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Distribution of landslips in the Wairarapa hill country

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Abstract Data gathered from airphoto and field surveys are statistically analysed to establish the distribution of landslips which occurred in the Wairarapa area, North Island, New Zealand, during the winter of 1977. The pattern of landslip occurrence is closely related to slope aspect and position on the hillslope. Slipping was concentrated on the upper parts of northerly facing slopes. The preference for northerly aspects is evident in each of the distributions of slips drawn separately from the upper, middle, and lower parts of the hillslopes. The 1350 km^2 area studied yielded a mean density of 0.98 slips/ha. For 1 catchment field measurements of 4.78 slips/ha and a surface lowering of 69 mm were recorded. In comparison with other recorded events the degree of erosion experienced was severe.

Slope angle, slope hydrology, and rainfall distribution appear to have little influence on the distribution of landslips. However, much of the hillslope regolith had been affected by mass movement in the past and it was found that the amount of "undisturbed" regolith remaining prior to the landslip episode showed a positive correlation with the occurrence of mass movement during the event. It is concluded that the mantle of undisturbed regolith is less stable (particularly along its downslope edge) than slope material which has been subject to previous slipping. In the past, landslipping has been more effective on shady slopes and in this respect the distribution of landslips during the 1977 event (predominantely on sunny slopes) is a result of the unusual climatic conditions which prevailed and the distribution of slope material produced by previous events.

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Keywords Wairarapa; mass movement; distribution; slope aspect; slope stability; soil erosion

INTRODUCTION

During a period of 7 weeks from the end of July 1977, much of southern Hawke's Bay and Wairarapa experienced mass movement and flooding of sufficient severity for the region to be declared a disaster area. The mass movement occurred in at least 5 discrete episodes (Hawley & King 1978) involving mainly debris flows, mudflows, and a lesser number of debris slides (following nomenclature of Varnes 1958) (Fig. 1).

An early report on the storm damage (King & Blakemore 1977) drew attention to an apparent pattern in the distribution of landslips* in the Wairarapa hill country. The initial aim of this paper is to investigate this pattern by analysing the distribution of slips throughout the region using airphotos and statistical techniques. In addition, the results of a field survey are used as a check on this distribution of slips and to provide a measure of severity of mass movement. The locational pattern is then correlated with slope stability factors in an attempt to explain the occurrence of landslips throughout the region.

DATA COLLECTION

An area of 1350 km^2, east of Masterton, was selected for the regional study. This area included the majority of severely affected properties identified in the Wairarapa Catchment Board's initial survey of storm damage (King & Blakemore 1977), and was covered by aerial photography at a scale of 1:25 000, obtained by the Department of Lands and Survey late in 1977.

An airphoto mosaic was assembled on which a random sample of 101 points was established. Circular areas representing 0.25 km^2 of land surface were centred on the sample points and analysed with the aid of a mirror stereoscope with a ×3 magnification lens.

Each sample area was divided into a number of "slope units" on the basis of slope aspect (the

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*The terms "landslip" and "slip" are used throughout to refer collectively to all types of rapid mass movement.

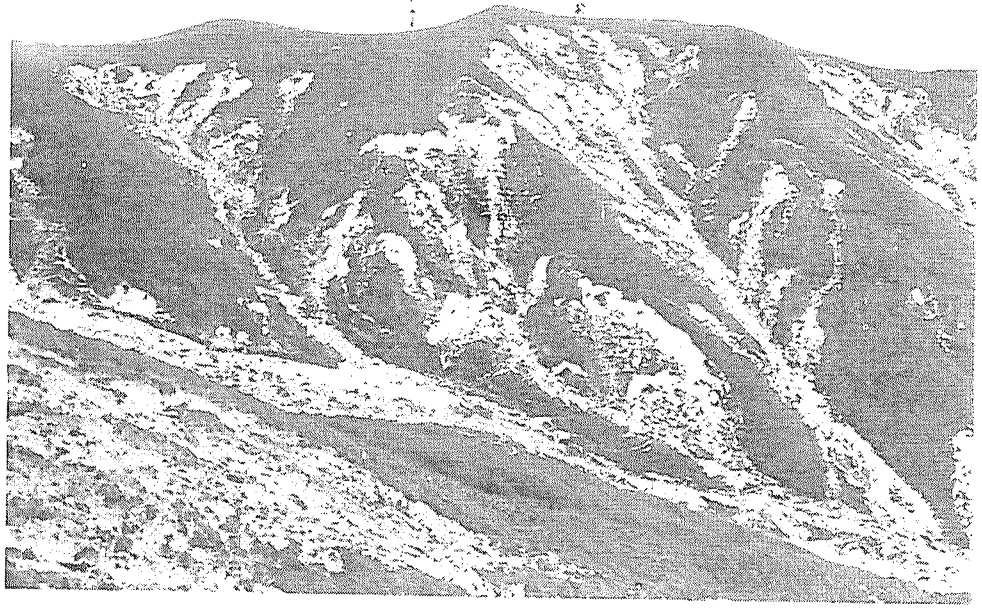

Fig. 1 Mudflows within silt-rich regolith, Wairarapa hill country, located NZMS N162/183572. Photo taken 10/11/77.

direction in which a slope is facing) and assigned to 1 of 8 aspect "octants" (N, NE, E, SE, S, SW, W, or NW) with respect to grid north.

Areas where the land surface inclination was insufficient for slope aspect to be determined (such as river flats and terrace surfaces) were excluded from subsequent calculations of slip density. The area of each slope unit was measured, and the number of landslips present, and the position of each on the slope (summit third, central third, or basal third), were recorded. At this stage the dominant vegetation cover associated with each slip was also recorded.

Reliability of landslip counts* was checked through field identification of slips in 12 of the circular sample areas. The regression equation: $F = 4.72 + 0.54P$, with $r = +0.95$ and $S_{F.P.} = 11.21$, where F = number of slips identified in the field, P = number counted through the stereoscope, r = product moment correlation coefficient, and $S_{F.P.}$ = the standard error of F on P, showed that, when slip frequency was high, the airphoto counts approached twice the field counts.

Errors were apparent in both aerial photograph and field analysis. In a few instances field checking indicated that some farm dams and gateways had been incorrectly recorded as landslips, but in a total sample number of more than 2000 landslips this was regarded as insignificant. Field checking was not undertaken until December 1978, and while most slip faces were still clearly visible, in several sample areas pasture over-sowing or growth of thistles made identification difficult.

Common to both field and airphoto analysis was the basic problem of the definition of mass movement features. This had 3 components: (1) how much displacement of material was required before a tension crack across a slope was defined as a landslip; (2) how was renewed or partial movement on a large earthflow to be represented; and (3) how were merging slip crowns on severely affected hillsides to be represented?

In the field, a landslip was recorded where a tension crack indicated downslope displacement in excess of 1 m or if compression rolls were evident downslope of a zone of tension cracks. The same rule was followed in the airphoto analysis. Discrepancies between photograph counts and field counts occurred where, for example, a large active earthflow could be identified in the field as 1 movement because of the ease of identifying displacement beneath the vegetation cover. However, displacement could only be identified from the air photographs where a break in the vegetative cover was apparent; this may occur in different parts of the earthflow and lead to the counting of several landslips.

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*Statistical data and procedures can be obtained from the authors.

In other cases, by the time the field checking was carried out, debris tracks had been masked by revegetation. As the photographic coverage was obtained soon after the erosion events had occurred, the separate debris tracks were discernible through the stereoscope, aiding landslip identification on severely affected hillsides.

It was decided that for statistical analysis, unaltered data obtained from the airphotos would be used in the regional survey because the photographs were taken immediately after the slipping, they were at a constant scale, and the data were extracted by the one operator—"internal" homogeneity and comparability of data could reasonably be assumed. A decision was also made to extract only numbers of slips and their frequency per unit area from the airphotos as other measures of erosion severity would introduce additional uncertainties of measurement into the data.

For the regional survey, mean slope was calculated for each circular sample area using the standard contour intersection method of Wentworth (1930). This was applied to pre-publication prints of the NZMS 270 topographic map series which are at a scale of 1:25 000 and have a contour interval of 20 m.

In the field survey, slope angle for each landslip was taken as the mean of Abney level sightings made along the line of maximum slope on both flanks of the erosional scar. The volume of each slip was calculated from the dimensions of the erosional scar measured by tape along the length and at right angles to the axis of movement. The angle of the newly exposed slope was obtained by Abney level sighting along the axis of the surface of rupture.

Information available on the distribution of soil types was of insufficient detail to be included in the survey. However, a number of unpublished studies provided a basis for assessing the influence of various rock types on the occurrence of landslips. Geological boundaries were transferred onto the 1:25 000 topographic maps from MSc theses (Bunopas 1966; Eade 1963; Holgate 1972; McGill 1956; Senior 1966; Vella 1949). These represent the only geological mapping of a suitable scale that has been carried out for this part of Wairarapa and provided information for 72 of the sample unit areas. Each area was classified as 1 of 5 general lithological groups: Mesozoic sandstone, Tertiary mudstone, Tertiary limestone, alternating Tertiary sediments (mudstone, siltstone, sandstone, and conglomerate), and Quaternary gravels.

RESULTS

Aspect and position on slope

Airphoto interpretation indicated that the area of land surface in the region shows only minor variation amongst the slope aspect classes (Table 1). In contrast, the preferential location of slips with respect to aspect is clearly demonstrated by the number of slips per hectare listed in Table 1. The values for "expected number of slips" shown in this table provide the distribution required for the Chi Square test and are determined by assuming that the number of slips in any class will be proportional to the area of land surface.

The dearth of mass movement in S, SE, and SW aspect octants (9.8% of slips on 33.5% of the area), and the concentration of mass movements in N, NE, and NW octants (61.6% of slips on 35.5% of the area) evident in Table 1 is confirmed by the extremely high Chi Square value of 951. The probability of the observed distribution of landslips occurring by chance is negligible, and therefore the number of slips and the derived density function of slips per hectare is related to slope aspect.

Table 1 Aspect preference for slip occurrence.

	Compass Octant								
	N	NE	NW	E	W	SE	SW	S	Total
Land area (ha)	242	259	301	395	305	253	285	220	2260
Area percent	10.7	11.5	13.3	17.5	13.5	11.2	12.6	9.7	100
Observed number of slips	547	404	407	426	206	97	75	44	2206
Slips percent	24.8	18.3	18.5	19.3	9.3	4.4	3.4	2.0	100
Slips per hectare	2.26	1.56	1.35	1.08	0.68	0.38	0.26	0.20	0.98
Expected Number of Slips	236	253	294	386	297	247	279	214	2206

degrees of freedom = 7, chi square = 950.8
critical value of chi square at $P_{.001}$ = 24.3

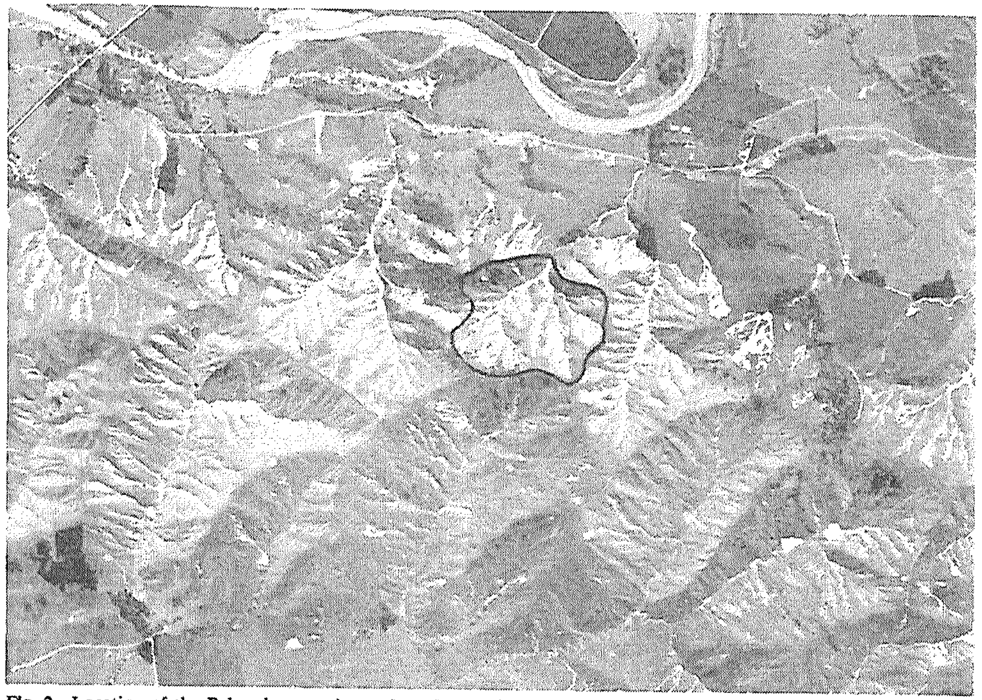

Fig. 2 Location of the Pakaraka experimental catchment (NZMS 1 N162/177574) and contrasting slip densities with aspect. *Photo: Lands and Survey, 10/10/77.*

A detailed field survey of the Pakaraka experimental catchment (Fig. 2) indicated that the pattern of local slipping was similar to that obtained by airphoto interpretation of the region as a whole. However, this catchment which was primarily established for microclimatic studies has a much greater density of slipping as it was intentionally located in the most severely affected part of the region and is exposed to the northwest. A total of 110 slips was measured in the field within a catchment area of 23 ha, yielding a density of 4.78 slips/ha—much higher than the regional mean of 0.98. Although northerly slopes (N, NW, NE octants) predominate in the catchment, the concentration of slips on them was disproportionately high (68% of total slips in catchment).

In addition to the marked relationship between landslip occurrence and slope aspect, there is an equally strong pattern in the location of slips on the slope profile. If the distribution of slip crowns was independent of hillslope position and other factors, one-third of the total number of slips would occur in each of the 3 profile segments (lower, middle and upper). However, of the 2206 landslips recorded in Table 1, the crowns of 1189 were located in upper slope positions, 681 in middle slope positions and only 336 in lower slope sites. This distribution shows a statistically significant preference for slips to occur on upper slopes. The possibility that debris from slips further upslope might obscure slip crowns in middle and lower slope positions appears unlikely as no examples were detected in field checks and the same preference of slip crowns for upper slope positions was apparent in the field counts for the Pakaraka experimental catchment.

A series of Chi Square tests applied to slip frequencies in each slope profile position and each slope aspect octant, with corrections for variations of land area with aspect, showed that landslips occurring on lower, middle, and upper slope positions all tended to prefer northerly octants. This indicates that northerly slopes were more susceptible to slipping on all parts of the slope profile than westerly, southerly, or easterly slopes. The distributions of landslips in each profile position were, however, significantly different from each other in minor respects, for example, lower profile slips showed a relatively high representation in the SE and SW octants.

Fig. 3 Valley floor aggradation by accumulation of mass movement debris, located N162/183572. Photo taken 10/11/77.

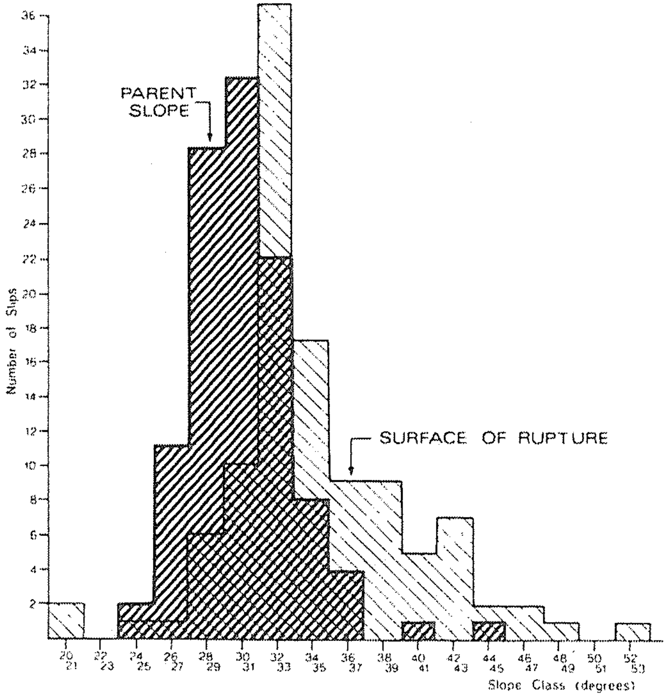

Fig. 4 A comparison of the hill-slope angle (parent slope) with the slope angle developed by landslipping (surface of rupture), Pakaraka catchment.

Table 2 Volume of material displaced and area eroded during periods of landslide activity.

Volume (m^3/ha)	Area Surveyed (ha)	Area eroded percent	Period	Locality	Source
1150	24 000	25	1970	Adelbert Rg. Papua N.G.	Pain and Bowler, 1973
100-800	2000-50	-	1966	Mangawhara Valley NZ	Selby, 1976
690	23	9.7	1977	Pakaraka Wairarapa NZ	This study
400	280	-	1973	Matahuru & Mangapiko NZ	Selby, 1976
337	112	5-12	1960-67	Bell Canyon California	Rice, Corbett & Bailey, 1969
125	550	< 10	Mid 1960s	Notown W.Coast NZ	O'Loughlin & Pearce, 1976
77	162	1	1971	Hawkes Bay NZ	Eyles, 1971
26	1 267	0.3	1976	Stokes Valley NZ	McConchie,1977

Table 3 Comparison of slip densities (number/km²) from New Zealand localities.

(1)	Pakaraka Wairarapa, 1977	478	(6)	Wellington City Dec.1976	16
(2)	Wairarapa, 1977 Regional mean	98	(7)	West Coast S I Waimaugan gravels 1973-75	11
(3)	Tangoio, Hawkes Bay May.1971	31	(8)	West Coast S I. Old Man gravels 1973-75	10
(4)	West Coast S I Sandstone, 1973-75	10	(9)	Stokes Valley Dec. 1976	6
(5)	Wellington City Winter, 1972	19			

Source:
1 and 2, this study
3, Eyles (1971)
4, 7, and 8, O'Loughlin & Pearce (1976)
5 and 6, Eyles et al. (1978)
9, McConchie (1977)

SEVERITY OF MASS MOVEMENT

With a density of 4.78 slips/ha the Pakaraka experimental catchment can be considered as being within the most severely affected part of the region. Consequently other measures of severity derived from the catchment can be interpreted as indicating maximum values for the region as a whole.

The catchment consists of moderately steep, pasture-covered hill country. The underlying Tertiary siltstone is covered by a silty regolith averaging less than 1 m in depth. Particle size analysis of 4 samples of undisturbed regolith yielded the following mean values: sand 3%, silt 63%, and clay 34%. The types of mass movement are similar to that for the region as a whole except that there are no deep-seated, seasonally moving earthflows which characterise the wetter and more clay-rich parts of the region.

The 110 slips measured within the catchment range in volume from 1.17 to 2205.8 m^3 and have a mean depth of 0.64 m. For 27% of the slips, in situ bedrock was exposed on the surface of rupture, and in most other cases the base of movement appeared to be close to the bedrock surface.

The effect of slipping was to remove the regolith from mainly the upper slopes and redistribute it by flowage on the lower slopes and valley floors (Fig. 3). This process has led to a steepening of the upper part of the slope profile (Fig. 4). The angle of limiting equilibrium for landslips appears to be approximately 24° for the conditions that prevailed during 1977.

The slip debris did not pass out of the catchment and most was superimposed on earlier mass movement deposits on the floors of the main valleys. In total, 15 874 m^3 of material were displaced from an area equivalent to 9.7% of the catchment. Expressed per unit area of the catchment as a whole, this represents a displacement of 690 m^3/ha or equivalent to a "surface lowering" value of 69 mm. Thus, in comparison with other recorded landslide episodes, the Wairarapa area experienced a high degree of erosion during the winter of 1977 in terms of both volume of material displaced (Table 2) and slip density (Table 3).

DISTRIBUTION OF LANDSLIPS AND SLOPE STABILITY FACTORS

The regional survey of the Wairarapa hill country showed that slope aspect provided a strong influence on the location of slips which occurred during the winter of 1977. The most unstable locations were the upper segments of slopes facing north. In most cases slips in this location were observed to be eroding the edge of a cap of "undisturbed" material which mantles ridge crests and hilltops throughout the region. A similar pattern of erosion has been observed in northern Hawke's Bay (Eyles 1971). Thus, under the conditions prevailing in 1977, some factor or factors conducive to slipping operated more effectively on the upper segments of northerly facing slopes than in other locations. The principal factors which might theoretically explain the distribution of slips are: rainfall distribution at the time of slipping, spatial variation in factors controlling slope hydrology, distribution of slope angle, and variation in resistance of slope material.

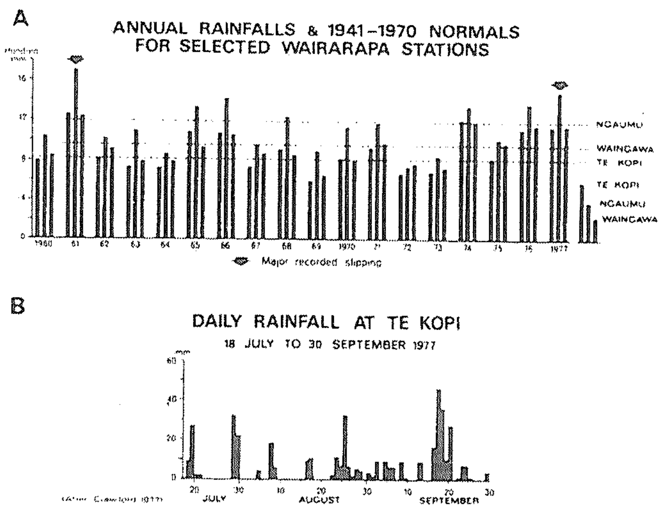

Fig. 5 A Annual rainfalls for 3 stations within the region affected by slips. **B** Daily rainfalls at Te Kopi for the period of mass movement—each of the 5 peaks was associated with the occurrence of slips.

Table 4 Slip location on slope profile comparison with other New Zealand localities.

		Per cent				Number
		Upper	Middle	Lower	Valley Axis	
1	Pakaraka Rd	48	28	21	3	109
2	Notown	58	46	23	-	127
3	Omoto	8	11	23	58	277
4	Stokes Valley 1976	-	-	-	60	78
5	South Auckland	46	36	18	-	120

Source:
1, this report
2 and 3, O'Loughlin & Gage (1975)
4, McConchie (1977)
5, Selby (1976)

Rainfall distribution

The year 1977 was preceded by 3 years of above-average rainfall (Fig.5A), and the summer of 1976/77 was also relatively wet. The period April–September 1977 was characterised by an unusually high number of rain days; daily amounts were not great (Fig.5B), but the cumulative rainfall total for the 6 months as recorded at Waingawa (Masterton) was estimated to have a return period of 50 years (King & Blakemore 1977). Repeatedly during the period June–September, depressions were lying off the east coast of the North Island with ridges of high pressure in the Tasman Sea and to the southeast of the country (Crawford 1977) giving rise to a predominance of moist, onshore southwest–southeast winds in Wairarapa, and an almost complete absence of drying winds from the northerly quarter. The months of June–September also experienced the lowest sunshine hours recorded at Waingawa since readings began in 1930 (Crawford 1977). Not only were cumulative rainfalls high, therefore, but evapotranspiration rates were exceptionally low, allowing a buildup of soil moisture values such that hill country soils remained close to field capacity throughout much of the winter and early spring of 1977. While slopes with a northerly aspect would have been wetter than in a normal season, there is no evidence to suggest that they were wetter than slopes with other aspects which were more stable in 1977.

Slope hydrology

It is not uncommon for landslides which have been triggered by wet weather to be preferentially located on parts of the slope where landform contributes to the convergence of subsurface and surface water (locations 3 and 4, Table 4). The distribution of landslips occurring in Wairarapa in 1977, however, favours the upper slopes; areas least likely to experience concentration of water. The upper-slope position is not only close to the drainage divide, and therefore has a smaller catchment area than other parts of the slope, but its morphology generally promotes rectilinear or divergent flow. As landslips are therefore concentrated in the hydrologically least susceptible sites this factor is unlikely to account for landslip location.

Slope angle

The relationship between landslip activity and slope angle is well established in the literature on both theoretical and empirical grounds. There is generally a well defined threshold (limiting) angle below which landslips will not occur under a given set of hydrological and inherent slope conditions; for example, the limiting angle in the Pakaraka catchment was approximately 24° for the 1977 episodes. In addition, the incidence of slipping in any one area will increase with slope angle. This tendency was illustrated in Wellington in 1974 (Eyles et al. 1978) and can be attributed to the fact that given a random distribution of slope material with varying resistance to movement, more material will be close to its critical angle of stability on steeper slopes than on gentler slopes.

The obvious question in Wairarapa, then, is whether the preferred slip location had steeper slopes than the less preferred. As an example, the following mean slope angles were obtained from 105 locations in the Pakaraka catchment using an Abney level : upper third slope segment 30.9°, middle third 31.0°, upper third position on slopes with N, NE or NW aspect 30.6°, upper third position on slopes with other aspects 31.3°. Students *t* tests among pairs of mean slope angles showed no significant differences; thus, even on the most preferred upper slope position, the slope angle of the northerly aspects is not significantly different from that of other aspects. Thus, slope angle cannot be used to explain the spatial distribution of landslip occurrence.

Slope material

In terms of resistance-related properties, slope material can be divided into 3 broad components: bedrock, regolith, and biomass cover (including root zone). As the 1977 landslips consisted almost entirely of regolith and biomass, the strength of the bedrock had little direct significance to the resistance mobilised within the unstable regolith. Theoretically, the importance of bedrock properties in such circumstances is provided indirectly through their influence on slope angle, permeability, and residual properties imparted to the regolith cover.

The geological and soil maps which are available for the region were found to be at too small a scale to be correlated reliably with the pattern of landslip occurrence. However, the broad pattern indicates that there were fewer slips per unit area on alluvium, limestone, and Mesozoic sandstone than on the less permeable formations of mudstone and alternating sedimentary rocks (Table 5). The characteristic slope angle developed on these geological formations could not account for the difference in the incidence of landslips, except in the areas of gently sloping alluvium.

As nearly 90% of the area under study is covered in pasture and contains 99% of the slips the distribution of forest and scrub cannot be invoked to account for the pattern of slipping for most of the region. However, those areas covered in forest and scrub showed fewer slips than expected on the basis of area occupied.

With the elimination of other possible factors in the explanation of the preferential location of slipping, attention becomes focussed on variations in the resistance of slope material under pasture.

It was assumed that if there was a major difference in strength conditions on north and south aspects it would be reflected in the penetration resistance of the regolith. A north and a south facing slope in the Pakaraka experimental catchment were chosen for testing with a Vicksburg penetrometer. The tests were carried out on 17 May 1979, following the procedure outlined by Strahler & Koons (1960), and measured the combined influence of grass roots, soil material, and soil moisture on penetration resistance. No attempt was made to isolate the individual contribution of these 3 factors as it was the resultant resistance, obtained in the field under winter conditions, which was of interest.

The 45 readings taken in the uppermost 10 cm of the soil indicated a small but significant difference between aspects in penetration resistance of undisturbed regolith. The mean value for the north aspect was 1677 kN/m² and for the south 1422 kN/m²—the difference is significant at the 0.1% level. The least resistance offered at depth within the regolith was encountered in a zone extending for about 10 cm above the bedrock surface. It was this zone, located at a depth of between 50–60 cm, which provided the greatest difference in penetration resistance between aspects—1216 kN/m² on the north aspect, and 628 kN/m² on the south aspect. Soil samples taken in this zone yielded a water content of 22% for the north aspect and 30% for the south aspect. These differences suggest that at least under the conditions prevailing at the time of the test and possibly under normal climatic conditions (which favour higher moisture contents on southerly slopes), the base of the undisturbed regolith on south facing slopes is generally at lower strength than that on northerly slopes. However, the number of factors which influence regolith strength and the problems of obtaining soil shear strength values from penetration resistance point to the need for a more direct test of shear strength before the independent influence of regolith material can be determined.

Two further points emerged from the penetration resistance study: (1) the bedrock surface has about twice the strength of the regolith and, (2) on slopes which have been subject to extensive landslipping in the past, the regolith forms a much thinner cover than on undisturbed slopes. The latter observation indicates a net removal of material from the hillslopes as a result of slipping and associated slope processes.

Table 5 Lithology, average slope and slip number in the 101 unit areas.

Lithological Class	Number of Unit Areas	Number of Slips Mean	Number of Slips Standard Deviation	Average Slope Mean	Average Slope Standard Deviation
Alternating sedimentary	23	35.4	60.7	18.3	4.6
Mudstone	18	23.4	24.4	16.9	4.2
Limestone	8	0.3	0.5	12.4	4.0
Mesozoic sandstone	7	6.4	9.9	23.6	6.6
Quaternary alluvium	16	0	.	3.4	.
No recorded geology	29	27.2	23.0	14.8	4.0

Distribution of undisturbed regolith

An examination of airphotos taken before the winter of 1977 shows the pre-1977 slip topography to consist of 2 distinct types of microrelief: land surface which shows evidence of slipping, and land surface which shows no surface expression of slipping. The disturbed surfaces are generally located on the lower and mid slopes whereas the undisturbed surfaces commonly represent a capping on upper slopes and ridge crests. As noted previously most of the slips occurring in 1977 were located on the upper slopes and appeared to be eroding the edge of this undisturbed cap. The preferential location of slips might therefore be a function of the distribution of undisturbed regolith. The elimination of other possible causes would also imply that undisturbed regolith provided less resistance to the triggering climatic conditions of 1977 than previously disturbed surfaces.

A test was therefore carried out to see whether variation in the proportion of undisturbed surface within each aspect class prior to the slipping episodes could account for the variation in the frequency of slipping during 1977. The expectation was that an increase in the availability of undisturbed material would lead to an increase in the frequency of slipping.

Data were gathered in a manner similar to that which established the regional pattern of slipping. A 500 ha area, containing a wide range of slope aspects and slipping density and centred on the Pakaraka experimental catchment, was selected for airphoto analysis at a scale of 1:12 000. Thirty sample circles (5 ha in area) were randomly located, providing 123 individual slope units which were analysed to produce the data in Table 6.

Statistical analysis of the data indicates that, when all aspect classes are considered, the distribution of the amounts of undisturbed surface does not differ significantly from the distribution of total land area. Similarly, analysis of variance of the percentage of undisturbed surface amongst the 123 slope units indicates that there is too much internal variance

Table 6 Distribution of undisturbed land surface with aspect.

	W	S	SE	N	E	NW	NE	SW
Land area sampled (ha)	24.44	10.84	15.79	19.44	20.62	28.99	15.62	10.84
Area undisturbed (ha)	10.96	5.67	8.37	10.96	12.25	18.48	10.39	8.54
Area undisturbed as percent of land area	44.8	52.3	53	56.4	59.4	63.7	66.6	78.8
Number of slope units sampled	13	14	13	15	11	29	11	17

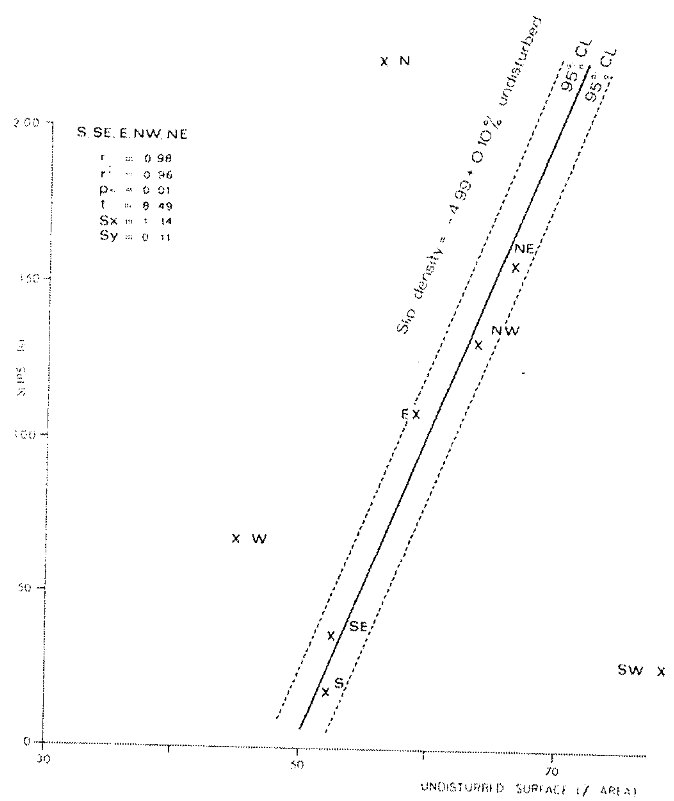

Fig. 6 Correlation between the density of slips and the amount of undisturbed regolith within slope aspect groups.

within each aspect class to make a statistically significant distinction among classes.

Correlation analysis indicates that for 7 of the 8 aspect classes (SW excluded) 31% of the variation in slip frequency can be explained by variation in the percentage of area which is undisturbed (r = 0.56, significant at the $P_{0.2}$ level). When north and west aspects are further excluded (Fig. 6) variation in slip frequency on the remaining 5 aspects can be almost totally explained by variation in the percentage of undisturbed surface (r = 0.98). This correlation covers a range of 1.36 slips/ha (62% of the range for all aspects) and a range of 14.3% of undisturbed surface (42% of the range for all aspects).

Compared to the regression of the 5 closely correlated aspect classes the north and west aspects have an unexpectedly high frequency of slips and the southwest aspect has a low frequency.

CONCLUSIONS

During the winter of 1977 the Wairarapa hill country experienced a high degree of mass movement erosion in terms of the volume of material displaced and number of landslips per unit area. The distribution of slips was strongly influenced by slope aspect. Based on the number of slips per hectare, the northerly aspects (N, NE, and NW octants) were much more susceptible to slope failure than the southerly aspects (S, SE, and SW octants). Slips were also more common on the upper third of the slope compared to the middle and lower parts of the hillslope. There was a concentration of slips on northerly slopes irrespective of whether slips occurred on the upper, middle, or lower thirds of the hillslope. The lower third of the hillslope had a greater proportion of its slips occurring on southerly slopes compared to the distribution of slips occurring in other parts of the hillslope. Thus, the most unstable locations during 1977 were the upper parts of hillslopes facing north.

The preferential location of slips which occurred in the Wairarapa area in 1977 cannot be accounted for by variations in rainfall distribution, slope angle, slope hydrology, bedrock lithology, or vegetation cover. There is some indication, however, that bedrock with high permeability and slopes covered with bush and scrub experienced a relatively low frequency of slipping.

The pattern of slipping in 1977 is best, but not completely, explained by the nature of the terrain which existed prior to the slipping episode. The proportion of undisturbed regolith on slopes within each aspect class appears to influence the frequency of slipping—the more undisturbed surface available the greater the number of slips per unit area. This relationship is particularly strong for 5 of the aspect classes where 96% of the variation in slip density is explained by variation in the proportion of undisturbed material.

With the elimination of the other possible causes from the explanation it is reasonable to conclude that undisturbed regolith is inherently less resistant to movement than the material constituting previously disturbed surfaces. At the periphery of the mantle of undisturbed material there is generally a minor scarp formed by tensional failure at the crown of previous slips. This, in effect, represents an unsupported "free" face which must also render the regolith immediately upslope less stable than similar material in other locations.

Another reason for the difference in resistance to movement of the 2 types of terrain is that the disturbed areas, apart from areas of accumulation on footslopes and valley floors, consist partly of exposed bedrock surface or surface where the bedrock is covered by only a thin layer of redistributed regolith. As the penetration resistance tests indicated, the bedrock surface is much stronger than the regolith. The reduction in regolith depth resulting from previous erosion allows vegetation roots to bind the soil close to the bedrock surface.

A further conclusion that can be drawn from the relationship between undisturbed surface and the 1977 slipping frequency is that the 1977 episodes were unusual in that slips favoured slopes which have experienced less mass movement in the past.

Although the distinction is not clear cut, sunny slopes (those with a north or west aspect) tend to have a more undisturbed surface than shady slopes (those with a south aspect). This observation suggests that climatic conditions on the shady slopes permit greater accumulation and longer retention of soil moisture levels conducive to slipping than on the sunny slopes. In fact, the penetrometer survey carried out in the winter following the slipping episodes, revealed that the weakest conditions sampled occurred at the bedrock/regolith interface on southerly slopes.

In summary it would appear that a period existed (perhaps under the original forest cover) which allowed the establishment of a stable regolith over much of the hill country. This was followed by a period of regolith instability (still in progress) in which mass movement processes, operating more effectively (perhaps more frequently) on the shady slopes, have stripped off much of the regolith cover, leaving a more extensive cover of undisturbed regolith on sunny slopes.

The unusual climatic conditions of 1977 were sufficient to saturate the undisturbed regolith to an unstable level on all slope aspects—northerly aspects apparently reach this condition much less frequently. The greater availability of weak, undisturbed regolith on northerly aspects was sufficient in most cases to account for the higher incidence of slipping.

The explanation is not entirely complete as there was still a higher incidence of slipping on north and northwest slopes than expected from the relationship outlined above, and a lower incidence on southwest slopes. This observation points to an area for possible future research, namely, an examination of changes in the structure and composition of the regolith in response to the contrasting microclimatic regimes experienced on shady and sunny slopes.

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A reconstruction of late Quaternary erosional events in the West Tamaki River catchment, southern Ruahine Range, North Island, New Zealand

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Abstract Evidence is presented for the sequential nature of erosional events within a selected catchment of the southern Ruahine Range during late Quaternary time. The mapping of depositional surfaces, together with description of soil profiles and vegetation maturity on these surfaces, has enabled a chronology of erosional events to be established within the main channel of the West Tamaki River catchment. This chronology is aided by ages determined by: (1) radiocarbon dating of wood, and (2) a tephra, the Aokautere Ash, which has been identified on the main channel valley-side. An examination of the Takapari peaty loam, a Histosol which occurs at the head of the selected catchment, and the recognition of Taupo Pumice and Waimihia Formation tephras within it enable an interpretation of the erosional history of this soil site to be made.

Keywords Aokautere Ash; erosion; erosion events; late Quaternary; radiocarbon dates; drainage basins; Ruahine Range; Takapari peaty loam; Taupo Pumice; tephrochronology; Waimihia Formation

INTRODUCTION

In recent years, the southern Ruahine Range has been an area of intensive study by governmental and other agencies, due to concern over large amounts of gravel and associated debris which are transported from the eroding range onto the adjoining farmland. This detritus chokes many river beds and is threatening between 24 300 and 28 300 hectares of fertile, flood-free plains of the Manawatu and southern Hawke's Bay regions (Poole 1973). To investigate whether present erosion rates are abnormally high for this area, the erosional history of a selected catchment has been partially reconstructed from the late Otiran Stage to the present day.

Prior to the Otiran Stage, sediments which are today mapped in the Ruahine and Tararua Ranges as the Torlesse Supergroup were deformed and raised above sealevel, during the Rangitata Orogeny in early Cretaceous times (Fleming 1975; Kingma 1959). Subsequent peneplanation occurred between the Late Cretaceous and Paleocene when a marine transgression submerged the southern North Island (Kingma 1959). During Plio-Pleistocene time the peneplain was slowly uplifed and tilted westwards. Covering strata were stripped, leaving the marked summit accordance seen today both in the southern Ruahine Range and to the south in the Tararua Range (Wellman 1948). During the Quaternary, the Ruahine Range was subjected to a sequence of alternating climatic periods, the cold or glacial periods having the most profound effect on the landscape. Willett (1950) estimated the snowline during glacial periods to have been at 1250 m elevation based on a 6°C drop in mean annual temperature, but this is now considered an overestimate; the temperature decrease was probably less than 4.5°C (Soons 1976). In the Wellington district, to the south, solifluxion was widespread during the glacials (Cotton & Te Punga 1955) and similar periglacial conditions probably existed in the Ruahine Range. Milne (1973a) suggests that the mountainland in the southern North Island was largely devegetated above the 900 m contour. Resulting increased erosion rates produced aggradational gravels that now form extensive terraces in parts of the adjoining lowlands (Milne 1973b). With subsequent wind removal of silt and fine sand particles, loess deposits accumulated on older, stable surfaces. During interglacial periods vegetation advanced up the mountain flanks resulting in decreased erosion rates and an increase in soil profile development on stable sites.

LOCATION OF STUDY AREA

The catchment selected for this study was that of the West Tamaki River, located 13 km northwest of Dannevirke, on the eastern flank of the southern Ruahine Range. The river flows 5 km along the foot

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