TUNNEL EROSION IN THE LOESS OF
BANKS PENINSULA

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University of Canterbury
in partial fulfilment of the
requirements for the degree of
Master of Science in Geography

by
F.J. Hughes
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ABSTRACT

This study has examined in more detail than previous studies, and within the framework of the erosion model, the physical setting in which tunnel erosion occurs on Banks Peninsula. Two selected parameters were studied in detail using quantitative techniques, that is, slope aspect and soil erodibility.

Tunnel erosion on Banks Peninsula is largely a culturally induced form of erosion. European man disrupted the balance between the climate, soil and primitive tussock cover by removing this protective cover, allowing the increased runoff easier access to the highly erodible parent material loess below the compacted layer in the soil. It appears most of the tunnel systems on Banks Peninsula today may be relict features corresponding to a period of maximum pasture deterioration prior to the late 1940's.
CHAPTER ONE  INTRODUCTION

TUNNEL EROSION ON BANKS PENINSULA

The loess covered lower slopes of many parts of Banks Peninsula are susceptible to tunnel erosion. The physical setting in which these tunnels occur, and a theoretical sequence of events from their initiation to the final stage of collapse, has been described by Hosking (1962, 1967).

Briefly, under certain climatic, topographic, vegetation and soil conditions, water is able to penetrate through the surface soil into the loess beneath, and eventually to erode small tunnels. Once these tunnels become continuous down slope, erosion can proceed rapidly, the tunnels increase in diameter at the expense of the soil above and the loess beneath, until finally they collapse to form gullies. Erosion then continues by the processes of gully erosion.

AN EROSION MODEL

Water erosion is due to the dispersive action and transporting power of water (Baver 1956). For tunnel erosion these in turn are determined firstly by the amount and velocity of subsurface runoff and secondly by the resistance of the soil to dispersion and movement (soil erodibility). Subsurface runoff is a function of the rainfall and surface runoff characteristics and the water transmission properties of the soil. The surface runoff characteristics depend on the topography and the nature of the surface vegetation.
cover. The relationship between tunnel erosion and the various contributing factors is shown in figure 1.

The tunnel erosion problem then involves the following variable factors: climate (C), topography (T), vegetation (V) and soils (S). A descriptive equation or model can be used to express the relationship between erosion and the factors mentioned.

\[ E = f (C.V.T.S.) \]

A fifth variable can be added; the effect of man's activities in causing erosion (H).

\[ E = f (C.V.T.S.H.) \]  

This is accelerated erosion (Land Use Capability Survey Handbook 1969), that is, there is deterioration and loss of soil as a result of man's activities in excess of that through geologic or natural erosion. Cumberland (1944) calls it "culturally induced erosion". It has been shown that tunnel erosion on Banks Peninsula is largely a form of accelerated or culturally induced erosion where the effects of man's activities act through a change in the vegetation cover.

Each of the variables in the model can be considered independently of the others. For example if the climate, vegetation and land use of an area are the same, then erosion
FIGURE 1

Relationships between Tunnelling and the Contributing Variables in the Erosion Model
TUNNEL EROSION

Due to

THE DISPERSE ACTION AND TRANSPORTING POWER OF SUBSURFACE RUNOFF

Affected by

THE AMOUNT AND VELOCITY OF SUBSURFACE RUNOFF

Determined by

SURFACE RUNOFF CHARACTERISTICS

Determined by

VEGETATION

THE RESISTANCE OF THE SOIL TO DISPERSION AND MOVEMENT (SOIL ERODIBILITY)

Determined by

ABILITY OF THE SOIL TO ABSORB AND TRANSMIT WATER

Determined by

PRECIPITATION

SLOPE

SOIL PROPERTIES
losses will vary only with variations in soil properties. Usually the variables are to some extent interrelated, for example the relationship between soil type and climate which forms the basis of the zonal soils concept.

THE PURPOSE AND NATURE OF THIS STUDY

This study attempts to review, within the framework of the erosion model, previous investigations that help elucidate the tunnel erosion phenomenon of Banks Peninsula. Whereas other studies of tunnel erosion in loess in New Zealand have been largely qualitative, this study places more emphasis on a quantitative approach. Two selected parameters are studied in detail using quantitative techniques, that is, slope aspect and soil erodibility.

This study involves both a consideration of the individual relationships between the variables in the model and tunnel erosion and of the interrelationships between the variables themselves. This thesis is structured so that, except for the vegetation and human factors, each of the variables is considered individually and that interrelationships between these variables are discussed within this framework where such discussion is considered relevant. The effect of man on tunnel erosion has been through his modification of the vegetation cover. These two factors, vegetation and man, are therefore considered together. The soil factor is dealt with more fully than the others, especially in terms of soil erodibility, because if the site
conditions determined by the other variables are such that tunnelling should ideally occur, whether or not tunnels form will depend on the soil conditions.

Descriptive data concerning the physical conditions under which tunnelling occurs are included in the text for two reasons, the main one being to help in understanding the conditions under which tunnelling occurs and consequently in accounting for their distribution and mode of formation. However, a second reason is that, as will be shown, tunnel and related forms of erosion can occur under a wide range of physical conditions and before any meaningful comparisons of tunnelling phenomena in different areas can be made, a sound knowledge of the physical conditions of the areas is needed. Unfortunately, much of the literature on tunnelling is accompanied only by very brief descriptions of the physical settings.

**Banks Peninsula and Its Loess Cover**

Descriptions of the topography of Banks Peninsula are given by Milligan (1941) and Speight (1916). Banks Peninsula is the eroded remnant of the Lyttleton and Akaroa volcanoes and occupies an elliptical area 31 miles by 18 miles (figure 2). Radiating outwards on the flanks of these volcanoes are numerous short valleys. In the east, these valleys end in bays whereas the landward facing valleys have their lower reaches filled with alluvium (Speight 1916).
FIGURE 2

Banks Peninsula - Location and Localities
Separating the valleys from each other are long, sloping, steep sided spurs. The spur ridges and the slopes at the tops of the valley commonly reach to 1500 - 2000 ft except along the western rim of Lyttleton Harbour. The break of slope between the flanks of the volcanoes and the Canterbury Plains is usually very marked. On the seaward flanks the spurs terminate in plunging cliffs.

Loess has been deposited on the inner and outer slopes of both volcanoes and is continuous except on very steep slopes or at altitudes above about 1500 ft. It is especially thick on the lower slopes below 500 feet. The age, origin, thickness and mode of deposition of this loess has been discussed elsewhere (Sparrow 1948, Hoskings 1962, Raeside 1964, Langbein 1967).

There are no obvious marked regional variations in the thickness of loess on these slopes and the inner slopes of both volcanoes are apparently covered by similar thicknesses as the outward facing slopes. The loess was derived not only from the glacial outwash surfaces that form the present Canterbury Plains, but their seaward extension during glacial advances when, because of the lowering of sea level, the outwash surface extended to the east of Banks Peninsula. (Raeside 1964).

Much of the loess has been reworked by processes such as slope wash, solifluction and soil creep (Langbein 1967). Nearly every loess sample taken for this study contained
some coarse volcanic material in it, indicating that at least the surface zone of the loess deposits, where tunneling occurs, has been re-worked to some extent.

**PREVIOUS INVESTIGATIONS AND A REVIEW OF THE LITERATURE**

Tunnel and related form of erosion have been reported from many parts of the world and in a wide range of materials other than loess. In New Zealand, tunnel erosion in loess has been reported from Wairarapa and various parts of the South Island downland and foothills, that is, from Marlborough in the north to Otago in the south, including Banks Peninsula (Cumberland 1944). It is particularly serious in the coastal region of Marlborough from Ward to Blenheim, in North Canterbury to the north of Waipara, and on Banks Peninsula. Four investigations have been made that discuss in some detail tunnel erosion in loess in New Zealand (Cumberland 1944, Gibbs 1945, Harris 1952 and Hosking 1962, 1967).

Cumberland (1944), as part of a comprehensive investigation into erosional problems as a whole in New Zealand, studied what he called subcutaneous erosion in many parts of the South Island but specifically on Banks Peninsula and the Timaru Downs. Gibbs (1945) investigated what he called tunnel gully erosion on the Withers Hills, Marlborough. Harris (1952), in a study of the soils and erosion in Horotane Valley, Port Hills, described in detail the
occurrence of tunnel erosion. The sequence of events leading to, and the explanations for, the formation of gullies in loess by tunnelling proposed by these workers are essentially those proposed later in more detail by Hosking.

Hosking (1962, 1967) described the occurrences of, and attempted an explanation of, tunnel erosion on the Port Hills, Banks Peninsula. He suggested the development of tunnels and the stage to which erosion had proceeded were related to slope aspect and angle, climate, soil and vegetation. He found tunnelling was more serious on west-northwest facing slopes and that it occurred on a wide range of slope angles. The annual rainfall of the area is 25”-30”, with droughty summers and periodic heavy rainstorms. The soils are loess derived with a predominance of fine silt particles and have a distinct hard pan beginning one to two feet below the surface.

The vegetation cover has deteriorated since the arrival of European man, due to burning and overgrazing and the replacement of deep rooted tussocks by European species. This has led to an increase in the area of exposed soil, increasing the susceptibility of the soil to dessication and cracking.

He suggested that erosion occurs in periods of intense activity, separated by lulls.

He then proposed a sequence of events to account for
the initiation and growth of tunnels that is essentially the same as those of Gibbs and Harris. "Depletion of vegetative cover exposes the surface soil to sun and wind. The bare soil dries out and shrinks. Deep fissures develop which may extend through the subsoil and the hard pan into the parent material. Rainfall, which normally runs down slope on the surface or percolates slowly through the top soil, flows into the cracks and moves downslope from crack to crack below the surface. Small quantities of silt are carried with it. The subterranean channels between cracks are enlarged by the movement of water, with its silt load, out onto the surface again via some of the cracks lower on the slope. This removal of silt to the surface forms a tunnel under the hard pan. The tunnel, an inch or two in diameter and situated immediately below the hard pan, extends slowly downslope and also, by headward erosion, upslope. However, not until the tunnel finds some larger outlet at the base of the slope - usually just percolating into the main valley stream - can it erode freely." (Hosking 1967 pg. 150). From here the tunnels grow in size through a series of theoretical stages he calls youthful, advanced and gully stages until there is complete collapse of the tunnel roofs.

The areas of tunnel erosion studied by Cumberland, Gibbs, Harris and Hosking had the following basic conditions in
common. The soils were loess derived yellow-grey earths, the climates were similar with 20 to 30 inches of rain and droughty summers, the vegetation cover had deteriorated due to European occupation, resulting in the formation of fissures and cracks in the soil. The tunnels formed in the highly erodible parent material below a hard pan in the soil and the water apparently entered the parent material below the hard pan by flowing down the fissures and cracks.

Tunnel and related forms of erosion in materials other than loess have been reported from Hawkes Bay, Gisborne, inland Taranaki and the Volcanic Plateau (Cumberland 1944) and Northland (Ward 1967, Visser 1969). The climate and soil conditions in these areas are different from those described above.

Tunnel erosion is a serious problem in many parts of N.S.W. and Victoria, Australia. In most areas a similar sequence of events to that proposed in New Zealand has been suggested with similar climatic conditions and severe pasture deterioration since European occupation. (Downes 1946, 1956, Monteith 1954 and Newman and Phillips 1957). However, these areas have very different soils to New Zealand loess derived yellow-grey earths. The clay content is much higher and erosion takes place above an impermeable layer. Charman (1969, 1970) has studied tunnel erosion that affects a large
area of N.S.W. where the rainfall is in the order of 40 to 50 inches a year. The conditions described by Charman appear to resemble those in Northland described by Ward (1967). Most of the Australian soils which are affected have a relatively high sodium ion content which has been shown to cause excessive dispersion of the clays in the subsoil.

Tunnel and related forms of erosion are a widespread problem in the arid and semi-arid mid-west, west and south-west states of the U.S.A. (Rubey 1928, Parker 1967). The materials that are subject to tunnel erosion are mainly alluvium and colluvium, including loess, and most commonly have a clay, silt and fine sand texture.

Other parts of the world where tunnel and tunnel like forms of erosion have been reported are Bolivia, China, Hawaii, Iran and South Africa (Parker 1967), Tasmania and Madagasca (Commonwealth Bureau of Soils No. 107 1961) and British Columbia (Buckham & Cockfield 1950).

As Parker points out, most occurrences of tunnel and related forms of erosion occur in arid areas with a rainfall of less than 15" with a sparse vegetation cover often due to the deleterious effects of man. The rainfall may be higher if circumstances allow pasture deterioration and subsequent cracking of the subsoil (Downes 1956, Gibbs 1945). Apparently more important is intensity and duration of rainfall and whether protective vegetation cover exists. (Parker 1967).
CHAPTER TWO METHODS AND MATERIALS

GENERAL

Data used in this study were obtained from field observations, laboratory analyses, maps, aerial photographs and from various published and unpublished sources. The areas covered by the topographic maps and aerial photographs are shown in figure 3. The maps are Lands and Survey N.Z.M.S. 1 sheets. The aerial photographs have a scale of approximately one inch to 40 chains. Runs 3150 to 3160 were taken in 1966, runs 2113 to 2116 in 1952 and runs 135 to 147 in 1941.

Before any attempt could be made to investigate the causes of tunnel erosion, or explain the distribution of tunnelled areas, the areas of Banks Peninsula affected by tunnelling had to be located. The spatial variations of the factors in the erosion model could then be compared with the spatial distribution of areas affected by tunnelling. Tunnelled areas were identified from the aerial photographs and their location plotted on the topographic maps. A visual scale of the degree of seriousness of tunnelling was devised (plates 1 to 6) and the areas affected by tunnelling classed as seriously, moderately or slightly affected. Most of the tunnelled areas in the western part of the peninsula were checked in the field. From this information a map showing the distribution of areas affected by tunnelling was
FIGURE 3

Areas Covered by the Topographic Maps and the Aerial Photo Runs
Plate 3. Seriously Affected - Birdlings Valley

Plate 4. Moderately Affected - Francis Valley
Plate 1. A Seriously Affected Slope - St Martins Valley

Plate 2. A Seriously Affected Slope - Kaituna Valley
Plate 5. Moderately Affected - Hoon Hay Valley

Plate 6. Slightly Affected - Kaituna Valley
produced (figure 4).

It is probable that many slightly affected areas exist which are not shown on the map. These were very difficult to identify from the aerial photographs. It is assumed that the pattern of tunnelling has not changed radically in the areas covered by the 1941 and 1952 runs since these photographs were taken. Evidence to support this contention for the 1941 runs is presented in Chapter 6 and the area covered by the 1952 runs was checked in the field and no major changes were observed.

SLOPE

Field observations were made of slope profiles at various localities affected by tunnelling. Slope angle was measured with an abney level to the nearest degree. Slope length was measured with a tape and the slope angle was noted at every 100 feet or significant break of slope.

Using maps and aerial photographs, every occurrence of tunnelling that could be identified (377) to the west of a line connecting Lake Forsyth to Little Akaloa Bay was noted, and its aspect, degree of seriousness and the width (length along the contour) of slope affected noted. Each occurrence was weighted to allow for differences in the degree of seriousness and width of slope affected. A slightly affected slope was given a rating of one, a moderately affected slope two and a seriously affected slope three. Each one eighth of a mile of affected slope was rated as one, that is, an
affected slope one mile wide was rated as eight. For example, a slightly affected slope one mile wide would be weighted as $8 = (1 \times 8)$, whereas a seriously affected slope one half mile wide would be weighted as $12 = (3 \times 4)$. The weighted occurrences of tunnelling for each aspect class ($22^\circ$) were then added. If the total distribution of slopes potentially liable to tunnelling was such that the number of slopes facing in any one direction was no different from that facing in any other direction, then the distribution of the aspects of the tunnelled slopes determined above would be a true indication of the relationship of slope aspect to tunnelling. However, in this area, in part because of its elliptical nature, it was apparent more slopes faced the N.W. and S.E. than any other direction. To allow for this, the aspect of every slope facet below an altitude of 500 feet and more than one half mile wide that could be determined from the topographic maps was noted and weighted as above for slope width. 335 such slopes were identified, and these were summed for every $22^\circ$ aspect class as above. The number of tunnelled slopes was expressed as a fraction of the total number of slopes in each aspect class. These values were expressed as a percentage. From this, figure 8 was constructed showing the relationship between slope aspect and tunnelling. Three other figures were constructed, one weighted only for slope width, one only for the degree of seriousness and one with no weighting at all. These were
essentially similar in appearance to figure 8.

SOIL

The soil terms used in this study, unless otherwise stated, are those used by the N.Z. Soil Bureau (Taylor and Fohlen 1962), with the exception of the textural classes, which are those used by the U.S. Department of Agriculture (Soil Survey Manual 1951). The location of the sampling sites and the individual soil samples is given in Appendix 1 and figure 23.

Three types of soil samples were taken, those used for bulk densities (method A), those used for the erodibility tests and the determination of the sand silt and clay percentages, and those used for the detailed particle size analyses (figure 5).

Because of the degree of compaction and hardness when dry of all but the top soil it was not practical to dig pits for sampling purposes. Instead, all the samples were taken from outcrops of loess, especially the exposed sides of collapsed tunnel systems. It must be noted that this non random sampling method may have introduced some bias into the results and conclusions based on the analyses of the samples collected. The surface of the exposure was cut back with a spade to expose fresh material. For each of the samples used in the erodibility tests about 1.5 kilograms of soil was taken, placed in a polythene bag and sealed. Surface soil material was removed carefully with a hand
FIGURA 5

Flow Diagram Showing the Analyses of the Various Soil Samples
SOIL SAMPLES
METHOD A

BULK DENSITIES

SOIL SAMPLES
METHOD B

SAND %

PARTICLE SIZE
DISTRIBUTIONS

SOIL SAMPLES
METHOD C

ERODIBILITY TESTS

A.S test

D test

CLAY %

CDB test

DBT test

CDA test
trowel to preserve the natural aggregates. However, generally sub-surface material, because of its hardness and lack of structure, had to be removed by vigorous chipping with a hand trowel or a spade. Of the material chipped off, those chips greater than about 2 cm. across were collected and subsequently broken down to the required size range for the erodibility tests. Occasionally larger blocks about 8 to 15 cm. across could be removed intact and broken down in the laboratory. In the case of the samples used for particle size analyses the same procedure was used except all the material was collected regardless of the degree of breakdown.

Bulk density samples were taken using a 1.5 inch cylindrical soil corer. The corer was pushed in as far as it would go, usually about 4 inches. The soil core was removed from the corer and its ends trimmed until the length of the core was about 3 to 3¼ inches long. The volume of the sample was then determined and the sample dried at 105° for 24 hours. The soil at the sites was damp and this would have led to some compaction of the samples as they were taken. Consequently, the bulk density values are probably all slightly high. Bulk density is expressed as the volume of the sample over its dry weight.

Figure 9, the map showing the loess derived soils is a modified form of the soils map in the Soil Bureau Bulletin 27, 1969 (sheet 9).
The six particle size distribution analyses were determined using a standard hydrometer method, with modifications, as outlined by T.N. Caine 1965 (unpublished laboratory procedure sheet, Physical Lab.). Histograms and cumulative curves were constructed from this data (figures 11 to 16).

The percentage of sand, silt, and clay were determined for most of the samples used for the erodibility tests. The U.S. Department of Agriculture system was used (Soil Survey Manual 1951). The clay percentages were obtained from the dispersal index test. Another sub sample was taken, weighed, and wet sieved through a 300 mesh sieve and then dry sieved on 200 and 300 mesh sieves for about 15 minutes on an Endrock shaker. Having determined the sand and clay percentages the percentage of silt could be calculated.

Five laboratory tests were used to determine indices of soil erodibility, the dispersal index test (D.I. test), the clay dispersion A test (C.D.A. test), the clay dispersion B test (C.D.B. test), the disintegration B test (D.B.T. test), and the aggregate stability test (A.S. test). These methods, and their limitations, are outlined in Appendix 2. The first three tests were used to determine clay stability and the latter two aggregate stability, as indices of erodibility.
CHAPTER THREE  CLIMATE

MACROCLIMATE

The macroclimatic conditions on the Port Hills are well summarised by Hosking (1962) and Fitzgerald (1966). The climatic data presented by them are rainfall, rainy days per month, temperature, humidity and days with frost, in the form of monthly and yearly totals and averages. Fitzgerald presents data which are probably representative of those areas of Banks Peninsula affected by tunnel erosion, that is, from sea level to 500 feet in altitude with a rainfall of less than 35 inches per year. The highest temperatures occur in January which has a mean daily maximum temperature of 70.2°F and a mean daily minimum temperature of 53.3°F. The corresponding temperatures for July, the coldest month, are 50.0°F and 34.3°F.

The rainfall pattern is shown in figure 6. A comparison of figures 4 and 6 shows that most of the areas affected by tunnelling have a rainfall of less than about 35 inches per year. The lowest rainfall is at Godley Head (at the extreme eastern end of the Port Hills) where the average annual total is 19 inches. The predominant rain bearing winds occur in the winter with a maximum rainfall in May. Figures for the monthly rainfall and number of rainy days for Horotane Valley, Port Hills, is given in table 1. These
<table>
<thead>
<tr>
<th>Month</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>Yearly Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean rainfall (inches)</td>
<td>1.79</td>
<td>1.49</td>
<td>2.32</td>
<td>2.14</td>
<td>3.95</td>
<td>2.67</td>
<td>2.49</td>
<td>2.65</td>
<td>1.62</td>
<td>2.09</td>
<td>1.89</td>
<td>2.72</td>
<td>27</td>
</tr>
<tr>
<td>Mean No. of Rainy Days</td>
<td>7</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>12</td>
<td>10</td>
<td>11</td>
<td>11</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 1

MONTHLY RAINFALL CHARACTERISTICS FOR HOROTANE VALLEY
FIGURE 6

Mean Annual Rainfall Isohyets
appear to be typical of the data presented for various rainfall recording stations by Hosking (1962). Although the summer monthly rainfall totals exceed 1.5 inches, humidities are low, especially during periods of hot, dry, gusty north west winds. For most of the summer potential evapotranspiration exceeds the supply of moisture and the soils dry out rapidly (Hosking 1962). Thus, in the summer, drought conditions prevail on the slopes affected by tunnelling.

The macroclimatic conditions discussed above are mainly mean conditions and give no indication of the extremes or daily or hourly fluctuations in weather events. As Hosking (1962) points out, it is the extremes in macroclimatic conditions, along with microclimatic variations, that are responsible for erosion in the loess of the Port Hills (and Banks Peninsula as a whole). "Downpours then, and their opposites, droughts, are probably more influential in erosion formation than normal average weather conditions." (Hosking 1962 pg. 34). Little is known about the hourly or daily fluctuations of macroclimatic conditions or their extremes over the areas affected by tunnelling. Some data on rainfall intensities are available for Christchurch (Hosking 1962). 89% of the rainy periods have an intensity of less than 0.10 inches/hour, 9% of 0.1 to 0.2 inches/hour and 2% of 0.2 to 0.49 inches/hour. Other data is available for Christchurch (table 2). The calculated 24 hour values for Magnet Bay
### Table 2.

**Maximum Rainfall Intensities - Christchurch**

<table>
<thead>
<tr>
<th>Duration</th>
<th>10 minutes</th>
<th>1 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest value to be expected once in 20 years (inches)</td>
<td>0.40</td>
<td>0.78</td>
</tr>
<tr>
<td>Highest value to be expected once in 50 years (inches)</td>
<td>0.48</td>
<td>0.86</td>
</tr>
</tbody>
</table>

*Source: N.Z. Met. Service (pers.comm.)*
(S/84, 093181) and Brockworth (S/84, 318394), two stations with mean annual rainfalls of 30 and 22 inches per annum respectively, for the highest rainfall once in 20 years are as follows: Magnet Bay, 6.9 inches, Brockworth, 6.2 inches. (N.Z. Met. Service, pers. comm.). Hosking (1962) gives data for the maximum 24 hour rainfall that occurred between 1921 and 1950 for other stations in areas affected by tunnelling. These range from about 4 to 8 inches.

The volume of both surface and subsurface runoff that would result from periods of rainfall such as these would be very large, especially on slopes with a poor vegetation cover and with a severely cracked and fissured soil. These are infrequent events and of more interest would be perhaps the hourly and daily intensities of the four or five or so most severe storms a year. From the data presented by Hosking these would have maximum intensities of about 0.2 to 0.5 inches/hour with a 24 hour total rainfall of about 2.5 inches (assuming an average intensity of 0.1 inches/hour.)

MICROCLIMATE

As with fluctuations in macroclimatic conditions, very little is known about microclimatic variations and the effect they have on tunnel erosion. However, as will be shown in Chapter 5, W.N.W. facing slopes are more susceptible to tunnel erosion than other slopes and this can largely be
explained in terms of microclimatic differences. These slopes face the summer afternoon sun when temperatures are highest and are also exposed to the N.W. winds. As a consequence, the soils on these slopes dry out to a greater degree than on other slopes and this leads to greater pasture deterioration and the formation of more cracks at depth in the soil.

**DISCUSSION**

To understand and explain the relationship between climate and tunnel erosion three aspects of this relationship have to be considered. These are

(1) the role climate has played in soil forming processes and in influencing the nature of the primitive cover;

(2) the way in which, along with the effects of European man, the summer drought affects the vegetation cover and the structure of the soil so that the soil becomes susceptible to tunnelling; and

(3) the way in which, in the form of periods of high intensity rainfall, it provides the subsurface runoff to initiate and form tunnels.

These interrelationships between climate, soil, vegetation and tunnel erosion are discussed further in Chapters 4, 5, 6 and 9.
CHAPTER FOUR
THE VEGETATION COVER AND ITS MODIFICATION BY EUROPEAN MAN

INTRODUCTION

The climate, topography and, to a lesser extent, the soils of the areas of Banks Peninsula affected by tunnel erosion have undergone little or no change since the arrival of the first European settlers. The same cannot be said of the vegetation cover. European man has greatly altered the primitive vegetation cover, not only of the areas previously covered by forest (Petrie 1963) but also the areas which were covered with tussock grassland. The occurrence of tunnel erosion after modification of the primitive vegetation cover by Europeans has been reported not only in New Zealand (Cumberland, Gibbs and Hosking) but in Australia (Downes 1946, 1956, Monteith 1954, Newman and Phillips 1957) and the United States (Parker 1967).

In figure 7, a map of the forest cover in 1860, the unshaded areas, with the exception of some areas of low lying swamp and scattered scrub, represent tussock grassland. (Petrie 1963). Therefore, as a comparison of figures 4 and 7 shows, the areas affected by tunnelling were largely covered by tussock grassland immediately prior to European occupancy. Maps and descriptions tend to confirm this relationship between a primitive cover of tussock and tunnel erosion, for example in Akaroa County (Ford 1949), Le Bons Bay (Kearney 1947), Kaituna Valley (1946) and the Port Hills
FIGURE 7

The Forest Cover in 1860
(Boyce 1939, Hosking 1962, Fitzgerald 1966).

It must be noted however that the forests had already disappeared from some parts of Banks Peninsula before the arrival of European man. For example, on the N.W. facing slopes of Mt Herbert, the tussock covered summits above Wainui, and on the exposed treeless spurs between Little Akaloa Bay and Pigeon Bay, ancient buried and surficial root systems, stumps and logs have been found (Petrie 1963). There is similar evidence for the removal of forest in other parts of the South Island. Holloway (1954) and Johnston (1958) consider that the retreat of the forest and its replacement by tussock was caused by a change in climate to colder and drier conditions, probably about 1200 A.D., aided by the burning of parts of the forest by the Moa Hunters. Cumberland (1962) attributes the removal of the forest to cultural intervention by the Moa Hunters and said that the effect of climatic change was small. To what extent the tussock covered areas of Banks Peninsula had previously been forested is not known. The yellow-grey earths of the South Island, the soil group to which the loess derived soils affected by tunnelling belong, were formed under a predominantly tussock grassland cover (Soil Bureau Bulletin 27 1969). However, Raeside (1948) presents evidence that the structures of most Canterbury yellow-grey earths have certain features that suggest that for at least part of the time while they were
forming, or since they were formed, they were covered with forest.

**THE PRIMITIVE VEGETATION COVER**

The descriptions of the primitive tussock grassland cover for the various parts of Banks Peninsula are all essentially the same (Boyce, Barley, Kearney, Ford, Hosking and Fitzgerald). That given by Fitzgerald (1966 pg. 6) is used here. The dominant species were silver tussock (*Poa Caespitosa*), blue tussock (*Poa colensi*), fescue tussock (*Festuca novae-zealandiae*) and blue wheat grass (*agropyron scabrum*) with the latter being most widespread and more abundant on the drier and more exposed ridges. Patches of scrub and fern and isolated cabbage trees (*Cordyline Australis*) were common.

These tussocks were deep rooted (Cumberland 1944), giving a thick sod that was capable of trapping and absorbing much of the surface runoff and protecting the soil from excessive dessication. The droughty summers have a limiting effect on plant growth and to survive, especially in exposed positions, the primitive vegetation had low transpiration rates to conserve soil moisture (Fitzgerald 1966).

**MODIFICATION OF THE PRIMITIVE COVER**

There has been considerable modification of the primitive cover by the land use activities of European man. In
places it has been completely removed by cultivation of the land, especially on the lower slopes of Horotane, Avoca, Heathcote and Bowenvale Valleys, for fruit growing and market gardening. More important and widespread have been the effects of 100 years destruction of the cover by continual burning off of the tussock and grazing by sheep, cattle and rabbits (Hosking 1962). This has lead to the dying out or decrease in importance of many of the original species and their replacement by species, both native and exotic, resistant to drought, fire and stock trampling.

THE PRESENT COVER

The grassland cover today is an extremely variable one in which silver tussock and various introduced grass species are dominant (Fitzgerald 1966). The variations in the composition of the pasture are largely determined by the slope aspect and the incidence of grazing and burning (Hosking 1962). On the damper, shady slopes the tussocks are closely spaced but on dry exposed slopes they are either absent or widely spaced. The introduced species brown top (Agrostis tenuis) and to a lesser extent Yorkshire fog (Holcus Tanatus) are most common on damp slopes with the native species danthonia (Danthonia pilosa) on dry, warm, sunny slopes where tussocks are few in number (Fitzgerald 1966). Petrie (1963 pg. 81) gives a fuller description of the grasses that cover most of Banks Peninsula today.
Danthonia, which is able to withstand burning and trampling by stock, is spreading, but on its own provides insufficient protection against erosion. By 1935 danthonia was firmly established as a dominant species in a few South Island localities only, including the Withers Hills and the lower slopes of Banks Peninsula (Hilgendorf 1935). These are two of the areas today most affected by tunnel erosion. The present vegetation cover, especially that of danthonia, is not as thick as the primitive cover was, especially when the effects of burning and grazing are taken into account. Also these plants tend to be shallower rooting, forming a shallower sod which is less able to absorb surface runoff. Finally, there is less protection against soil dessication in the summer.

VEGETATION CHANGE AND TUNNEL EROSION

The effect the change in vegetation cover could have in leading to the initiation of tunnel erosion would vary depending on the nature of the resultant vegetation cover.

On damp, shady slopes or on the flat to rolling interfluves between valleys, the moisture regime of the soil would likely be such that a good grass sward with numerous deep rooting tussocks could be maintained despite the deleterious effects of grazing, burning and the summer drought. Such a grass sward would also aid in decreasing surface runoff by trapping surface water and allowing much of it to infiltrate
To the thick absorbent sod (plate 7).

On the steeper slopes, exposed to the dessicating effects of the summer drought, the moisture regime would be such that, with the added effects of grazing and burning, a thick grass sward with numerous silver tussocks would have difficulty surviving and would be replaced by more drought, grazing and fire resistant species such as daanthonia. The cover would likely be thin with less dense sod and surface runoff would be higher (plate 8).

It is in the latter situation that tunnel erosion has been found to occur. Depletion of the vegetation cover has led to an increase in the area of exposed soil, increasing the susceptibility of the soil to excessive drying out and subsequent cracking (Hosking 1962). This is most likely to occur on steeper slopes exposed to the sun and N.W. wind.

Modification by man has led to an increase in the bare surface area with a decrease in the permeability of the soil surface due to rainsplash effects and baking by the sun. This has been accompanied by a decrease in the absorbent capacity of the soil sod. The result has been an increase in surface runoff which could, in various ways (Chapter 9), infiltrate into the loess below the "hardpan". An added factor is that cracks along which water could flow would in turn be, in part at least, the result of pasture deterioration and subsequent soil dessication.
Plate 7. A Remnant of Tussock Cover – about 25% of the surface covered with tussock

Plate 8. A Poorly Vegetated Surface – it appears surface runoff is greatest on this type of surface
DISCUSSION

It appears that much of the tussock grassland of the South Island had already been modified by European man by the turn of the century. By 1860 they were being used for extensive grazing and the deleterious effects of grazing and burning were already apparent (Cumberland 1944 appendix 3). C.S. Harris (pers. comm.) considers it is likely that by 1880 the Withers Hills, Marlborough, had been swept by fire many times and that probably the tussock grasslands of Banks Peninsula had been similarly affected. Therefore conditions which could lead to culturally induced tunnel erosion have probably existed since the last two decades of the 19th Century.

By the 1940's, because of overgrazing by livestock and rabbits and repeated burning, culturally induced erosion was a serious problem on the tussock grasslands of the South Island (Taylor 1938, Zotov 1938, Cumberland 1944). E. Griffiths (pers. comm.) has suggested that the tunnels which led to the formation of the numerous collapsed tunnel systems on Banks Peninsula today were initiated prior to the late 1940's, that is, they are largely relict features. Field observations confirm that the number of tunnels at present in an early stage of development, although large in number, probably form only a small percentage of the total number of tunnel systems and that the majority of tunnels are in
an advanced state of collapse. This is confirmed by a study of the aerial photographs. The runs taken in 1941 show a degree of tunnelling that is similar to that affecting the areas covered by the 1952 and 1966 runs. Photographs 141/7, 8, 9, taken in 1941 cover the same area as photographs 2114/78, 79, 80, taken eleven years later in 1952, that is, lower and middle Prices Valley and neighbouring areas. A close comparison of these sets of photographs showed that there had been little apparent development of the tunnel systems over this period. The major features identified on the photographs were checked in the field and again no obvious major changes had taken place. Since 1941 tunnels probably have been initiated in this area, but the soil loss resulting from these is probably small compared with the loss prior to 1941. This all adds weight to the argument that the collapsed tunnel systems, which are the most common form, may be relict features corresponding perhaps to the period of greatest pasture deterioration.

During the 1950's and 1960's the vegetation cover on these areas of Banks Peninsula improved as land management practices improved. (D. Saunders pers. comm.). For example, surface cracks, reported as common by Cumberland, Gibbs and Harris, seem to be largely absent today and this may reflect the improvement in the vegetation cover.
CONCLUSION

As with rainfall, there appears to be a close relationship between the areas affected by tunnelling and the areas with a primitive vegetation cover of tussock. In turn there is a close relationship between the vegetation and rainfall patterns of Banks Peninsula, and, as will be shown, both of these are closely linked with the soils pattern.

At the time of the arrival of European man it is probable that there was little tunnel erosion compared with today because of the stabilising effect of the tussock cover on the soil and its effect in controlling excessive runoff. The activities of European man disrupted the balance that existed between the climate and the soil and its associated vegetation cover. The result was a culturally induced acceleration of the rate of tunnel erosion, leading to the serious tunnel erosion problem that developed this century and still exists today.
CHAPTER FIVE  SLOPE

INTRODUCTION

The topographic factor in the erosion model is expressed here in terms of the slope parameters elevation, aspect, angle and length. Each of these slope parameters is looked at separately. However they are all closely interrelated, and in attempting to determine the overall effect of slope on tunnelling at any given location it is difficult to assess the relative importance of the individual parameters.

Only a limited number of slope profiles were surveyed as it was later realised that far too little data had been collected to assess the individual relationships between slope angle and length and tunnelling because of the complicating effects of the other slope parameters and the other factors in the erosion model.

In the vicinity of Francis Valley 13 slope profiles, with varying aspects and degrees of tunnelling, were surveyed. Other slope profiles, all moderately or seriously affected by tunnel erosion, were surveyed at Shelly Bay, Holmes Bay, Port Levy, Birdlings Flat and Prices Valley.

ELEVATION

Most tunnel erosion occurs at altitudes below 250 feet above sea level and few occurrences were observed, either in the field, or from the aerial photographs, above 500 feet (figure 4). The occurrence of tunnelling almost entire-
ly at low altitudes is related mainly to the effects of loess thickness and climate. The thickest deposits of loess are generally found around the lower slope margins of Banks Peninsula. The amount of precipitation increases with altitude due to orographic effects. The higher the rainfall, the less favourable will the soil and vegetation conditions be for the initiation of tunnels (Chapters 4 and 6).

**ASPECT**

Hosking (1962, 1967) found on the Port Hills that the most serious and frequent tunnelling occurred on the W.N.W. facing slopes. He pointed out that a comparison of different aspects was difficult for this area because of the lack of slopes facing south east and east.

The aspect of slopes affected by tunnelling in the western part of Banks Peninsula (where about 75% of the tunnels occur), expressed as a ratio of the aspects of a sample of the total number of slope aspects, is given in figure 8. This confirms Hosking's contention that slopes in the W.N.W. facing sector were most likely to be affected. A secondary mode occurs of easterly facing slopes, for which there is no apparent physical explanation. The number of slopes facing this direction, both affected and unaffected, is small compared with most of the other aspect categories, and this could mean that the sample collected is too small to be representative. The least affected slopes were those facing in a S.E. to S.S.W. direction.
FIGURE 8

The Aspect of Slopes Affected by Tunnelling

(Expressed as a Ratio of the Aspects of a sample of the Total Number of Slope Aspects)
As has been shown, aspect influences climatic parameters such as exposure to solar radiation, rainbearing winds and the drying N.W. winds. These in turn lead to differences in the nature of the vegetation cover and land use.

For example sheep prefer to graze on sunny rather than shady slopes (Hosking 1962). The result is that on slopes facing the N.W., pasture deterioration tends to be greatest, the soils suffer the greatest degree of cracking and dessication, runoff is higher and consequently tunnelling is more extensive.

**Angle**

Tunneled slopes in the field where slope profile characteristics were measured have angles of 12° to 31°. Tunnels do occur on lower angles, especially at slope bottoms, but these are probably the downhill extensions of tunnels formed on steeper slopes. A comparison of Hosking’s (1962) slope and erosion maps (figures 9 and 13, Hosking 1962), shows a close relationship between tunnelling and slopes ranging from 34° to 14°. Tunnelling is found on slopes less than this (14° to 8°) but only where these slopes occur below steeper tunneled slopes. Slopes above 34° have a loess cover too thin or discontinuous to permit tunnel formation, and are often associated with rocky outcrops (Hosking 1962).

Not all slopes with angles above 12° are affected by tunnelling even if aspect and altitude are ideal for the
formation of tunnels. Slopes in the 15 to 20° angle range in the areas surveyed were commonly unaffected and slopes up to 25° remained totally unaffected. Except for the broad generalisations made above about the relationship between tunnelling and slope angle, because of the lack of data, the effect of slope angle could not be separated from a consideration of the other variables in the erosion model or the other slope parameters. Insufficient slope angle data was collected to allow any meaningful specific conclusions to be made. As will be shown in Chapter 9, changes in slope angle (convexities and concavities) and the steepness of the slope may be very important in influencing the nature of sub-surface water flow.

LENGTH

Again insufficient data was collected for other than broad generalisations to be made. Ideally, the longer the slope, the greater may be the accumulation of both surface and sub-surface runoff. Hosking (1962) considers the slope lengths on the Port Hills are not excessive and accumulation not too great. However very short slopes, which otherwise have ideal conditions for the formation of tunnels, are not usually affected by tunnel erosion, perhaps because the total build-up of runoff is not great enough to initiate tunnels. Such short slopes are common at the end of spurs between valleys and tend to be less than 200 feet in length. At the other extreme, other parts of Banks Peninsula have slopes over 1000 feet long with the possibility of a correspondingly
greater build up of runoff. It appears the longer the slope the larger are the tunnels that are formed. On the Fort Hills, where the slopes are relatively short (less than about 800 feet), the tunnels seldom extend to more than about 5 feet below the surface before collapsing. In Prices Valley, where the total slope length is over 1000 feet, tunnel systems in a partial state of collapse extend down to 10 feet below the surface. Similarly, tunnels in Shelly Bay, where the slope length is about 2000 feet, are commonly over 7 feet deep. This is possibly due in part to the fact the hard pan occurs at greater depths at the bottom of longer slopes (Chapter 6), and in part to the increased volume of water available for erosion and transport of debris.

DISCUSSION

Certain relationships between the slope parameters of altitude and aspect, and the occurrence of tunnelling have been shown and explanations proposed. However, the relationship between slope angle and length, and tunnel erosion are less clear and apparently far from simple. It seems that if the angle is too low (less than about $10^\circ$), or the slope too short (less than about 200 feet), tunnels do not form. It appears, from the limited data collected, that tunnels may form on loess covered slopes on a wide range of angles and lengths above these minimum values. However it also appears that many slopes with a similar range of angles
and lengths, and with ideal altitude and aspect conditions for the formation of tunnels, are not affected. It is possible these relationships are being masked by the effects of variations in the other slope parameters and in micro-climatic, soil and vegetation conditions. Thus, within a certain range of slope angles and lengths (above 10° and 200 feet), variations in these other factors may be more important in influencing tunnel erosion than variations in slope angle or length.

Interrelationships between climate, vegetation and soil are demonstrated in Chapters 3, 4 and 6. These in turn are affected by slope, especially altitude and aspect, but also, particularly in the case of soil, by angle and length (see Chapter 6). The slope parameters of altitude, aspect and length have been largely determined by the topographic nature of the underlying volcanic rock, and by the processes that lead to the deposition of the loess. However, the present slope angles of the loess deposits are a response to past slope forming processes which were in turn influenced by the climatic, vegetation and soil conditions.
CHAPTER SIX

INTRODUCTION

The soils of Banks Peninsula affected by tunnel erosion are yellow-grey earths. A full account of the properties and classification of this soil type and its occurrence in the South Island is given in Soil Bureau Bulletin 27 (pp. 22-25). Briefly, yellow-grey earths are formed mainly on loessial parent materials under rainfalls ranging from about 20 to 30 inches per annum with a tussock grassland cover at the time of European occupation. Seasonal moisture deficiency is a characteristic of these soils, as is the occurrence of a hard, compact pan in the subsoil.

The chemical properties of these soils vary widely with the climatic conditions under which they are formed. At the dry limit, where rainfall may be as low as 20 inches per annum, weathering and leaching are weak and their properties approach those of the adjacent brown-grey earths. At the wet limit, weathering is more pronounced, leaching is moderate to strong and their properties approach those of the intergrades between yellow-grey and yellow-brown earths. Clay content, commonly between 18 and 20%, tends to increase the wetter the climate. The chief clay minerals are hydrous micas and illite.

Tunnelling is almost entirely confined to a sub-type of the Takahe soil, namely the Takahe hill complex. The Takahe soil has been described for the Heathcote County
by Fitzgerald (1966) and this soil type has subsequently been mapped for the whole of Banks Peninsula. (Soil Bureau Bulletin 27, sheet 9 and figure 9.)

Very limited data concerning the physical and chemical properties of the Takahe soils are available but as the properties of many of the other loess derived yellow-grey earths are very similar much of the discussion is based on data concerning these other soils (see Soil Bureau Bulletins 26 and 27). Of particular relevance and use was data concerning the Withers and Waipara silt loams, soils which are very similar to the Takahe soils, and are also severely affected by tunnel erosion.

Takahe soils occur on the lower slopes from sea level to an altitude of about 1000 feet and have the characteristics of weakly leached yellow-grey earths. They have grey top soils, overlying pale yellow to yellowish brown sub soils with a compact layer (pan) about 18 to 30 inches from the surface. In the winter, these soils may absorb moisture in excess of field capacity, but in spring and summer evapotranspiration exceeds moisture supply and they dry out quickly. This limits plant growth during the summer.

The Takahe soil can be divided into three sub groups, the Takahe silt loam, the Takahe silt loam, easy rolling phase and the Takahe hill complex.

The Takahe silt loam occurs on the rolling tops of
FIGURE 9
Soil Map Showing Loess Derived Soils
SOILS ON ROLLING LANDS AND HILLS

YELLOW-GREY EARTHS

- Takahe 1
- Takahe-Kiwi 2

YELLOW-GREY TO YELLOW-BROWN EARTH INTERGRADE

- Pawson 3

LOWLAND YELLOW-BROWN EARTHS

- Akaroa 4
spurs. When the soil dries out, cracks form in the compact horizon but only in extremely dry summers do they extend into the loess below.

The Takahe silt loam, easy rolling phase, occurs on gently undulating to easy rolling spurs. These soils are very similar to the Takahe silt loam but they retain moisture for longer periods and do not dry out to the same extent in summer.

The Takahe hill complex occurs on strongly rolling and moderately steep short slopes. This is the subgroup most susceptible to tunnelling and is described in detail in subsequent parts of this thesis. Tunnelling may occur in the other sub groups, especially on W.N.W. facing slopes.

Tunnel erosion also affects the intergrades between the Takahe and the Kiwi soils, the latter being formed on predominantly loess covered steeper slopes at higher altitudes. Tunnel erosion is probably not initiated in these soils but results from the upslope extensions of tunnels which started in the Takahe soil (see Harris 1952).

It is evident, from a comparison of figures 4 and 9, that a very close relationship exists between tunnelling and the Takahe soils. Some notable exceptions occur, especially in the vicinity of Port Levy where tunnelling apparently occurs on yellow-grey - yellow-brown earth intergrades and even yellow-brown earths. However, the scale
at which these soils are mapped on the original source
map is large (1 : 250,000) and subtle variations in soil
type cannot be mapped at this scale. The soils of a
tunnelled area in the vicinity of Port Levy (Site T figure 22)
had a definite "hardpan", indicative of a yellow-grey
earth, but this was not very distinct in appearance. The
soils of this area are mapped as Pawson soils which are
described as having a very poorly developed "hardpan" or
no "hardpan" at all.

A more detailed study of the relationship between
tunnelling and soil type was made for the Heathcote County
portion of the Port Hills, an area 5 miles by 2, extending
from Cashmere Valley to Mount Pleasant. The sub groups of
the Takahe soil have been mapped in detail by Fitzgerald
(1966) and the areas affected by tunnelling have been mapped
by Hosking (1962, figure 13) and can be identified on
aerial photographs. As far as could be determined, tunnelling
was almost entirely confined to the Takahe hill com-
plex. In a few places in upper Bowenvale, St. Martins,
Avoca, Horotane and Heathcote Valleys, tunnelling appeared
to extend beyond the Takahe hill complex into the Kiwi
soils. Also, in the vicinity of St. Martins and Avoca
Valleys and in Cashmere Valley, tunnels extended into the
Takahe silt loam. However, it appeared in all of these
cases the tunnels were headward extensions of tunnels de-
veloped in the Takahe hill complex.
THE SOIL PROFILE

All subsequent soil descriptions refer to the Takahe hill complex unless otherwise stated. The profiles, structure, chemical and physical properties of the subgroups are very similar (Soil Bureau Bulletins 26, 27, Fitzgerald, 1966 and tables 7 and 8).

The profiles of Takahe hill complex soils "usually consist of 7 inches of a greyish brown powdery loam with a weakly developed very firm, nutty granular structure, passing diffusely into 8 inches of friable pale yellow silt loam overlying a very firm pale yellow silty clay loam. This becomes sandier below 30 inches and has many distinct fine yellowish red mottles" (Fitzgerald 1966 pg. 15 and figure 10 and plates 9 and 10).

The moisture supply to these soils is less, and the evaporation rate greater, than in the soils of the rolling lands. This has resulted in the compact horizon being permanently fissured and cracked.

The compacted horizon tends to occur deeper in the profile down slope due to erosion on the upper part of the slope where there is less moisture and vegetation and the soil surface is more susceptible to sheet erosion. Material eroded is transported down slope, increasing the thickness of soil above the compacted horizon (Griffiths pers. comm. See figure 21). This effect is not so marked in the Port Hills area, although some good examples occur,
FIGURE 10
Takahe Hill Complex Soil Profile
GREYISH BROWN POWDERY LOAM WITH A WEAKLY DEVELOPED VERY FIRM NUTTY GRANULAR STRUCTURE

FRIABLE PALE YELLOW SILT LOAM

VERY FIRM PALE YELLOW SILTY CLAY LOAM

SANDIER

SURFACE SOIL LAYER (S-LAYER)

COMPACTED LAYER (C-LAYER)

PARENT MATERIAL LOESS LAYER (P-LAYER)
Plate 9. Soil Profile - Francis Valley. The extent of the C layer indicated between the fingers.

Plate 10. Soil Profile - Francis Valley. Note the apparent disruption of the C layer to the right of the tape.
for example at sites C and D on the east side of St. Martins Valley (plate 11). Where the slopes are long, the effects are usually more obvious, for example Prices Valley and Shelly Bay (site P).

Fitzgerald and others in the Soil Bureau describe the hardpan as being part of the B horizon of the soil, implying it is part of the active soil system. However, Kaeside (1964) argues that the hardpan is a fossil feature inherited from the period of loess deposition and is not a product of the current pedological environment. He says the use of pan or hardpan for this layer implies it is pedogenic in origin and suggests that as it is a fossil feature, it should be called a fossil pan, C pan or loess pan.

To avoid the problem of deciding to what extent the soil horizons, especially the hardpan, are a result of, or influenced by, current pedological processes, the soil will be considered in terms of three layers:

1. the surface soil layer (S layer);
2. the compacted layer (C layer) and
3. the parent material loess layer (P layer)

The term soil refers to the profile as a whole including the P layer (figure 10).

SOIL PHYSICS
Texture and Mineralogy

The basic soil separate classes (sand, silt and clay) can be delimited in several different ways. The N.Z.
Plate 11. Soil Profile - St Martin's Valley.

Note the greater thickness of the S layer compared with Plates 9 and 10.
Soil Bureau and Department of Agriculture use the International System, and all previous size analyses of loess on Banks Peninsula have been expressed using this system.

Another system is the Wentworth or Phi scale. This is a logarithmic scale, and is considered to express the hydrodynamic properties of the various separates more accurately than the International System (Krumbein and Pettijohn 1938, Chapter 4).

A third system is the U.S. Department of Agriculture System. This gives a close approximation to the size classes of the Wentworth scale. Most of the literature on soil erodibility concerns North American soils and uses this system and this is the one used here.

Mechanical analyses for loess and loess derived soils, expressed in the International System, are given in Sparrow (1948), Birrell and Packard (1953), Hosking (1962), Fitzgerald (1966), Langbein (1967) and Soil Bureau Bulletins 26 and 27.

Six samples from two sites in Cashmere Valley were analysed in detail and their particle size distributions are shown in figures 11 to 16. From cumulative curves of these distributions, the percentages of sand, silt and clay were abstracted and expressed in terms of the three systems outlined above (table 3). The Phi and U.S.D.A. systems give similar results. However, much of what is classed as fine sand in the International System is classed as silt in the U.S.D.A. system.
Table 3.
The Percentage of Silt, Sand and Clay in the Cashmere Valley samples a to f Expressed in Terms of Three Different Textural Classifications

(a) International Classification

<table>
<thead>
<tr>
<th>Sample</th>
<th>Clay &lt; 0.002 m.m. %</th>
<th>Silt &lt; 0.002 m.m. %</th>
<th>Fine Sand &lt; 0.2 mm %</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>20</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>b</td>
<td>19</td>
<td>31</td>
<td>50</td>
</tr>
<tr>
<td>c</td>
<td>15</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>d</td>
<td>15</td>
<td>31</td>
<td>54</td>
</tr>
<tr>
<td>e</td>
<td>18</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>f</td>
<td>14</td>
<td>31</td>
<td>55</td>
</tr>
</tbody>
</table>

(b) Ø Scale (Wentworth scale)

<table>
<thead>
<tr>
<th>Clay &lt; 8Ø</th>
<th>Silt &lt; 4Ø</th>
<th>V.Fine Sand 3Ø</th>
<th>11Ø</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0039mm</td>
<td>0.0625mm</td>
<td>&lt; 0.125 mm</td>
<td>&lt; 0.00005mm</td>
</tr>
<tr>
<td>a</td>
<td>24</td>
<td>70</td>
<td>6</td>
</tr>
<tr>
<td>b</td>
<td>22</td>
<td>72</td>
<td>6</td>
</tr>
<tr>
<td>c</td>
<td>21</td>
<td>72</td>
<td>7</td>
</tr>
<tr>
<td>d</td>
<td>18</td>
<td>70</td>
<td>12</td>
</tr>
<tr>
<td>e</td>
<td>22</td>
<td>69</td>
<td>9</td>
</tr>
<tr>
<td>f</td>
<td>17</td>
<td>74</td>
<td>9</td>
</tr>
</tbody>
</table>

(c) U.S. Department Agriculture Classification

<table>
<thead>
<tr>
<th>Clay &lt; 0.002 m.m.</th>
<th>Silt &lt; 0.05 m.m.</th>
<th>V.Fine Sand &lt; 0.1 mm</th>
<th>&lt; 0.001 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>20</td>
<td>67</td>
<td>13</td>
</tr>
<tr>
<td>b</td>
<td>19</td>
<td>69</td>
<td>12</td>
</tr>
<tr>
<td>c</td>
<td>15</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>d</td>
<td>15</td>
<td>66</td>
<td>19</td>
</tr>
<tr>
<td>e</td>
<td>18</td>
<td>65</td>
<td>17</td>
</tr>
<tr>
<td>f</td>
<td>14</td>
<td>69</td>
<td>17</td>
</tr>
</tbody>
</table>
FIGURES 11 - 16

Histograms and Cumulative Curves of the Particle Size Distribution for Cashmere Valley. Samples a to f
SAMPLE a

CUMULATIVE CURVE

% 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0

10 9 8 7 6 5 4 3

CLAY  SILT  SAND

U.S.D.A. SYSTEM
SAMPLE b

% 

100
90
80
70
60
50
40
30
20
10
0

10 9 8 7 6 5 4 3 2

CLAY | SILT | SAND
SAMPLE e

%  

0 10 20 30 40 50 60 70 80 90 100

Ø  

CLAY | SILT | SAND
The mechanical analyses for soils at twelve sites (appendix 1) are given in table 10 and plotted on a soil texture triangle (figure 17).

Discussion of the Mechanical Analyses

**Sand** Usually 7 to 15% of the sample consists of sand and nearly all of this is in the very fine sand class (0.05 - 0.1 m.m.). Most samples contain some volcanic rock fragments (up to 30% of the total sand fraction and commonly up to granule size). The percentage of sand varies from locality to locality, but in any one profile it appears to be very constant from layer to layer. These results do not confirm Fitzgerald's observation that the soil becomes sandier with depth, especially below about 30 inches (table 4, pg. 22 in Fitzgerald 1966). However, he used the International System and it appears what he called fine sand would be called coarse silt in the U.S.D.A. system. The results in table 10 indicate there is no trend towards a marked increase in silt with depth (U.S.D.A. system), and it appears likely that this discrepancy can be accounted for by assuming the silt fraction in the F layer is coarser than that in the C layer.

**Silt** The dominant texture class is silt and the detailed particle size distributions for Cashmere Valley indicate the mode falls in the coarse silt range. Almost every sample had more than 50% silt. As the percentage of sand remains approximately constant from layer to layer the higher the percentage of clay the lower the percentage
FIGURE 17

Soil Texture Triangle Showing the Texture of Samples from 12 Sites
of silt. Consequently, in general, the highest percentage of silt is found in the S layer with C and P layers having approximately the same silt percentage. However, as has been pointed out in the section on sand, the silt in the P layer may be coarser than that in the C layer. As will be shown, small changes in the percentage of silt can lead to large variations in soil erodibility and this emphasises a need for more detailed subdivision of the textural classes.

Quartz and plagioclase feldspar usually together make up nearly 90% of most greywacke derived loesses (Raeside 1964). The remaining 10% or so consist of various clay minerals and locally derived minerals.

Clay Clay usually makes up about 15 to 35% of the sample and is generally lowest in the S layer and, on an average, slightly higher in the C than in the P layer (table 14). However, unlike the sand fraction, the clay percentage varies greatly between layers. A high percentage of the clay is colloidal. The upper limit for colloidal clay is set at 0.001 m.m. by many workers (Baver 1956). 30 to 80% of the clay in samples a to f was found to be colloidal (table 3).

The mineralogy of the clays in loess derived yellow-grey earths has been described by many workers (Fieldes and Swindale 1954, Fieldes 1958, Fieldes and Taylor 1961, Ives 1968 and Soil Bureau Bulletins 26(2)
and 27). The predominant clay minerals are illite and related hydrous micas, with small amounts of clay vermiculite and montmorillonite. (Soil Bureau Bulletin 26(2)). These are platy clays derived mainly from mica which is itself almost entirely absent. Other clay types are often present in small quantities. An analysis of the Withers Hill soil, which is very similar to the Takahe soil, showed that beside the clay minerals mentioned above, there were appreciable amounts of amorphous hydrous micas and amorphous hydrous iron oxide and primary quartz (Fieldes and Taylor 1961). Illite is a weakly weathered, non-expanding clay whereas clay vermiculite and montmorillonite represent later stages of weathering of micaceous clays and swell and shrink on wetting and drying (Soil Bureau Bull. 26(2) and figure 18). The sub soils of the yellow-grey earths generally contain more clay vermiculite than the top soils (Fieldes and Taylor, 1961).

A consideration of the clay mineralogy is important, not only in understanding pedogenic processes, but in explaining the structure and erodibility of the yellow-grey earths. Little is known about the genesis of these clays, that is, to what extent they are pedogenic and to what extent inherited from the parent material loess at the time of deposition.

It is generally accepted the compaction of the C layer is largely the result of the swelling and shrinking of the clay vermiculite and montmorillonite in the sub
FIGURE 18

Yellow-Grey Earth Clay Minerals and their Properties
MICA ➔ ILLITE ➔ CLAY VERMICULITE ➔ MONTMORILLONITE

<table>
<thead>
<tr>
<th>C.E.C.</th>
<th>Stage of Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>VERY LOW</td>
<td>2A</td>
</tr>
<tr>
<td>30</td>
<td>2B</td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

SOURCE: SOIL BUREAU BULLETIN 26 (2)
TABLES 6-32, 6-35 (MODIFIED)
soil, leading to a re-orientation of the particles into a more compacted state (Fieldes and Taylor 1961). Compaction has also occurred in the F layer, but to a lesser extent. However, there is much argument as to whether compaction is a current pedological phenomenon or whether it is inherited from the period of loess deposition (Hae-side 1964).

**Atterberg Limits (table 4)**

These were not measured but some data are available for Cashmere Hills loess (Alley 1966) and for Tai Tapu and Onawe Peninsula loess (Langbein 1967). Langbein showed for his samples that the liquid limit varied directly with the variation in the mean or median diameter of the sample or the percentage of sand. Alley concludes that, as the low liquid limit indicates, loess reacts badly to water and that saturation breaks down the cohesion to zero.

**Bulk Density and Porosity**

The sub soils of the yellow-grey earths are characterised by high bulk densities and low porosities. Bulk densities of sub soils range from about 1.60 gm/c.c. (40% porosity) to 1.93 gm./c.c. (equivalent to 28% porosity) (Arlidge 1966). These are high to very high bulk densities, and very low porosities and such values are uncommon for other soil groups. Some bulk densities are shown in tables 5 and 6. Others are given in Arlidge
### Table 4

**Atterburg Limits**

<table>
<thead>
<tr>
<th>Liquid Limits</th>
<th>Plastic Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cashmere Hills (Alley 1966)</td>
<td>20 - 22%</td>
</tr>
<tr>
<td>Tai Tapu  (Langbein 1967)</td>
<td>18 - 25%</td>
</tr>
<tr>
<td>Onawe Peninsula (Langbein 1967)</td>
<td>20 - 33%</td>
</tr>
<tr>
<td>Cashmere Hills (Alley 1966)</td>
<td>17 - 19%</td>
</tr>
</tbody>
</table>
Table 5
Bulk Densities (gm/c.c.)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Francis Valley</th>
<th>Lower Cashmere Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>S layer</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>C layer</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>F layer</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 6
Bulk Densities and Porosities

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (inches)</th>
<th>% Clay</th>
<th>Bulk Density (gm/c.c.)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0-6</td>
<td>20</td>
<td>1.00</td>
<td>61</td>
</tr>
<tr>
<td>B</td>
<td>18-21</td>
<td>29</td>
<td>1.93</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>24-29</td>
<td>20</td>
<td>1.84</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>below 47</td>
<td>23</td>
<td>1.84</td>
<td>32</td>
</tr>
</tbody>
</table>

Source: R.Q. Packard in "Soil Groups of N.Z."
(1966) which show the increase in bulk density and decrease in porosity in the sub soils.

The example from the Waipara soil seems similar to that of the Takahe hill complex, that is, a highly compacted layer underlain by less highly compacted material. As Packard in "Soil Groups of N.Z." points out, values of porosity below 40% are very low. Arlidge 1966, obtained values as low as 28% and this value he considered must be near the ultimate limit for a non cemented silt loam which has not apparently been subjected to heavy loading.

SOIL CHEMISTRY

The following properties are considered to be the most important ones in influencing the erodibility of the Takahe soils. Some of the limited data available is presented in tables 7 and 8 to illustrate the discussion.

(1) Calcium Carbonate

Unlike many deposits in North America, Europe and Asia there is generally little free calcium carbonate in New Zealand loess deposits. Concretions of calcium carbonate found in Banks Peninsula loess appear to be associated with enclosed Moa bones (Sparrow 1948, Alley 1966).

(2) Soil Acidity

The loess derived yellow-grey earths of New Zealand are generally slightly to moderately acid. The S layers of the Takahe soils are moderately acid (pH 5.3 -
Table 7

Chemical Properties of a Takahe Hill Soil Sample

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (inches)</th>
<th>pH</th>
<th>Organic C %</th>
<th>C.E.C. m.e.%</th>
<th>Na m.e.%</th>
<th>ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0 - 7</td>
<td>5.5</td>
<td>4.4</td>
<td>15.9</td>
<td>0.5</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>11-19</td>
<td>6.1</td>
<td>0.9</td>
<td>10.3</td>
<td>0.5</td>
<td>4.3</td>
</tr>
<tr>
<td>C</td>
<td>19-27</td>
<td>6.3</td>
<td>0.5</td>
<td>11.7</td>
<td>0.8</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>27-37</td>
<td>5.9</td>
<td>0.5</td>
<td>18.4</td>
<td>2.2</td>
<td>14.3</td>
</tr>
<tr>
<td>P</td>
<td>37-43</td>
<td>5.9</td>
<td>0.4</td>
<td>13.5</td>
<td>3.4</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Source: Fitzgerald (1966, pg. 2C) modified

Table 8

Chemical Properties of a Takahe Silt Loam Sample

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (inches)</th>
<th>pH</th>
<th>Organic C %</th>
<th>C.E.C. m.e.%</th>
<th>Na m.e.%</th>
<th>ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0- 9</td>
<td>5.3</td>
<td>5.5</td>
<td>20.4</td>
<td>0.8</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>9-17</td>
<td>5.5</td>
<td>1.2</td>
<td>10.4</td>
<td>0.6</td>
<td>6.0</td>
</tr>
<tr>
<td>C</td>
<td>17-23</td>
<td>5.7</td>
<td>0.6</td>
<td>13.5</td>
<td>1.3</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>23-29</td>
<td>5.6</td>
<td>0.4</td>
<td>13.3</td>
<td>1.8</td>
<td>13.5</td>
</tr>
<tr>
<td>P</td>
<td>41-45</td>
<td>5.1</td>
<td>0.2</td>
<td>9.4</td>
<td>2.3</td>
<td>41.0</td>
</tr>
</tbody>
</table>

Source: Soil Bureau Bulletin 27 pg. 98 (modified)
5.5) with perhaps a slight increase in pH in the C layer. Soil acidity is indicative of the degree of leaching and the Takahe soils are considered to be slightly to moderately leached.

(3) **Organic Matter**

The Takahe top soils have a medium organic matter content. However, the sub soils, especially the C and P layers are characterised by very low organic matter contents.

(4) **Cation Exchange Capacity (C.E.C.)**

The C.E.C. of a soil is indicative of its ability to absorb cations. The Takahe soils, like most other yellow-grey earths, have a medium to low C.E.C. Generally silt and sand particles are chemically inert and the clay and humus particles form the chemically active fraction of the soil. However, organic matter is only present in significant amounts in the S layer so it would be expected that the C.E.C. of the S layer would be much larger than that of the other layers. For Takahe and most other similar soils, the C.E.C. of the top soil is only a little higher than that of the sub soil layers. This may be because, in general, there is less clay in the top soils and clay vermiculite, a clay with a higher C.E.C. than the dominant illite, is more common in the sub soils.

(5) **Sodium (Na)**

The cations Ca, Mg, K and Na are all important when considering both plant growth and soil erodibility. Es-
especially important, in terms of soil erodibility, is the presence or absence of Na ions in the soil. In Australia, the presence of Na in the sub soils has been shown to play an important role in tunnel erosion (Downes 1956, Monteith 1954, Newman and Phillips 1957 and Charman 1969, 1970).

The data on exchangeable sodium in tables 7 and 8 indicate that in the Takahe soils the amount of Na rises sharply with depth to very high levels, especially in the P layer. It is generally assumed that there is a marked increase in Na with depth in yellow-grey earths (Ives 1968). However, he looked at the Na contents of 17 profiles in the published literature and found only 6 showed a constant increase in Na with depth (table 9).

In Australia, in soils susceptible to tunnelling and with a high exchangeable sodium content, it has been shown that the salt is mainly Cyclic in origin, that is, salt brought in by rain coming off the sea. In a study by Downes (1956), it was calculated that the amount deposited varied from about 300 lbs/acre/year on the coast to 5 lbs/acre/year 250 miles inland.

It appears the Na in the Takahe soils is cyclic in origin. Mr H. Horne, Lincoln College, has been measuring the mineral content of rain water at various locations in Canterbury. At Lincoln and on Banks Peninsula the amount of cyclic salt deposited (NaCl) is about 50 lbs/acre/year.
Table 9

Variation in Exchangeable Sodium Content Between Horizons

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>A rise through A and B to C</td>
</tr>
<tr>
<td>3</td>
<td>A rise from A to B and decrease to C</td>
</tr>
<tr>
<td>1</td>
<td>A decrease from A to B and a rise to C</td>
</tr>
<tr>
<td>3</td>
<td>A decrease through A and B to C</td>
</tr>
<tr>
<td>4</td>
<td>No change</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>17</strong></td>
</tr>
</tbody>
</table>

Source: D. Ives, 1968.
decreasing inland to about 5 lbs/acre/year at Cass (pers. comm.). He estimates that on the coastline the amount could be much higher, in the order of 250 lbs/acre/year.

**SUMMARY AND DISCUSSION**

The relationship between soil properties and tunnel erosion is discussed in terms of soil erodibility and subsurface runoff in Chapters 7, 8 and 9. The sub groups of the Takahe soils are very similar physically and chemically although they do differ in one important respect, namely the greater degree of soil cracking in the Takahe hill soils. It appears the reasons tunnels form on the Takahe hill soils are related to a consideration of their site characteristics (slope, vegetation, microclimate and runoff characteristics), which differ from those of the Takahe silt loam.

So far in this study an attempt has been made to separate from the complex interrelations that exist the individual relationships between tunnel erosion and the factors in the erosion model. These relationships have been described to a greater or lesser degree and explanations have been put forward to account for them, in some instances with a considerable amount of supporting evidence. In other cases, where little or no evidence has been presented, tentative explanations have been proposed or suggestions and findings of other workers outlined, that may or may not be confirmed with further investigation.
It is evident, from a comparison of figures 6, 7 and 9 that the spatial variations of the climatic vegetation and soil factors are closely interrelated. These interrelationships have been described where relevant and to a certain extent explained. A comparison of these patterns with figure 4 shows that a close spatial relationship exists between the climate, vegetation and soil factors of the erosion model and tunnel erosion.
CHAPTER SEVEN  

SOIL ERODIBILITY RESULTS

INTRODUCTION

Most studies of soil erosion and soil erodibility are confined to a consideration of the erosion and erodibility of surface soils. When considering sub surface erosion the importance of many of the variables changes. For example, a consideration of the effect of the dispersion of the surface soil by raindrop impact is no longer directly relevant as it does not lead directly to erosion at sub surface levels. However, its indirect effects are important in that splash effects may cause sealing of the surface and thus lower the rate of percolation into the sub soil.

Soil erodibility may be assessed either by actual measurement of the soil loss under controlled conditions, or by isolating certain soil properties as indices of erodibility (Bryan 1968(a)). The latter approach has been used in this study.

INDICES OF ERODIBILITY OF THE THREE LAYERS

That the material in the P layer is highly erodible compared with the C and S layers has long been realised. However, no attempt has been made to express the differences in erodibility in a quantitative manner.

In Australia, the dispersal index test (Charman 1969) and the clay dispersion test (Rallings 1966) have been
used as indices of the erodibility of soils susceptible to tunnel erosion. The dispersal index (D.I.) test expresses soil erodibility in a quantitative manner and a modified version of this test was used here. The clay dispersion test, a qualitative index of erodibility, was also used, but in a modified form that allowed a quantitative estimate of the degree of clay dispersion. Two different methods, using the principle of clay dispersion as described by Rallings, were devised, the C.D.A. and C.D.B. tests. These methods measure the dispersion of the clay fraction, not aggregate stability. One, the D.I. test, simulates in an extreme manner the effects of running water and the other, the clay dispersion test (in its two forms), the effect of still water conditions. The latter probably better approximates natural conditions because it appears the rate of sub surface water flow is likely to be slow.

Two other tests were devised to examine the stability of the aggregates as a whole and not just the clay fraction. Again one of these, the aggregate stability (A.S.) test, is indicative of the effects of running water and the other, the disintegration B (D.B.T.) test, of still water conditions. The D.B.T. and C.D.B. tests were carried out on the same aggregate at the same time.

Another index of erodibility used by Rallings (1966) was the exchangeable sodium percentage (E.S.P.) where

\[
E.S.P. = \frac{\text{exchangeable Na. (m.e. \%)}}{\text{C.E.C. (m.e.\%)}} \times 100
\]
E.S.P. for two samples, from the Takahe silt loam and the Takahe hill complex, were calculated from the data in tables 7 and 8.

Both the C and P layers have a weakly developed blocky structure and the naturally occurring aggregates are those blocks of material contained between the crack systems. The aggregates used in these tests were artificial in that they were produced from a breakdown of these large, naturally occurring aggregates.

RESULTS

The results are shown in tables 10 to 13 and figures 19 and 20. Table 15, a summary of results, shows that in terms of the A.S., C.D.B. and D.B.T. tests, the P layer is significantly more erodible than the C layer. The D.B.T. test significantly distinguishes between the S and C layers whereas the A.S. (30 secs pre soaking period) and C.D.B. tests do not. However, as the pre soaking period before shaking in the A.S. test is increased, the differences in erodibility between the S and C layers becomes more and more apparent (tables 10 and 18 and figure 23). The S layer material remains relatively stable even after 12 hours pre soaking whereas the stability of the C layer rapidly falls off as the pre soaking time increases above about 5 minutes. The P layer aggregates rapidly lose their stability even with very short pre soaking periods.

The results of the D.I. test are shown graphically
<table>
<thead>
<tr>
<th>Site and Sampling</th>
<th>Textural Classes (U.S.D.A System)</th>
<th>Erodibility Tests</th>
<th>Pre soaking periods (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>% Clay</td>
<td>% Silt</td>
<td>% Sand</td>
</tr>
<tr>
<td>A 01</td>
<td>S 7</td>
<td>0 0 0 0 0 89 85 71</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>C 24</td>
<td>0 0 0 1 2</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>P 40</td>
<td>0 0 4 0</td>
<td></td>
</tr>
<tr>
<td>B 11</td>
<td>S 7</td>
<td>26 60 14 3.0 0 0 0 89 85 71</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>C 22</td>
<td>0 0 1 4 86 28 -</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>P 40</td>
<td>3 3 4 6</td>
<td></td>
</tr>
<tr>
<td>D 31</td>
<td>S 7</td>
<td>7 82 10 2.1 0 0 0 89</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>C 26</td>
<td>0 0 0 3 67</td>
<td></td>
</tr>
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<td>33</td>
<td>P 46</td>
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<td>S 7</td>
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<td>42</td>
<td>C 22</td>
<td>0 0 2 79 -</td>
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<td></td>
</tr>
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<td>52</td>
<td>C 20</td>
<td>0 0 1 0</td>
<td></td>
</tr>
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<td>53</td>
<td>P 38</td>
<td>0 0 1 0</td>
<td></td>
</tr>
<tr>
<td>J 61</td>
<td>S 8</td>
<td>6 0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>C 20</td>
<td>0 0 1 0</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>P 48</td>
<td>3 3 4 4</td>
<td></td>
</tr>
<tr>
<td>Site No.</td>
<td>Layer</td>
<td>Depth (inches)</td>
<td>% Clay</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>---------------</td>
<td>--------</td>
</tr>
<tr>
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<td>S</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>72</td>
<td>C</td>
<td>22</td>
<td>23</td>
</tr>
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<td>73</td>
<td>P</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>M 81</td>
<td>S</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>82</td>
<td>C</td>
<td>22</td>
<td>19</td>
</tr>
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<td>83</td>
<td>P</td>
<td>40</td>
<td>16</td>
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<td>S</td>
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<td>C</td>
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<td>C/P</td>
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<td>20</td>
</tr>
<tr>
<td>95</td>
<td>C/P</td>
<td>36</td>
<td>18</td>
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<td>F</td>
<td>42</td>
<td>13</td>
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<td>O 101</td>
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<td>6</td>
<td>11</td>
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<tr>
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<td>C</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>103</td>
<td>F</td>
<td>44</td>
<td>29</td>
</tr>
<tr>
<td>P 111</td>
<td>S</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>112</td>
<td>C</td>
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<td>19</td>
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<td>113</td>
<td>P</td>
<td>40</td>
<td>20</td>
</tr>
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<td>S</td>
<td>6</td>
<td>6</td>
</tr>
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<td>C</td>
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<td>17</td>
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<td>42</td>
<td>7</td>
</tr>
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<td>R 131</td>
<td>S</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>132</td>
<td>C</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>133</td>
<td>F</td>
<td>48</td>
<td>7</td>
</tr>
<tr>
<td>Sample Site No.</td>
<td>Layer</td>
<td>Depth (inches)</td>
<td>% Clay</td>
</tr>
<tr>
<td>----------------</td>
<td>-------</td>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
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<td>S</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>142</td>
<td>C</td>
<td>20</td>
<td>24</td>
</tr>
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<td>143</td>
<td>P</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>T 151</td>
<td>S</td>
<td>6</td>
<td>10</td>
</tr>
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<td>C</td>
<td>34</td>
<td>32</td>
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<td>P</td>
<td>52</td>
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<td>U 161</td>
<td>S</td>
<td>6</td>
<td>15</td>
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<td>C</td>
<td>26</td>
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</tr>
<tr>
<td>163</td>
<td>P</td>
<td>45</td>
<td>64</td>
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<table>
<thead>
<tr>
<th>Slayer</th>
<th>Median Degree of Dispersion</th>
<th>Sample Differences Compared</th>
<th>Level of Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.B.A. Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S layer</td>
<td>0</td>
<td>S and C layers</td>
<td>0.05</td>
</tr>
<tr>
<td>C layer</td>
<td>1</td>
<td>C and P layers</td>
<td>N.S.</td>
</tr>
<tr>
<td>P layer</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.D.B. Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S layer</td>
<td>0</td>
<td>S and C layers</td>
<td>N.S.</td>
</tr>
<tr>
<td>C layer</td>
<td>0</td>
<td>C and P layers</td>
<td>0.01</td>
</tr>
<tr>
<td>P layer</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>D.B.T. Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S layer</td>
<td>0</td>
<td>S and C layers</td>
<td>0.01</td>
</tr>
<tr>
<td>C layer</td>
<td>1</td>
<td>C and P layers</td>
<td>0.05</td>
</tr>
<tr>
<td>P layer</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N.S. Difference not significant

In each test there were 15 samples from each layer.
Table 12
The A.S. Test (30 second pre soaking period)
The Significance of the Difference in Erodibilities of the Three Layers using the "t test" (Folk 1965)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Mean %</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S layer</td>
<td>77</td>
<td>12</td>
</tr>
<tr>
<td>C layer</td>
<td>76</td>
<td>13</td>
</tr>
<tr>
<td>F layer</td>
<td>28</td>
<td>14</td>
</tr>
</tbody>
</table>

Sample Differences Compared Level of Significance

<table>
<thead>
<tr>
<th>Differences Compared</th>
<th>N.S.</th>
<th>0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>S and C layers</td>
<td>N.S. Difference not significant</td>
<td></td>
</tr>
<tr>
<td>C and F layers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

12 samples from each layer
Table 13
A Summary of the Significance of the Differences in Erodibility of the Three Layers for the Various Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>C.D.A.</th>
<th>C.D.B.</th>
<th>D.B.T.</th>
<th>A.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S and C layers</td>
<td>0.05</td>
<td>N.S.</td>
<td>0.01</td>
<td>N.S.</td>
</tr>
<tr>
<td>C and P layers</td>
<td>N.S.</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>
FIGURE 19

Results of the C.D.B. and D.B.T. Tests
CDB TEST

DEGREE OF DISPERSION

SITE

DBT TEST

DEGREE OF DISINTEGRATION

SITE

- S LAYER SAMPLES
- C LAYER SAMPLES
- P LAYER SAMPLES
FIGURE 20

Results of the D.I. Test
in figure 20. The dispersal index decreases, and hence soil erodibility increases, from the S through the C to the P layer. However, the method as it is used here is suspect for the reasons outlined in appendix 2. Probably the values for the S and C layers are lower than those determined. Charman (1969) concluded for the soils he worked with that if the dispersal index was less than 3, then the soil could be considered to be susceptible to tunnel erosion. If this limit was used here then all the C layers, and many of the S layers, of the Takahe hill complex soils could also be considered to be susceptible to tunnelling. The soils considered are different, making any meaningful comparison between the two examples impossible. However, it is apparent that the dispersal indices for both the C and P layers are very low.

The C.D.A. test distinguishes between the S and C layers but not between the critically important C and P layers. However, this test was also suspect, for reasons outlined in appendix 2.

Finally, E.S.P. values increase markedly with depth in both the Takahe soil samples (tables 7 and 8). The effect of Na (and E.S.P.) in influencing tunnel erosion is discussed in the next chapter. Rallings (1966) studied failures in dams constructed from soils that were susceptible to piping. He found that dams that failed had at least one soil with an E.S.P. greater than 13. He also
found that where E.S.P. was greater than 8 the clays tended to disperse. The soils of the two areas are very different, making direct comparison meaningless, but there is a marked increase in E.S.P. with depth in the Takahe soil samples to much greater values than those associated with piping in the soils studied by Rallings.

In all cases the S layer is shown to be highly resistant to erosion compared with the layers below. The P layer is generally shown to be highly erodible, especially in terms of aggregate stability. However, the erodibility of the C layer appears to vary considerably (see figure 19). Griffiths (pers. comm.) considers that the C layer is highly variable in nature. He recognises in the field, from personal experience, at least four types of C layer, for example, one that is extremely hard when dry and remains comparatively hard on wetting (the usual case), and another which is extremely hard when dry but breaks down readily on wetting. Also the C layer may be absent or greatly fragmented due to disruption by erosional processes such as slumping, or collapse of tunnels (plate 10).

**SUMMARY**

Three of the tests, the A.S., C.D.B. and D.B.T. tests, show there is a significant difference in erodibility between the C and P layers. All the tests show that, in general, the P layer is highly erodible. As Cumberland (1944 pg. 89) points out, "Loess is perhaps the
most highly erodible sub soil material in New Zealand." Finally it appears, from the limited data presented here, there could be some relationship between E.S.P. and tunnel erosion as has been shown in Australia.

DISCUSSION

It is implied that the results of the tests used, when allowance is made for their practical limitations, indicate the true resistance of the soil to erosion by the processes leading to the initiation and subsequent development of tunnels. In practice, the degree to which these results are truly indicative of soil erodibility under these conditions would be very difficult to determine. Any variation in the techniques used in these tests would lead to different values for the indices of erodibility. This is exemplified by the pre soaking times in the A.S. and the variations in the results that occur. Thus each method must be operationally defined, and comparisons of erodibility made within the limits of these operational definitions. These indices of erodibility could not, without justification, be applied outside Banks Peninsula. This makes comparison between different areas difficult, for example, as has been shown, between Banks Peninsula and Australia.

Besides the problems of operational definitions as discussed above, all these methods involve subjecting the aggregates to a disintegrating process that may not occur
under natural conditions. Emerson (1954) showed that the breakdown of aggregates on wetting is due to slaking (disruption by entrapped air on wetting), and to the dispersion of clays. However laboratory techniques for slow wetting of aggregates are relatively time consuming and most workers place the aggregates straight into the container of water. This is called wetting by immersion, or flood wetting, and was the method used in all the erodibility tests applied here. Flood wetting leads to the maximum breakdown by slaking.

Water movement through the sub surface layers, either along cracks or through pore spaces in the soil before tunnels are initiated, will in most circumstances be very slow compared with the rate of wetting that a single aggregate is subject to by flood wetting. The degree of slaking under natural conditions then, is likely to be less than that under laboratory conditions. This implies that the amount and rate of aggregate breakdown in the A.S. and D.B.T. tests is likely to be artificially high. Also rapid breakdown could lead to more clay dispersion than would occur in natural conditions. However, as has been pointed out, wetting by immersion is the most rapid and convenient and easily standardised method available (Clement and Williams 1958).

Finally, it has been implied in this chapter that on Banks Peninsula tunnel erosion is confined to the P layer. However tunnels were occasionally found that were confined
to the C layer or, more commonly, to the lower portion of the S layer between the top soil and the C layer.
INTRODUCTION

It has been shown that the erodibilities of the three layers in the soil are different, that the erodibility of the P layer is very high and that it is susceptible to tunnel erosion. An explanation of the variations in soil erodibility is attempted here in terms of soil texture, organic matter content, the clay-humus complex, clay mineralogy, cementation, compaction and exchangeable sodium content. Permeability, and the ease of dispersion of the soil, are the major factors in determining the erodibility of soil (Baver 1956). All the factors mentioned above will to some extent affect both permeability and ease of dispersion of the soil.

As has been pointed out, studies of soil erodibility have been largely confined to a consideration of surface soils where erosion is a result of the action of raindrops and surface runoff, not sub surface runoff. The following studies referred to in this chapter are all largely concerned with surface soils: Robinson and Page (1950), Emerson (1954), Baver (1956), Quirk and Panabokke (1967), Bryan (1969) and Wischmeier and Mannering (1969). It is assumed here that the difference in behaviour of the soils in these different conditions is largely one of magnitude, not kind.

SOIL TEXTURE

Wischmeier and Mannering (1969) studied the relation
of soil properties to erodibility for a large number of soils and found soil texture was the most significant indicator of erodibility. They found, in general, that soils with a high silt content, and low clay and organic matter content, are the most erodible. The C and P layers are both high in silt, very low in organic matter and have medium to low clay contents (tables 7, 8 and 10). Usually soils become less erodible with a decrease in silt content, regardless of whether the corresponding increase is in the sand or clay fractions (Wischmeier and Mannering 1969). However, the percentage of silt, sand and clay must be considered in relation to other properties. They showed that erodibility is often so sensitive to small changes in particle size distribution that conventional texture classifications are far too broad to serve as reliable guides to a soil's capacity to resist erosion. The range of erodibilities of the silt loams seems to include about three quarters of the range for all soils. If this is true for Takahe soils, then the comparatively small textural differences that exist from sample to sample, especially C and P layer samples, could be very important in considering erodibility differences. The silt fraction of the P layer may be coarser than that of the C layer (chapter 6) and this could have a marked effect on the erodibilities of these layers. However the effects of these small textural variations on the erodibility of the Takahe soils is not known.
Wischmeier and Mannering's study also indicates that the arbitrary limit between silt and sand in the U.S.D.A. system is not the most logical one in terms of soil erodibility. Very fine sand (0.05 - 0.1 m.m.) particles appear to behave more like silt than sand. Therefore, in terms of erodibility, perhaps the Takahe soils can be thought of as consisting of silt with 10 to 30% clay.

Erodibility decreases as the clay fraction increases (Wischmeier and Mannering 1969). Most of this effect is probably attributable to the increased cohesiveness of the soil. Apparently clay particles themselves act as binding agents independent of organic matter (Baver 1956). The effect of increased clay percentage in decreasing erodibility decreases with increased organic matter content, and with an increased sand/silt ratio. (Wischmeier and Mannering 1969.) As both the sand/silt ratio and organic matter contents in the C and P layer are small, the sensitivity of erodibility to clay content variations will be marked. Thus the observed small overall increase in clay content in the C layer could have an increased cohesive effect and decrease the erodibility of the C layer compared with the P layer. However this difference was not significant (table 14).

**ORGANIC MATTER**

Organic matter plays a very important role, not only in aggregate stability but in aggregate formation. In general, an increase in organic matter content leads to a decrease
Table 14

Mean Clay % of the C and P Layers

<table>
<thead>
<tr>
<th>Mean Clay %</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C layer</td>
<td>22.2</td>
</tr>
<tr>
<td>P layer</td>
<td>20.1</td>
</tr>
</tbody>
</table>

16 samples from each layer

The means are not significantly different
in soil erodibility (Baver 1956). All forms of organic matter appear to have a beneficial effect, from living root matter, through decaying litter and roots, to humus and colloidal organic matter. Wischmeier and Mannering (1969) ranked organic matter content second only to soil texture as an indicator of soil erodibility. The variations in texture with depth in the Takahe soils are small compared with those of organic matter. Thus, in terms of texture, all the layers in the Takahe soil are potentially highly erodible, and the major property that separates the S layer from the layers below is its organic matter content.

Living roots, and dead and partially decomposed plant litter incorporated in the soil, have a physical binding effect on it, thus decreasing its erodibility. Also it has been shown that very fine root hairs can play a role in the formation of stable aggregates (Swarby 1950, Bryan 1969). The top layer of the Takahe soils, especially the top 6 inches, has a thick root matting compared with the C and P layers. The living root system extends into the C layer but the network is poorly developed. With increased depth the root system becomes markedly less developed and is largely absent in the P layer.

Soil fauna, for example worms, and micro organisms, play an important role in stabilising the soil and adding to its total organic matter content (Baver 1956). The effect of such organisms is greatest in the top soil where
most plant matter is found. However worm holes were occasionally observed in the C, as well as the P layer.

The stabilising effect of humus and colloidal organic matter is overall probably more important than that of living matter. Emerson (1954) noted that aggregates from arable fields (low in organic matter) wetted more quickly than those from a permanent pasture. He found that organic matter, after drying, is not easily wetted and that the higher the organic matter content of the soil the less slaking on immersion. In this study it was found that S layer samples seldom slaked at all whereas samples from the C, and especially the P, layers tended to slake very easily. Quirk and Pannabokke (1967) suggested that organic matter strengthens the coarse pores against the tendency to slake. Bryan (1969) showed with his samples that there was a marked deterioration of aggregate stability with depth, and he attributed this to the decrease in organic matter with depth. At depth the stability was governed by the clay content.

Robinson and Page (1950) showed that of the total organic matter content, the fraction associated with the clay fraction, and presumably absorbed onto the clay particles, is the most important in stabilising soil structure. They observed that slaking was the result of two processes; firstly the swelling of clays on wetting, and secondly, the pressure developed by the capillary forces of the entering
liquid on the entrapped air. Therefore to reduce slaking the prerequisites are to reduce or remove the swelling properties, and either reduce the forces exerted by the entrapped air, or strengthen the aggregate. Organic matter, especially colloidal, does all three of these. Swelling properties of the clays are reduced by the absorption of organic matter, the destructive forces of entrapped air are reduced because of the decreased wetability of the aggregate, and the aggregate is strengthened by the aggregating effect of roots and the cementing effects of colloidal organic matter.

In summary, organic matter in all forms has a stabilising effect on soil aggregates and an increase in organic matter leads to a decrease in soil erodibility. The relatively low erodibility of the S layer is due to the stabilising effects of its organic matter content. The C and P layers are potentially highly erodible because of their texture and almost complete lack of organic matter.

**CLAY-HUMUS COMPLEX**

Both organic matter and clay particles can have an independent effect on stabilising aggregates. However, as indicated by Robinson and Page, colloidal clay and organic matter usually act together and the greatest aggregate stability results from the action of the clay-humus complex. Weight for weight, the organic components of the clay-humus complex possess a much higher C.E.C. than the
inorganic components. Because humus has both positively and negatively charged components it is generally assumed that there is interaction between the clay and organic material within the soil, with the result that the C.E.C. of the clay-humus complex is probably rather less than the sum of the C.E.C.'s of the various components (Soil Bureau Bull. 26(2) pg. 67).

CLAY MINERALOGY

The predominant clay minerals in loess derived yellow-grey earths are illite and related hydrous interlayered micas with clay vermiculite and montmorillonite. Fieldes (Soil Bureau Bull. 26(2)) shows there is a marked difference between the soil structure of the yellow-grey earths and the more highly weathered, and more moist, yellow-brown earths. The sub soils of the yellow-grey earths have a massive structure, whereas the sub soils of the yellow-brown earths contain nutty aggregates and have generally a more open structure. The clay types of both are often comparable and it is possible for some yellow-grey earths to have essentially the same platy clay mineral assemblage as some yellow-brown earths. He argues it is unlikely the nature of the clays causes the difference in soil structure. He considers the massive sub soil of the yellow-grey earths is due to the colloids being in a dispersed state, whereas those of the yellow-brown earths are in an aggregated state. The amounts of free iron oxide and free alumina were each
below 1.5% in the yellow-grey earths considered, and above 1.5% in the yellow-brown earths considered, and it appears that the higher amounts of these oxides may contribute to the aggregation and improved structure of the yellow-brown earth sub soils. Also the breakdown of feldspar occurs at a faster rate in the yellow-brown earths and some fine particles of hydrous feldspar may assist in aggregate formation.

The clays in the Takahe soils are largely weakly weathered platy clays such as illite, with a low C.E.C., and their potential for binding the soil particles together is lower than that of the more weathered clays with higher C.E.C.\textquotesingle s such as clay vermiculite and montmorillonite. Also, in the C and P layers, there is almost a complete lack of colloidal organic matter, oxides of iron, and alumina and hydrous feldspar, to aid the clays in binding the soil particles into a stable structure.

CEMENTATION

Generally, cemented soil material is little altered by moisturing and its hardness persists in the wetted condition. (Taylor and Pohlen 1962 pg. 91). However, as the erodibility results show, the C layer is much more erodible than would be expected if it was cemented to any degree. Indeed, as Arbuckle (1952) points out, the ease of dispersion of pan material disposes of any theory of a cemented pan.
Even so, it is probable that small amounts of cementing take place in both the C and P layers. Organic matter is present only in small amounts in the C layer and even less in the P layer and its cementing effect will be small. Small amounts of alumina and iron oxides are released in weathering and could have a minor cementing effect. Very small quantities of silica are released in soil weathering processes operating on the Takaha soils (Griffiths pers. comm.). Finally, calcium carbonate, another major possible cementing agent, is present in small amounts.

If the C layer is a zone of accumulation (B horizon), then these cementing agents will tend to accumulate in this zone, leading to a greater degree of cementation in the C than in the P layer. However, the effect of cementation as a stabilising agent on the C layer is probably very small.

**COMPACTION**

From the discussion so far, it is apparent that the comparatively low erodibility of the S layer is due to the beneficial effects of organic matter, and that the other layers are more highly erodible. However the C layer is significantly less erodible than the P layer, the main reason being its higher degree of compaction as reflected by its very high bulk density and very low porosity (tables 5 and 6).

The mechanics of compaction are not clearly understood but it is generally agreed that it is a consequence of
alternate wetting and drying and swelling and shrinking of the clay Vermiculite and Montmorillonite clay minerals (Arlidge 1966). This leads to a re-orientation of the clay particles in the soil into a more compacted state. This re-orientation also affects the silt and sand fraction. New Zealand loess is generally poorly sorted to unsorted, with angular shaped particles of silt and sand (Young 1964, 1967). As Arlidge (1966) concludes, in such material, with about 20% clay, much of it colloidal and subject to alternate wetting and drying, it is conceivable that the particles will pack into the closest mutual arrangement.

There is much debate as to whether compaction is a current pedological phenomenon (Gibbs 1964), or is inherited from the period of loess deposition (Raeside 1964). Gibbs points out that often there is only a small range in depth where compaction is marked (as in the Takahe soils), and this favours a pedological rather than a purely geological origin.

Baver (1956) discusses in detail the increased soil structure stability that results from a closer orientation of clay particles, as in the C layer. When clay particles become oriented closer together, the cohesive forces become much stronger. Dehydration is also a basic requirement for the formation of stable aggregates because bonds other than liquid ones are set up between particles, and these are less reversible than liquid water bonds. The greater the degree of orientation and dehydration, and the more platy the nature
of the particles, the more stable is the structure formed likely to be. These stabilising conditions all apply to the C layer.

Compaction, besides increasing the strength of the soil structure, also acts to reduce soil erodibility in another way. Because of compaction, the pore spaces along which water can move will likely be fewer and smaller in the C layer than in the P layer. The degree of slaking will also be lower, firstly because the rate of entry of water will be slower, allowing air to escape more freely, and secondly, because of the lower porosity of the C layer, the amount of air that could be trapped would be less. The result would be an overall decrease in aggregate disruption in the C layer compared with the P layer.

**SODIUM**

Dispersion and deflocculation of clays and loss of soil structure have long been associated with the percentage of exchangeable sodium in the soil (Rallings 1966). In Australia, the presence of sodium in the sub soils, causing clay dispersion, has been shown to be a major factor in tunnel erosion. A concise account of the way sodium affects clay dispersion is given by Rallings (1966). Briefly, the effect of the presence of considerable amounts of sodium in association with the clay particles is to cause the diffuse layer of cations around the clay particle to expand considerably. When two clay particles approach each other, two opposing sets of forces come into play. Firstly, there are
repulsive forces due to the interaction of the predominantly positively charged diffuse layers. Secondly, there are attractive forces (Van der Waals forces) which act between the clay surfaces. If the diffuse layers surrounding the clay particles are greatly expanded, due to the presence of sodium, the repulsive forces can predominate over the attractive forces and there is no tendency for the clays to flocculate. When dry soil such as this is wetted, the clays disperse.

The degree of clay dispersion also depends on the concentration of sodium salts in the soil water. If this concentration is high compared with that within the clay complex itself then the opposite effect occurs, and the soil stability is increased. This occurs in some coastal soils where the supply of salt is large (for example see Raeside 1964). If the soil water sodium content is low compared with the clay sodium content, then the clays will tend to disperse. Where the supply of salt is not excessive and drainage is reasonably free, the latter situation will exist. Loess deposits on the East Coast of the South Island are apparently well drained and show little sign of water-logging (Young 1967). Field observations confirm that water-logging is apparently absent in Takahe soils.

As has been shown, exchangeable sodium and E.S.P. appear to rise sharply in the P layer, and sodium effects could account in part for the high erodibility of the P
layer. Without any direct investigation of the relationship between sodium content and soil erodibility in the Takahe soils, no estimate of the significance of this relationship, if any, can be made. Direct comparison with the Australian results is not valid because of the difference in conditions.

Perhaps the dispersed state of the colloids in the subsoils of the yellow-grey earths, as suggested by Fieldes, is in part caused by the presence of sodium. Sodium cations are the easiest to remove from the soil colloidal complex by leaching (Baver 1956). The yellow-brown earths are formed under higher rainfall conditions, and leaching is more pronounced than in the yellow-grey earths. Perhaps the excessive sodium has been leached out of the yellow-brown earth subsoils, aiding the formation of a more stable aggregate structure.

SUMMARY

The textural characteristics of the three layers are similar, that is, predominantly silt with about 10% very fine sand and 10 to 30% clay. In terms of texture, the three layers are all potentially very highly erodible. The organic matter content of the S layer in all forms is adequate to provide a comparatively stable soil structure resistant to erosion. Both the C and P layers have a very low organic matter content. The C layer is less erodible than the P layer, mainly because of its high degree of compaction and the stabilising effect this has.
The P layer is characterised by a highly erodible texture with insufficient organic matter or compaction to counteract this. In addition, it seems possible that the higher exchangeable sodium content of this layer accentuates its already highly erodible nature.
CHAPTER NINE  WATER TRANSMISSION PROPERTIES  OF THE SOIL

INTRODUCTION

Two features of sub surface flow have to be explained to account for the initiation and subsequent development of tunnels. The first is how water gets into the P layer in sufficient quantities to cause erosion, and the second is how it moves and carries material with it to initiate the tunnels. The accounts presented below of both the way the water enters the soil, and subsequent sub surface flow, are purely tentative and not based on any field experiments or tests. It is probable the rate of water entry and sub surface flow are only sufficient to lead to the initiation of new tunnels, or the continued erosion of existing ones, during periods of high intensity rainfall.

ENTRY OF WATER INTO THE P LAYER

The way in which the water enters the P layer is not clear. Hosking, Harris and Gibbs all proposed that the water enters the P layer through cracks extending from the surface into the P layer. The modification of the vegetation by European man has led to greater surface runoff, and a greater development of the crack and fissure system, with the result that more water is able to enter the P layer via the system of cracks. Undoubtedly these considerations are important in the formation of tunnels; however some problems do arise.
The low liquid limit of loess (table 4) indicates that the cracks would fill in fairly quickly as the soil moisture increases. This would impede the flow of water down the cracks. Further, the summer of 1969/70 was a dry one yet very few surface cracks were observed, even in areas with pasture deterioration. It appears the cracks that form in the lower layers do not, in general, extend right through the S layer to the surface.

There are several other ways water could enter the P layer. One is that water could gain entrance along the upper margins of the loess where it lies against basalt rock. Harris (1952) showed this occurred in Horotane Valley where the upper margin of the loess had cracks in it an inch or so in width and up to a foot or more in depth. Runoff from the bare face of rock passed down the cracks into the loess. This could still happen even where there was a thin soil covering on the rock. Many localities where tunnels occur do in fact have large areas of outcropping or thinly covered rock above them (plate 12). However many tunnels occur where there is little or no exposed rock or where a thick cover of loess extends right on to the ridge spur.

As on Banks Peninsula, in parts of Australia where tunnelling has been a problem, the experience has been an association between pasture deterioration, droughty summers, and the formation of fissures. This has led to the formation of an impermeable surface crust and increased surface runoff.
which enters the surface cracks. However Downes (1956) implies the water does not necessarily enter directly into cracks which open on to the soil surface. He notes that in certain places there is an increase in the rate of infiltration because the rainfall, instead of soaking in where it falls, concentrates into small hollows, stump holes and rabbit scrupes which have been found to have an infiltration capacity of about 50 times that of the compacted soils around them. At such spots the water can percolate into the cracked sub soil. C. Vucetich (pers. comm.) has stated that a similar process may apply to loess derived soils. Often in an area with a seemingly uniform soil profile the wetting front will, for no apparent reason, extend far deeper, and at a faster rate, into one part of the soil than into the immediately adjacent parts of the same soil. That water extends deeper in surface depressions (channels or hollows) was confirmed by observations in the field. In the case of surface channels, surface runoff will be channelled into these, thus increasing the total possible volume of water that could be absorbed. As has been pointed out, the C layer is often fractured and discontinuous, and this will make entry into the P layer by infiltrating water easier.

Finally, where there is a continuous loess cover from the valley sides to the tops of the smooth rolling spurs, as in most of the Port Hills, but also in other parts of Banks Peninsula (plate 13) Griffiths (pers. comm.) has suggested another way by which the water could enter the P layer
FIGURE 21
Entry of Water into the P layer on the Shoulder of Loess Covered Interfluves where the C layer is Absent or Fragmented
Plate 12. Volcanic Rock Outcropping above a Tunneled area - St Martina Valley

Plate 13. A loess Covered Rolling Spur - Cashmere Valley
Sheet erosion has been greatest on the shoulders of the spurs and has removed the original S and C layers. The erosional products have been transported downslope. Runoff from the broad rolling spurs flows to the shoulder of the spur where it enters into the P layer. The area of these spurs, and consequently the runoff from them, is large compared with the steeper valley sides.

**SUB SURFACE FLOW**

It is generally accepted that the C layer is highly impermeable due to its high degree of compaction. In C layer material water generally moves purely by capillary action (Griffiths pers. comm.). In the laboratory experiments for erodibility it was generally found that the C layer material wetted comparatively slowly. The P layer, however, is much more permeable (Fitzgerald 1966). This again was confirmed in the laboratory where it was found the P layer aggregates wetted very rapidly. Thus, disregarding the system of fissures and cracks, water will permeate comparatively freely through the P layer but not the C layer.

When the P layer is wet under still water conditions the clays will often disperse. Any movement of water through the pore spaces of this layer will carry in suspension clay and fine silt particles, and over a period of time voids will form in the material. Movement of water along the cracks will accentuate this process. Besides forming due to the removal of particles in suspension, voids could also form
as a result of packing due to drying and wetting and the packing effect of deflocculation resulting from the solution of soluble salts (Gibbs 1945). The result of the continual removal of particles in suspension would be the growth of voids, especially along those cracks that run about parallel with the surface, leading to the formation of micro tunnels. Hosking and Harris consider that this suspended material is removed from beneath the surface by the movement of some of the water up cracks and onto the surface, and they report the occurrence of oozes on the surface, at intervals of a few yards, along the line of a developing tunnel. It is possible that much of the eroded material is re-deposited in other cracks and voids or in the individual pore spaces away from the zone of the developing tunnel. On any one slope segment it would be difficult to determine how much of the eroded material was brought to the surface as ooze, how much continued to travel down slope in suspension below the surface, and how much was re-deposited elsewhere beneath the surface. However once a small tunnel, say two inches in diameter, has formed, it must have a free outlet to the surface for development to continue unimpeded. Such outlets occur frequently, generally as holes greater than 2 inches in diameter, on the surface or as slits, one or more inches across, that may have developed from surface or sub surface cracks. It must be stressed that these are outlets for tunnels, not openings in the surface for surface runoff.
to enter.

One reason tunnels may be less common in the Takahe silt loam is that the P layer is subject to less cracking in the summer than the Takahe hill complex (Fitzgerald 1966). Only in extremely dry summers do cracks extend into the sandy silt below the C layer.

The account presented above of how the sub surface runoff flows and carries material with it to initiate tunnels does not explain why the water apparently concentrates in a narrow zone (below the C layer) and flows down slope more or less parallel to the soil surface.

Some of the findings of a recent investigation by Zaslavsky and Rogowski (1969) into the flow of water through anisotropic soils (soils in which the permeability is not the same in all directions) may be applicable to this situation. Whereas infiltration is usually assumed to be a vertical, unsaturated flow, they showed that the direction of flow may vary, depending on the degree of anisotropy and the slope angle. On steeper slopes and where the degree of anisotropy is large, the direction of flow of the infiltrating water will tend to become almost parallel to the soil surface. The existence in the profile of layers having markedly different permeabilities, and the presence of particles oriented during compaction, suggests that the degree of anisotropy of the Takahe soils will be large. This could explain why the sub surface runoff flows parallel to the
soil surface rather than infiltrating vertically into the loess deposits.

Furthermore, on the concave portions of the slope, the infiltration streamlines tend to converge, whereas on the convex portions they tend to diverge. Thus on the concave portions of slopes, sub surface flow will concentrate at some level in the soil and flow parallel to the soil surface. If the flow is not already saturated by this stage, then the concentration of flow lines on the concave portions of the slope is more likely to lead to saturated flow than on the other portions of the slope.

Most of the loess covered slopes of Banks Peninsula have a typical convex/concave profile, or where topped by rock outcrops, a purely concave profile, and the concave lower portions of these slopes are usually the most seriously affected by tunnelling. The convex portions of the slopes, rising to the interfluves, are usually not affected, or only slightly affected. This may be due to a combination of the effects of the greater volume of runoff on these lower slopes and their concave nature.

Where the flow lines concentrate in the profile is apparently of major importance in determining whether or not tunnels will be initiated. If the zone of concentration of flow lines is too deep in the loess deposit, then water infiltrating in will not be able to reach this level in sufficient quantities to provide the volume of water needed to transport material and initiate tunnels. If the zone
of concentration corresponds to the depth of the C layer, the water will be unable to move down slope through this layer because of its impermeable nature, and will possibly move in to the S or P layers along the crack system.

However if the zone of concentration of the flow lines corresponds to the upper part of the P layer beneath the C layer, infiltrating water will be able to reach this level in larger amounts than at greater depths, and the nature of the material will be such that, unlike in the C layer, subsurface flow and erosion can take place.

This is conjecture and should be the subject of further investigation.

SUMMARY AND DISCUSSION

Probably no one mechanism is responsible for water entering into the P layer. The importance of the various mechanisms outlined above will vary from place to place and others may well operate. In all cases surface runoff will concentrate on surface hollows or channels and it is in these areas infiltration, either through the soil, or cracks, or both, is likely to be highest. Once a complete tunnel system forms it will discharge water onto a narrow zone of the slope immediately below, increasing the chances of a sufficiently high rate of infiltration to cause tunnelling immediately down slope. Thus a new tunnel may form down slope from the outlet of an upslope tunnel. These tunnels may eventually link up to form one tunnel.
Once the water is in the P layer, a sequence of events that could lead to the initiation of tunnels has been suggested. However the actual detailed mechanisms have still not been explained. A suggestion has been put forward to explain the apparent concentration of water immediately below the C layer, where most tunnels are initiated, which could form the basis of a further study.
SUMMARY

1. This study has examined in more detail than previous studies, and within the framework of the erosion model, the physical setting in which tunnel erosion occurs on Banks Peninsula.

2. A part of this complex system, the soil, was selected for more detailed study. The properties of the soils affected by tunnelling were investigated and these findings used to help explain the erodibility and water transmission properties of the soil.

3. A number of techniques were used to measure quantitatively the erodibility of the soil. Three of these, using measures of the degree of clay dispersion as indices of erodibility, were originally developed in Australia and modified for use in this situation. Two tests were devised using different aspects of aggregate stability as indices of erodibility.

4. Using these indices, the erodibilities of the layers in the soil profile were determined, and explanations proposed to account for the variations in erodibility with depth.

5. Of the tests used, the C.D.B., C.B.T. and A.S. Tests were considered to give reliable, repeatable results, and could distinguish significantly between C and P layer material.
SUGGESTIONS FOR FURTHER RESEARCH

6. Of the many problems associated with tunnel erosion remaining unresolved, the outstanding one is of determining in detail where, when and how the tunnels are actually initiated. Before these can be determined, much more needs to be known about the water transmission properties and erodibilities of the soils concerned. Further research along these lines would therefore be profitable with the ultimate aim of explaining more fully the processes leading to the initiation of tunnels.

7. Water transmission properties. A study of the following could lead to a better understanding of the water transmission properties of these soils.

(a) The role of the C layer in influencing water flow through these soils. The C layer apparently greatly influences the entry of water into the P layer and its subsequent flow beneath the surface. The C layer should be mapped in areas where tunnelling is to be studied to see if any relationships can be found between the entry of water into the P layer and the occurrence of discontinuities in the C layer. The nature of the C layer (or whether or not it is present) could be determined by collecting samples with a motorised auger with a large diameter corer (for example a portable motorised post hole digger) which would produce large enough aggregates to use in the tests referred to in 6. above.
(b) The rate and direction of the flow of subsurface water, both into and through the soil, needs to be investigated. The application of theoretical considerations will probably help in understanding the nature of subsurface flow in this material (for example Zaslavsky and Rogwski 1969). Field experiments are needed to trace water flow, either by digging pits and observing the flow from the profile on the uphill side of the pit (for example see Whipkey 1966) or by using various tracers, of which the potentially most useful would appear to be pyranine conc., (Drew and Smith 1970, Reynolds 1966, G.K. Turner Associates 1968).

8. Soil Erodibility. A much more extensive study of the erodibility of the Takahe hill complex soils is needed.

(a) Samples should be collected from sampling pits and outcrops to test the validity of using the latter.

(b) The erodibilities of soils in areas affected and not affected by tunnelling should be compared.

(i) Within the Takahe hill complex

(ii) The Takahe hill complex with the Takahe silt loam

(iii) The Takahe hill complex with other loess derived soils with different parent material from different areas. Care must be taken in making any conclusions from these comparisons because the tests were
devised for the Takahe soils only.

(c) Before any such surveys were conducted the methods should be checked thoroughly for reliability and improvements made, or more suitable tests devised where necessary.

(d) The possible relationship between the presence of sodium and soil erodibility should be investigated by determining the C.E.C., exchangeable sodium content and E.S.P. for samples and comparing with soil erodibility.
BIBLIOGRAPHY

Alley, P.J. 1966: Cashmere Hills Loess. 
N.Z. Engineering 21(10) : 424.

Deposited in the Victoria University Library, Wellington

Proc. 16th. Soil Survey Conference (unpublished) 60 - 63 
Soil Bureau

Barley, A.V. 1946: The Settlement and Development of Kai-tuna Valley, Banks Peninsula 
unpublished M.A. thesis, University of N.Z. 
Deposited in the University Library, Christchurch : 74 pp

Baver, L.D. 1956: Soil Physics 
John Wiley and Sons. New York 489 pp

N.Z. Jl. Sci. Tech. 35 (B): 30 - 35

Boyce, W.R. 1939: An Ecological Account of tussock grassland and other plant communities of Cashmere Valley and adjacent areas on the Port Hills, Canterbury

Bryan, R.B. 1968(a): The development, use and efficiency of indices of soil erodibility.

_______ 1968 (b): Development of laboratory instrumentation for the study of soil erodibility.
Earth Sci. Jl. 2(1): 38 - 50

_______ 1969: Aggregation characteristics and maturity of Peak District Soils.
Earth Sci. Jl. 3(1): 1-12

Buckham, A.F.; Cockfield, W.E. 1950: Gullies formed by sinking of the ground.
Am. Jl. Sci. 248: 137 - 41

The Macmillan Co. Toronto. 7th Ed. 567 pp

Butzer, K.W. 1964: Environment and Archeology
Aldine Publishing Co. Chicago 524 pp
Charman, P.E.V. 1969: The influence of sodium salts on soils with reference to tunnel erosion in coastal areas.
Part I - Kempsey Area
Jl. Soil Conserv. Service N.S.W. 25(4): 331 - 347

1970: Part II - Grafton area
Jl. Soil Conserv. Service N.S.W. 26(1): 71-86

Jl. Soil Science 9(2): 252-268

Collie, D.M. 1968: Factors Influencing Agricultural Production on Banks Peninsula
Deposited in the University Library, Christchurch


No. 407 Christchurch. 3 pp.
Cumberland, K.B. 1944: Soil Erosion in New Zealand - a Geographic Reconnaissance

Whitcombe and Tombs Ltd, Wellington 227 pp.

1962: Climatic Change or Cultural Interference?
in Land and Livelihood. Ed. M. McCaskill

Dettmann, M.G.; Emerson, W.W. 1959: A modified permeability test for measuring the cohesion of soil crumbs.

Jl. Soil Science. 10(2): 215 - 226


Australian Jl. of the Council for Scientific and Industrial Research 19(3): 283-292

1956: Conservation Problems on Solodic Soils in the State of Victoria

Jl. Soil and Water Conservation.11:228-232


Jl. Soil Science. 5(2): 233 - 50


Jl. Soil Science.11(1): 149 - 158

Fenwick, I.M. 1965: Some problems of soil permeability measurement

in Essays in Geography for Austin Miller
Ed. J. Whittow; P.D. Wood.: 158 - 187

Swindale, L.D. 1954: Chemical Weathering of Silicates in Soil Formation 
N.Z. Jl. Sci. Tech. 36(B): 140 - 154

Taylor, N.H. 1961: Clay Mineralogy of New Zealand Soils 
Part 5: mineral colloids and genetic classification. 

Fitzgerald, P. 1966: Soils of the Heathcote County, Canterbury, New Zealand 
N.Z. Soil Bureau Report 1/1966 
Soil Bureau D.S.I.R. Christchurch.

Folk, R.F. 1965: Petrology of Sedimentary Rocks 
Hemphill's, Austin, Texas 159 pp.

Ford, J.H. 1949: Akaroa: A Geographic Survey of the County and Borough 
Deposited in University of Canterbury Library, Christchurch.

N.Z. Jl. Sci. Tech. 27(A): 135 - 146

1964: Some Reflections on Soil Formation and Loess
N.Z. Soil News No. 6
unpublished newsletter of N.Z. Society of Soil Science

Harris, C.S. 1952: Soils and Erosion, Horotane Valley Catchment, Port Hills, Christchurch

Harris A.C. 1939: Soil Survey of Duvauchelle Bay - Wainui District, Banks Peninsula

N.Z. D.S.I.R. Bulletin 47. 24 pp

Whitcombe and Tombs Ltd, Wellington 7th Ed. 86 pp

Deposited in the University Library, Christchurch.

Ives, D. 1968: The Pedogenesis and Classification of the New Zealand Yellow-Grey Earths
unpublished Masterate Project No. 3.
Soil Science Dept, Lincoln College. 22 pp

U.S. Geol. Survey Water-Supply Paper 1619-U

Deposited in the University library, Christchurch.
Deposited in the University of Canterbury library, Christchurch.


Land Use Capability Survey Handbook. 1969: 139 pp
Soil and Water Division
Ministry of Works, Wellington.


Jl. Soil Science. 5(1): 57 - 74

   *Jl. Soil Cons. Service N.S.W.* 10: 127-134

   *Jl. Soil Cons. Service N.S.W.* 13: 159-169

   *Soil Science.* 83: 185 - 195


   Deposited in the University Library, Christchurch.

   *Jl. Soil Science.* 13(1): 60 - 70

Raeside, J.D. 1948: Some Post Glacial Climatic Changes
and their effect on Soil Formation.


1964: Loess Deposits of the South Island, New Zealand, and the Soils Formed on them.


Water Research Foundation of Australia Bull. No. 10


Jl.Soil Science. 17(1): 127 - 132


Jl.Soil Cons.Service N.S.W. 19(3): 111-129

1965: Investigation into Earthwork Tunneling and Mechanical Control Measures using Small Scale Model Dams.

Jl.Soil Cons.Service N.S.W. 21(2): 80-89

Robinson, D.O.; Page, J.B. 1950: Soil Aggregate Stability


Rubey, W.W. 1928: Gullies in the Great Plain formed by sinking of the ground.

Ruhe, R.V. 1954: Relations of the properties of Wisconsin loess to topography in Western Iowa.
Am. Jl. Science 252: 663 - 72

Siegel, S. 1956: Nonparametric Statistics for the Behavioral Sciences

Soil Bureau 1968: Soils of New Zealand
N.Z. Soil Bureau Bull. 26 3 volumes
Parts 1, 2, 3

N.Z. Soil Bureau Bull. 27: 404 pp


Sparrow, Rev. C.C. 1948: The Loess Deposits of Banks Peninsula
unpublished M.A. thesis University of N.Z. Deposited in the University Library, Christchurch.

Swaby, R.J. 1950: The Influence of Earthworms on Soil Aggregation.
   Jl. Soil Science. 1(2): 195 - 197
   Pohlen, I.J.: 1962 Soil Survey Method
   N.Z. Soil Bureau Bull. 25: 242 pp
   Auckland Student Geographer 6: 49 - 58
   Advances in Agronomy 9: 159 - 176
Ward, A.J. 1966: Pipe/shaft phenomena in Northland
   J.C. Hydrology (N.Z.). 5(2): 64 - 72
   Intern Symposium Forest Hydrology: 255-260
   Soil Science 101(3): 157 - 163
Williams, R.J.B. 1963: A New Method of Measuring Soil
Stability.

**Chemistry and Industry**: 1032 - 1033

Wischmeier, W.H.; Mannering, J.V. 1969: Relation of a Soil Properties to its Erodibility


Young, D.J. 1964: Stratigraphy and Petrography of North East Otago Loess


_________ 1967: Loess Deposits of the West Coast of the South Island, New Zealand.


**Drew, D.P.; Smith D.I. 1970: Techniques for the Tracing of Subterranean Drainage.**

Brit. Geomorp. Research Group

Technical Bull. 2 : 36 pp
APPENDIX ONE  

SOIL SAMPLING SITES

The locations of the sites (A to U) are shown in figure 22. A brief description of the location of each site is given and what the samples were used for. The depth the samples were taken at is not shown below are shown in table 10.

SITE F  upper Cashmere Valley, grid reference S84/995492

Three samples taken for particle size analyses
(figures 11 to 13)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layer</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>C</td>
<td>21 inches</td>
</tr>
<tr>
<td>b</td>
<td>P</td>
<td>36 inches</td>
</tr>
<tr>
<td>c</td>
<td>P</td>
<td>55 inches</td>
</tr>
</tbody>
</table>

SITE G  middle Cashmere Valley 993497

Three samples taken for particle size analyses
(figures 14 to 16)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layer</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>C layer</td>
<td>20 inches</td>
</tr>
<tr>
<td>e</td>
<td>C/P layer</td>
<td>28 inches</td>
</tr>
<tr>
<td>f</td>
<td>P layer</td>
<td>30 inches</td>
</tr>
</tbody>
</table>

SITE H  lower Cashmere Valley 981501

Three samples for bulk density determination

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layer</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>S layer</td>
<td>9 inches</td>
</tr>
<tr>
<td>h</td>
<td>C layer</td>
<td>22 inches</td>
</tr>
<tr>
<td>i</td>
<td>P layer</td>
<td>38 inches</td>
</tr>
</tbody>
</table>
FIGURE 22

Location of Sampling Sites
SITE K  Francis Valley  979498  east side

Three samples for bulk density determination
Sample j  S layer  7 inches
Sample k  C layer  20 inches
Sample l  P layer  36 inches

Samples used for the various erodibility tests and for determination of sand, silt and clay percentages were taken at the following sites. The samples for each site are numbered and the last figure in each sample number indicates what layer it was taken from (except site N). All S layer sample numbers end in 1, C layers in 2 and P layers in 3.

SITE A Avoca Valley  046503  east side
B  "    "  043503  west side
D St. Martins Valley  027514  east side
E  "    "  023514  west side
I Francis Valley  979498  east side
J  "    "  979498  west side
O Hoon Hay Valley  973494
P  "    "  975476
Q Rifle Range Valley  945371  S.E. side
R  937367
S Kaituna Valley  052310
T Port Levy  174401
U Shelly Bay  115448

Besides these, three sets of samples were taken to show in more detail the variation of properties with depth
(site N) and of distance apart (sites L and M).

**SITES N, L, M** Francis Valley 979498 west side

SITE L was 6 feet upslope from site M.

Finally, samples taken from SITE C, about 20 yards up valley from SITE D, to test the variation in the results of the C.D.B. and D.B.T. tests when repeated 10 times and the A.S. (30 sec.) test repeated five times. The pre-soaking times for the A.S. test were varied (\(\frac{1}{2}, 1, 5, 10, 60\) and 720 minutes) and the effects on erodibility noted (appendix 2)

<table>
<thead>
<tr>
<th>SITE C</th>
<th>Sample</th>
<th>Layer</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21</td>
<td>S</td>
<td>6 inches</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>C</td>
<td>36 inches</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>P</td>
<td>55 inches</td>
</tr>
</tbody>
</table>
APPENDIX TWO  
SOIL ERODIBILITY TESTS

DISPERsal INDEX (D.I.) TEST

This test is a modified form of the test outlined by Ritchie (1963) and used by Charman (1969). The samples used for this test had been kept sealed in their polythene bags, thus retaining their moisture. However, except for a few slightly damp S layer samples, they had a very low moisture content (usually less than 5%) when collected in the field and could be considered to be in an air dry condition. The equipment used for this test is shown in plate 14.

1. Procedure

The sample is dry sieved on 15.9 m.m. and 11.2 m.m. sieves. The aggregates collected on the 15.9 m.m. sieve are divided into three sub-samples of 50 grams which are each weighed to 0.01 grams. Sub-sample a is dried at 105°C for 12 hours to determine the moisture content. Sub-sample b is subject to complete dispersion by chemical means and sub-sample c to mechanical dispersion.

2. Complete Dispersion (sub-sample b)

(a) Place the sample in a beaker and cover with dispersant (0.1 N. sodium oxalate) and leave for 15 minutes with occasional stirring.

(b) Transfer to a milk shake container, fill to about 500 mls. and agitate for 2 minutes.
Plate 14. Apparatus for the D.I. Test
(c) Transfer via a large funnel to a 1 litre measuring cylinder, top up to 1000 mls with sodium oxalate, agitate with a stirring rod and leave for 12 hours to allow for complete chemical dispersion.

(d) Agitate for 50 strokes to bring the material into complete suspension and note the time.

(e) 1 hour 55 minutes later lower the hydrometer slowly in and at 2 hours take a reading (to the top of the meniscus).

(f) Correct this reading by comparing with the hydrometer reading for a "blank cylinder" containing sodium oxalate only. This corrected value is the weight of material less than 0.002 m.m. in suspension.

(g) Express this as a percentage of the total dry weight of the sub-sample.

3. **Mechanical Dispersion (sub-sample c)**

   (a) Take the sub-sample, place in a litre flask and fill to about 600 mls. with distilled water, cork securely and shake end over end for $4\frac{1}{2}$ minutes (approximately 50 shakes per minute).

   (b) Then transfer into a 1 litre measuring cylinder and top up to 1000 mls.

   (c) Continue as in Section 2, d to g, except fill the blank cylinder with distilled water.
4. Calculations

(a) Correction for moisture content.

\[ \text{Wgt of dry sample} = \text{wgt of original sample} - \frac{\text{wgt of moisture}}{100} \times \text{wgt of o.sample} \]

(b) Dispersal Index (D.I.)

\[ \text{DI} = \frac{\text{total material less than 0.002 m.m.}}{\text{material less than 0.002 m.m. by mechanical dispersion}} \]

\[ = \frac{\% \text{material less than 0.002 m.m. by complete dispersion}}{\% \text{material less than 0.002 m.m. by mechanical dispersion}} \]

The aim of this method is to determine the degree of clay dispersion that occurs over the period of shaking. Aggregate breakdown must be as rapid as possible to allow all the clay to be subject to conditions conducive to dispersion. However, if the aggregates are pre-soaked to allow easier aggregate breakdown then some clay dispersion is likely to occur regardless of shaking. Thus, the aggregates used should be of such a size that the period of shaking required to breakdown the aggregates is small compared with the total shaking period. The aggregate size range and shaking time used were chosen to attempt to fulfil these requirements.

However, when the tests were being conducted it was apparent that, because of the comparatively large size of the aggregates, the rate and degree of breakdown were smaller than expected and a large proportion of the shaking time was
used in breaking the aggregates down. Occasionally at the end of a test small aggregates of S and C layer material still remained. As a result, the calculated dispersion indices for these layers are probably higher than in reality. The value of this method would be improved if the aggregates used were reduced to a much smaller size, say less than 2 m.m., and perhaps the shaking time increased to 10 minutes.
CLAY DISPERSION A (C.D.A.) TEST

This test is essentially that outlined by Rallings (1965 pg. 57). 5-10 gms. of air dry soil aggregates 0.25 to 0.50 cm. in size were placed into a 100 ml beaker which was filled with about 60 mls of water. After one hour the degree of turbidity was noted and rated on the scale given in table 15. Rallings only noted whether or not turbidity (dispersion) occurred.

This test cannot be considered to give a reliable estimate of clay dispersion because as the water was added, the crumbs (which are very small) were agitated considerably leading to an artificial amount of crumb breakdown and clay dispersion. Also it was difficult to duplicate results using this test.
<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no dispersion</td>
</tr>
<tr>
<td>1</td>
<td>very slight - a just perceptible degree of cloudiness</td>
</tr>
<tr>
<td>2</td>
<td>slight - distinct dispersion but the water still transparent</td>
</tr>
<tr>
<td>3</td>
<td>moderate - the degree of dispersion is such that the water is translucent.</td>
</tr>
</tbody>
</table>
CLAY DISPERSION B (C.D.B.) TEST

A 100 ml beaker was filled with about 80 ml of water and a single crumb of soil about 10-15 m.m. across was gently dropped in and the degree of dispersion (turbidity) after 30 minutes noted. There was a minimum of disturbance of the water and by the time the aggregate began to crumble and the clays disperse the water was still. The results could be duplicated adequately (table 17). From the limited amount of data in table 17, it appears the degree of clay dispersion can be assessed more accurately if the average values for about 3 tests on S layer material, and 4 on C and P layer material are taken.

DISINTEGRATION B (D.B.T.) TEST

This test was carried out in conjunction with the C.D.B. test. After 30 minutes the degree to which the aggregates had crumbled was noted and rated according to table 16. Again, from the limited amount of data presented in table 17, it appears the degree of disintegration can be assessed more accurately if the average values for about 3 tests on S, 4 on C and 3 on P layer material are taken.

DISCUSSION (C.D.B. and D.B.T. TESTS)

The quantitative estimates of the degree of disintegration and dispersion in these tests (and the C.D.A. test)
Table 16

Scale for Rating the Degree of Disintegration for the D.B.T. test

<table>
<thead>
<tr>
<th>Rating</th>
<th>Disintegration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>none</td>
<td>less than 5% of the aggregate has crumbled</td>
</tr>
<tr>
<td>1</td>
<td>slight</td>
<td>5-35%</td>
</tr>
<tr>
<td>2</td>
<td>moderate</td>
<td>35-65%</td>
</tr>
<tr>
<td>3</td>
<td>advanced</td>
<td>65-95%</td>
</tr>
<tr>
<td>4</td>
<td>complete</td>
<td>over 95%</td>
</tr>
<tr>
<td>Sample</td>
<td>Test</td>
<td>Results</td>
</tr>
<tr>
<td>--------------</td>
<td>--------</td>
<td>------------------</td>
</tr>
<tr>
<td>21 (S layer)</td>
<td>C.D.B.</td>
<td>0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td></td>
<td>D.B.T.</td>
<td>0 1 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>22 (C layer)</td>
<td>C.D.B.</td>
<td>0 0 0 0 1 1 0 0 1 0</td>
</tr>
<tr>
<td></td>
<td>D.B.T.</td>
<td>3 3 3 2 3 2 3 3 3</td>
</tr>
<tr>
<td>23 (P layer)</td>
<td>C.D.B.</td>
<td>2 1 0 0 1 1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>D.B.T.</td>
<td>4 4 4 4 4 4 4 4 3</td>
</tr>
</tbody>
</table>
are on an ordinal, not interval scale. These estimates were made visually and a series of photographs is included (plates 15 to 17) to help in interpreting the scales in tables 15 and 16.

The ease with which the C.D.B. and D.B.T. tests can be carried out, and their comparative reliability, suggests that with some modifications these tests could be used to determine the erodibility of loess and loess derived soils in the field. In practice it was found that within 10 minutes of dropping the aggregate into the water, most of the dispersion or disintegration had taken place so the time required to conduct these tests could be shortened considerably.
Plate 15. S Layer.


<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

D.E.T. Test Rating.


<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>2</th>
<th>2</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

D.B.T. Test Rating.
Plate 17 P. Layer.

<table>
<thead>
<tr>
<th>C.D.A.</th>
<th>C.D.B.</th>
<th>Test</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

D.B.T. Test Rating.
THE AGGREGATE STABILITY (A.S.) TEST

About 25 gms of air dried aggregates, 10-15 m.m. across, were placed in a 1 litre flask and pre soaked for 30 seconds in about 400-500 mls water. They were then subject to end over end shaking for 30 seconds and the contents of the flask passed through a 2 m.m. sieve. The remaining aggregates were then dried and weighed and this weight expressed as a percentage of the total weight.

For several samples the effect of different pre soaking periods were assessed (table 1C). Samples 21, 22 and 23 were tested for pre soaking times of $\frac{1}{2}$, 1, 5, 15, 30, 60 and 720 minutes (figure 23, table 18). Finally, sample 22 was tested 5 times to give an estimate of the repeatability of this test (table 19).

DISCUSSION

The A.S. tests results in tables 10 and 18 and figure 23 shows that, in general, with a 30 second pre soaking period the S and C layer aggregates are much more stable than those from the P layer. Often under these conditions the C layer material is more stable than the S layer. However, as the pre soaking time is increased the C layer aggregates rapidly decrease in stability whereas the S layer aggregates remain relatively stable. P layer aggregates are very unstable with little or no degree of aggregation remaining after one minute of pre soaking.
Table 18
The Effect of Different Pre Soaking Periods on the Results of the A.S. Test (see figure 23)

<table>
<thead>
<tr>
<th>Pre Soaking Period (minutes)</th>
<th>1/4</th>
<th>1</th>
<th>5</th>
<th>15</th>
<th>30</th>
<th>60</th>
<th>720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 21 (S layer)</td>
<td>69</td>
<td>69</td>
<td>75</td>
<td>66</td>
<td>63</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>Sample 22 (C layer)</td>
<td>59</td>
<td>41</td>
<td>37</td>
<td>16</td>
<td>4</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Sample 23 (P layer)</td>
<td>16</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

% of aggregates remaining

Table 19
Variations in the Results of the A.S. Test when Repeated 5 Times

Pre soaking period 30 seconds

Results (% of aggregates remaining)

| Sample 21 (C layer) | 62% | 65% | 70% | 71% | 77% |
FIGURE 23

The Effect of Various Pre Soaking Periods on the Results of the A.S. Test
It is easy to distinguish visually, on the basis of colour and structure, between C and S layer material, whereas it is difficult to distinguish between S and P layer material. It appears from the limited amount of data presented here that the A.S. test (along with the C.D.B. and D.B.T. tests) can reliably distinguish between C and P layer material. The range of values shown in table 19 indicates that about 5 to 10 sub samples of the material would be sufficient to give a reliable indication of the aggregate stability. Any pre soaking period up to about 15 minutes would readily distinguish C layer from P layer material and the period chosen would be somewhat arbitrary.