the Wairarapa experienced an unusually prolonged period of wet conditions. Between June and September a series of cold fronts brought over 700 mm of rain, approximately 150 percent of the normal rainfall for this period. The monthly rainfall departure was distributed unevenly, the highest monthly departure being recorded for September (325%) near the western edge of the hill country. A consequence of this prolonged wet period was an episode of widespread and severe slope failure in the hill country east of the plains.

The distribution of slope failure with respect to vegetation, hillslope profile, aspect, lithology and slope angle have been previously described (Crozier *et al.*, 1980). The major conclusions of that work are summarised as follows.

(1) Slope failures were shallow and essentially involved failure of the regolith only. (Mean depth of movement for over 100 slope failures in one drainage basin was 0.64 m.)

(2) Failures occurred on slopes ranging from the minimum limiting angle of 24° up to the steepest available slope of approximately 40°.

(3) The areal distribution of slope failure was strongly influenced by aspect. Based on the number of slips per hectare the sunny northerly aspects (north, northeast and northwest octants) were much more susceptible to failure than were the shady southerly aspects (south, southeast and southwest octants).

(4) Failures were more common on the upper third of the slope than on the middle or lower thirds.

(5) The areal distribution of slope failure could not be accounted for in terms of variability of rainfall distribution, slope angle, slope hydrology, bedrock lithology or vegetation cover.

(6) The areal distribution of slope failure was best accounted for by the distribution of undisturbed regolith prior to 1977.

Observation of slope failures occurring during 1977 indicate that the failure process operating during this episode involved an initial failure of the regolith followed by a subsequent failure of the restraining turf mat (Hawley and King, pers. comm. 1978; Hunter, pers. comm. 1978). In making this observation Hawley and King noted that the regolith was 'saturated' and behaved as 'fluid'. The sequence of failure is also indicated by the presence of incipient failures consisting of an ovate form having an unruptured turf bulge at the toe and a number of crescentic tension cracks at the head.

These observations suggest a failure mechanism similar to the model put forward by Crozier (1969) for shallow landslides in Otago. Essentially the model provides for an *in situ* failure of regolith as a result of fluidisation beneath a restraining turf mat, followed by subsurface movement of fluid regolith, the development of a down-slope bulge and subsequent rupture of the turf mat at the bulging toe. This paper aims to test certain requirements of this model by examining the relationship between the strength of the turf mat and of the underlying regolith at different water contents. The areal distribution of such properties will also be used in an attempt to explain the aspect preference of slope failures occurring in Wairarapa during 1977. The tests were carried out within the Pakaraka Experimental Catchment located in one of the most severely affected parts of the region near the western limits of the hill country.

ANALYSIS OF REGOLITH AND TURF MAT STRENGTH

Indices of regolith strength have been obtained using three independent methods:

1. (1) determination of the Atterberg limits
2. (2) field determination of penetration resistance using a Vicksburg penetrometer
3. (3) direct shear testing of drained regolith in a shearbox.

A measure of turf strength was obtained by penetrometer survey, as the nature of the material is incompatible with either laboratory shear testing or determination of the Atterberg limits.

Atterberg Limits

Liquid and plastic limit determinations were made on samples taken from the subsoils of slopes of opposing sunny and shady aspects at depths ranging from immediately below the turf mat (15–20 cm) to the contact between subsoil and bedrock (60–70 cm). Results from the analysis (Table 1) revealed an aspect-related difference in both liquid and plastic limits of approximately 5 percent. A listing of the Atterberg limits for a number of other New Zealand soils is provided in Table 2. By comparison, the Pakaraka soils have a low liquid limit (particularly on sunny aspects) and a low plastic limit. Both soils also have a low plasticity index, indicating that the range of water contents over which they are plastic is quite small. The data indicate that, when remoulded, the Pakaraka soils lose strength rapidly with rising water content and that loss of strength is particularly rapid once the soil is above its plastic limit; this behaviour is more pronounced in soil from the sunny aspects.

TABLE 1—Mean Atterberg limits[1] of the Pakaraka subsoils.

Aspect	Liquid limit	Plastic index	Plasticity index	Activity	% clay <2 μm	Sample size
Sunny	34.5	20.3	14.2	0.46	31	24
Shady	40.3	25.8	14.3	0.42	34	24

[1] Differences in the mean Atterberg limits are statistically significant in a one-tailed unpaired t — test with P = 0.01.

TABLE 2—Atterberg limits[1] of a selection[2] of N.Z. soils.

Soil	Parent Material	Slope	LL%	P.L.	P.I. %	Activity	Clay %
Arapohue clay	Limestone	12°	114	40	74	1.28	58
Judgeford silt loam	Loess/greywacke	5°	53	27	26	0.96	27
Belmont silt loam	Loess/greywacke	8°	48	30	18	0.82	22
Mangaweka silt loam	Upper Tertiary siltstone	11°	41	23	18	0.95	19
Paremata silt loam	Greywacke	9°	65	20	45	0.96	47
Porirua fine sandy loam	Windborne drift/greywacke solifluction debris	12°	46	20	26	1.0	26
Puhoi clay loam	Waitemata sandstone	12°	90	38	52	1.13	46
Taita clay loam	Greywacke	16°	95	38	57	0.98	58
Te kie stoney silt loam	Shattered dolerite	30–34°	75	44	31	1.19	27
Whangapiro clay	Waitemata sandstone	12–14°	125	48	77	1.22	63

[1] The tabulated limits are those of subsoil horizons from the 20–70 cm depth range.

[2] The data was obtained from NZ Soil Bureau (1968) and is limited to profiles and from sites where the slope was 5° or above and there were no site factors that differed extremely from the site factors at Pakaraka (e.g. soils with a strong volcanic influence are excluded).

Penetrometer surveys

Penetrometer surveys to determine variation of penetration resistance of the regolith were carried out in the autumn, winter and spring of 1979. This range of seasons provides a considerable range of moisture contents for both turf mat and subsoil. The general pattern of variation is illustrated in Figs 1–3.

TABLE 3—Turf mat penetration resistance (kg/cm^2)[1]

Slope profile position	Sunny aspect		Shady aspect	
	kg/cm^2	% water	kg/cm^2	% water
Upper	28.81	29.4	24.67	35.3
Mid	26.43	38.5	22.37	42.3
Lower	18.90	46.3	14.55	54.1

[1] The table values of penetration resistance are the means of 4 to 5 values, each of which is the mean of 20 penetration tests. Water contents are means of the values associated with each testing site.

The variation of turf mat penetration resistance both between aspects and among slope profile positions (Table 3) appears to be a function of water content. Figure 4 demonstrates that virtually all of the variation in turf mat penetration resistance can be explained by variation of the water content of the turf mat. Because water content differences between sunny and shady slopes are most pronounced near the surface, the relationship of turf mat resistance to that of the underlying regolith varies with aspect. On sunny slopes the turf mat is generally the most resistant part of the regolith. This relationship was not apparent on shady slopes, there being little difference in the penetration resistance of the turf mat and the subsoil immediately below it.

The weakest part of the regolith profile on both sunny and shady aspects is a narrow regolith-bedrock transition zone. On shady slopes the resistance of this zone may be a function of a higher water content at this depth but this does not appear to be the case on sunny slopes.

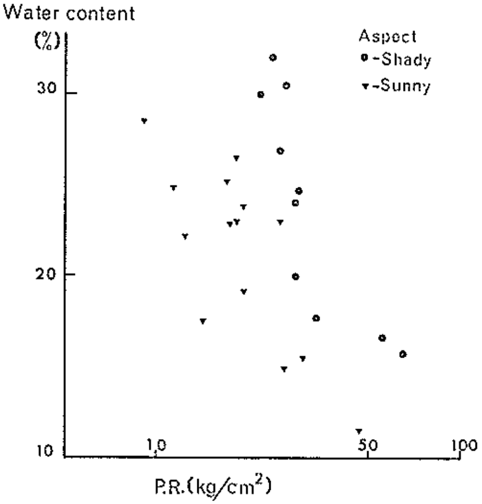

FIG. 1—Penetration resistance of the subsoil (depth 20–50 cm).

The most significant feature of the distribution of penetration resistance is that the subsoil of the shady aspect offers greater resistance than that of the sunny aspect despite its substantially higher water content.

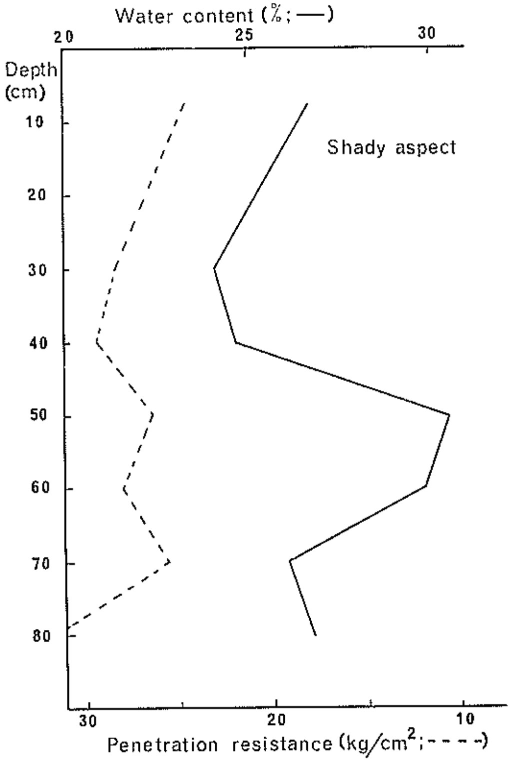

FIG. 2—The relationship of penetration resistance to water content and depth; Shady aspect.

Direct Shear testing

To obtain an indication of the undisturbed shear strength of the subsoil a series of direct shear tests on drained regolith was carried out. Samples were tested within a range of normal loads equivalent to those experienced in the field. Moisture contents of the samples varied over the range experienced during winter conditions (15–30 percent approximately). The lowest available strain rate (4.88 x 10^{4-} mm/min) was used to ensure dissipation of pore pressure and the determination of effective strength parameters. The results indicate the importance of water content in controlling the strength of the soil; correlation of log soil strength (s) with water content gave r=−0.75 and −0.90 for sunny and shady slopes respectively (Figure 5). The removal of the effect of variation of normal load (σ) in the analysis by correlating the ratio log s/σ with water content increased the values of r to —0.92 in both cases (Figure 6).

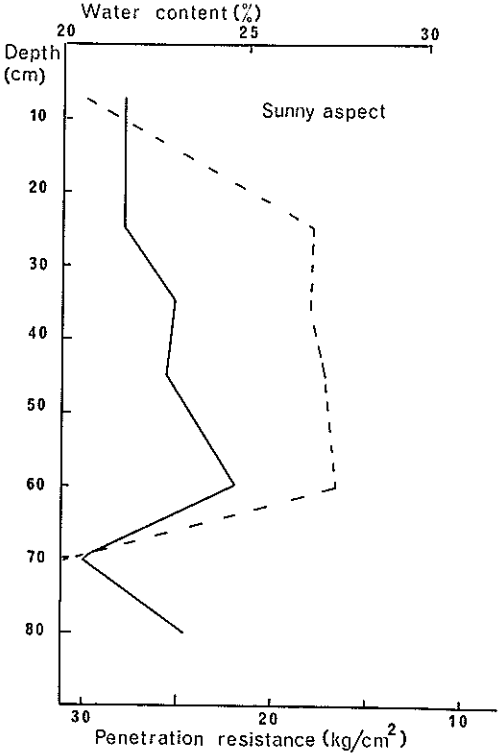

FIG. 3—The relationship of penetration resistance to water content and depth; Sunny aspect.

As was indicated by the Atterberg limits, these tests also show that the soils of the sunny aspect lose strength more readily with rising water content than do the soils of the shady aspect. The very low strain rate used in these tests allows the loss of strength at high water content to be attributed to reduction in the value of the strength parameters, cohesion and/or internal friction rather than the accumulation of excess pore pressure.

DISCUSSION

Three independent methods have shown that the strength of the undisturbed regolith of the Pakaraka basin differs with slope aspect. At normal winter moisture content the soils of the shady slopes are a little stronger than those of the sunny slopes, and at higher moisture contents this difference is accentuated. Figure 7 illustrates this point in a simplified form and shows the water content/soil strength relationships of the Pakaraka catchment for a normal winter (a) and for the conditions assumed to have existed during the winter of 1977 (b).

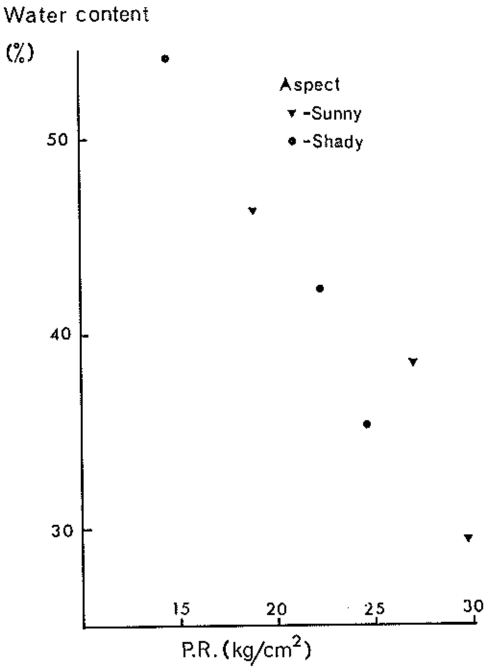

FIG. 4—Turf mat penetration resistance.

The 1977 climatic conditions were unusual in that prolonged rainfall and low evapotranspiration conditions allowed the normally drier sunny slopes to achieve a moisture content close to that of the shady slopes. The coincidence, on sunny slopes, of a high incidence of failure and low strength indicates that difference in regolith strength may be an important factor in accounting for the aspect preference of slope failure.

As observations suggested that the soil became fluid before the turf mat ruptured, the question arises as to whether water held in the soil was of sufficient quantity to reach or exceed the liquid limit. If reports of saturation being achieved are correct then a measure of porosity would provide the quantity of water held at saturation. The variation with depth of the bulk densities (from which porosities have been calculated) of the Pakaraka subsoils is illustrated in Figure 8. The soils which failed in the 1977 episode have bulk densities in the range 1.3–1.5 g/cm^3, and when saturated have a water content in the range

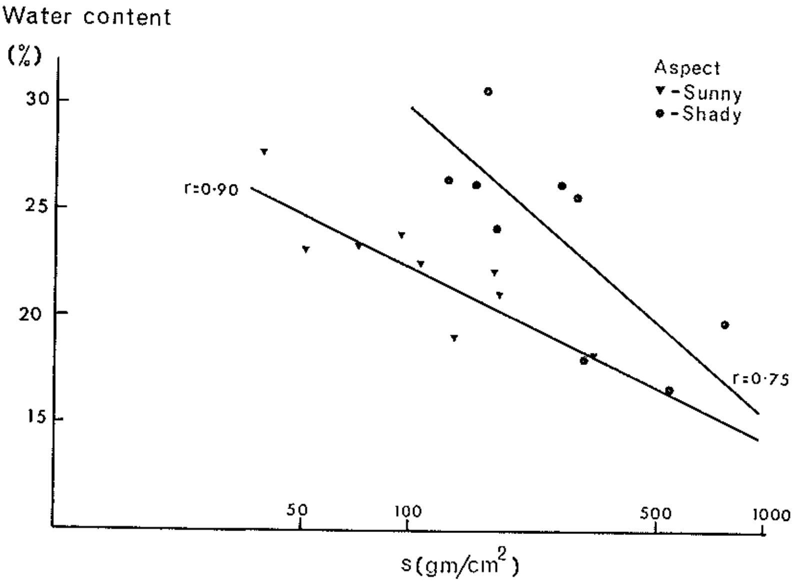

FIG. 5—Regolith shear strength, normal load and water content.

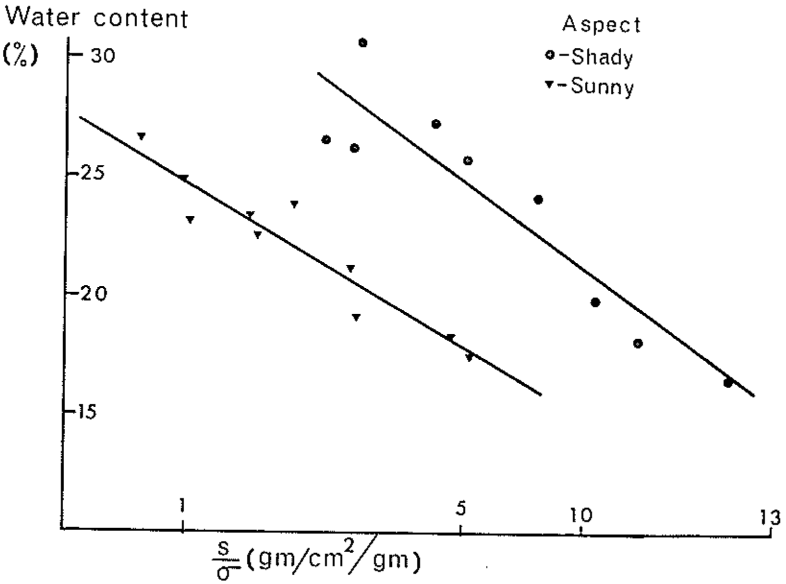

FIG. 6—Regolith shear strength, normal load and water content.

34%–38%. Thus when the soils are saturated the soils of the sunny aspect are at their mean liquid limit water content (34.5%) while the soils of the shady aspect are below their mean liquid limit water content. This implies that, at least on the slopes which experienced the highest incidence of failure, there would have been a sufficient water content at saturation to have produced a fluid state.

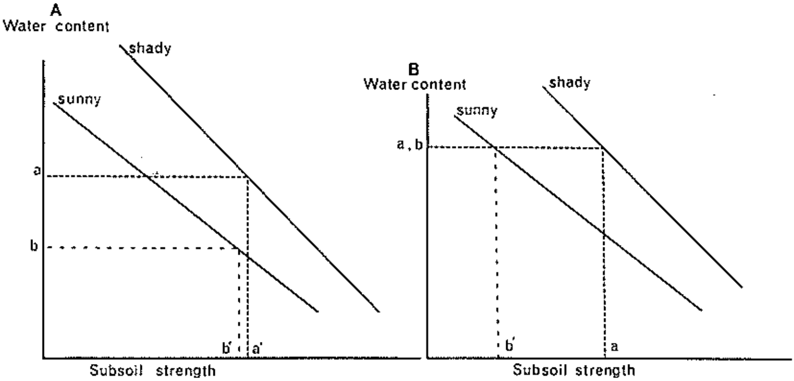

FIG. 7—Water content and soil strength relationships.
(A) Normal winter conditions
(B) 1977 winter conditions

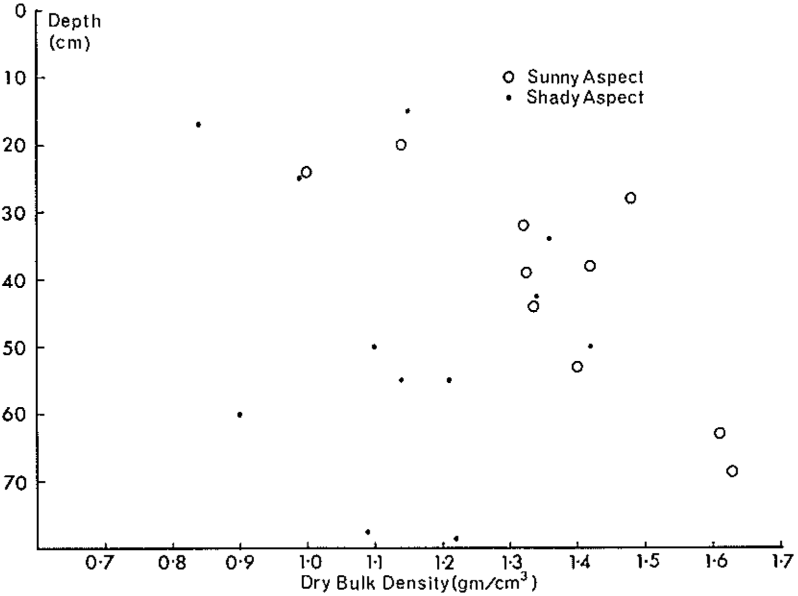

FIG. 8—Dry bulk density of the Pakaraka soils.

The results of this study therefore go some way in both explaining the aspect distribution of slope failure during 1977 and in supporting the model of slope failure put forward by Crozier (1969). The full implications of these findings to the stability of the slope remain to be tested by equilibrium stability analysis for individual cases of 'slope' failure.

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