Some Factors Affecting Tunnel Gully Erosion

Quelques Facteurs Affectant l'Erosion par Ruisseau Souterrain

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SYNOPSIS The loess soils which cover a large part of the Port Hills in Christchurch, New Zealand, suffer from a serious erosion problem known as 'Tunnel Gully Erosion'. In this form of erosion, an underground tunnel forms and enlarges with time until the tunnel roof collapses to form a gully. Using a modified version of the Sherard pinhole test for dispersive soils, quantitative values of soil erodibility can be obtained. Erodibility tests, particle size distribution measurements, saturated extract analyses, and SCS dispersion tests were performed. The relationships between these measurements and the type of erosion which takes place has been investigated, and changes of properties with depth in soil profiles have been studied.

Correlations have been observed between sodium content of the saturated extract, the SCS dispersion test results, and erodibility. Disturbed or compacted soils generally show a higher erodibility than the corresponding undisturbed soils. Susceptibility to erosion does not imply, however, that erosion will occur. It is also necessary to have the appropriate land form and climatic conditions. The effects of hydrated lime and phosphoric acid on erodibility of one erodible soil are reported. Under some conditions phosphoric acid treated material is apparently less erosion resistant than untreated soil.

INTRODUCTION

The Port Hills of Christchurch, New Zealand, form the northern slopes of the eroded basaltic-andesitic volcanic complex of Banks Peninsula. The volcanic rocks are often mantled with Late Pleistocene loess deposits. The soils formed in the loess and in the slope deposits derived from it suffer from a type of erosion known as tunnel gully erosion. In this form of erosion, an underground tunnel forms and enlarges with time by the action of flowing water, until the tunnel roof collapses to form an open gully.

Tunnel gully erosion has been observed (Hosking, 1962; Fitzgerald, 1966; Hughes, 1970; Miller, 1971; Griffiths, 1974) in some places on the Port Hills for many years, but was not perceived as a major hazard because the affected land was used mainly for semi-extensive grazing of sheep and cattle. More recently, urban development was permitted to occur. In some locations site works created only a minimum of disturbance. Elsewhere the loessial soil materials were redistributed over the landscape by earthmoving machinery to make the contours more suitable for housing. Problems with tunnel gully erosion ensued very quickly, especially where large scale landscaping had been done, and quantities of eroded sediment were deposited in the watercourses which drain the district.

This investigation attempts to characterise the erosion susceptibility of some of the soils and the possibility of corrective lime or phosphoric acid treatments. To this end a quantitative adaptation of the pinhole test for dispersive soil has been developed. The erosion index obtained from this test is used to compare undisturbed and remoulded (compacted) material and to assess some characteristics of lime and phosphoric acid treatments. Erosion index results are compared with SCS laboratory dispersion test results and with the results of the original qualitative pinhole test.

SAMPLE SITES

At elevations above about 360 m, the climate is humid with a mean annual rainfall greater than 900 mm. At lower elevations the climate of the Port Hills is sub-humid with a mean annual rainfall ranging from 550-900 mm. Soils in the humid zone are moderately to strongly leached, while those in the sub-humid zone are weakly leached.

Five of the profiles sampled (Takahe, Otahuna, Clifton, Kiwi and Scarborough soils) were taken from a transect down a representative slope in the sub-humid zone of the Port Hills (Fig.1). Two other profiles with similar parent material but with different leaching regimes were sampled to compare the results of the soils in the transect. A very weakly leached soil (Godley) was sampled on a ridge summit exposed to influxes of salts from off-sea winds in the lowest rainfall area of the sub-humid climate zone. The other profile sampled was from a moderately to strongly leached soil (Summit) on a ridge summit in the humid climate zone.

The Takahe, Godley and Summit profiles were all formed from in situ loess while the Otahuna, Clifton, Kiwi and Scarborough soils were formed from slope deposits derived mainly from loess but with small components of rock fragments derived from outcropping basaltic rocks.

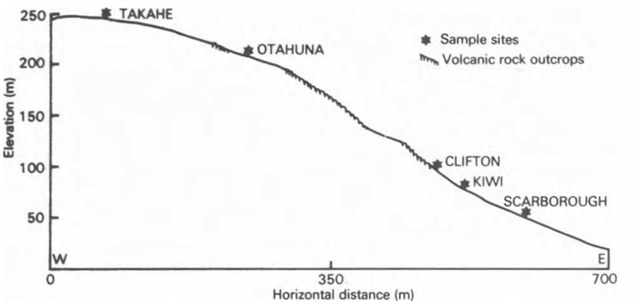

Fig.1 Schematic diagram of slope from which samples of Takahe, Otahuna, Clifton, Kiwi and Scarborough samples were taken.

Most of the reported data are for soil samples taken from the Port Hills, Christchurch, but a few other samples from Central Otago and Kaikoura were also tested. These other samples are not separately identified in the following text.

EXPERIMENTAL

Samples were transported and stored in polythene bags to prevent water loss. Apart from a few soils sampled under extremely dry conditions which were wetted with distilled water, all tests were done on soils of natural water content.

Erosion susceptibility was assessed using a quantitative adaptation of the pinhole test developed by Sherard et al. (1976a). The resulting erosion index represents the volume of soil which would be eroded from a 50 mm long specimen under a set of standard conditions (see Appendix).

Pinhole tests were performed first on undisturbed lumps (when available) from the bulk sample, and then on compacted specimens which included remnants of the undisturbed lumps. Thus, undisturbed and compacted specimens were at essentially the same water contents. Undisturbed lumps were prepared for testing by first coating with wax and then making the 'pinhole', and attaching inlet and outlet tubes. Compacted specimens were prepared in 52 mm diameter cylinders and compacted with a 30 mm diameter tamper driven by a 2.3 kg mass falling through 10 cm, 6 blows per 10 mm (nominal) layer.

The initial hole in each specimen (either undisturbed or compacted) was made with an approximately 1 mm diameter hypodermic needle, after which the specimen was either tested immediately or (with some compacted specimens) wrapped in polythene to prevent water loss, and cured 7 days prior to testing.

Most of the lime and phosphoric acid stabilised specimens for pinhole testing were prepared from the scarborough "C" layer (see Table I). This layer is known to be susceptible to erosion, although tunnels usually initiate just below it, in the "P" layer of this profile. After verifying that "C" and "P" layers appeared to respond similarly to lime treatment, "C" layer material was chosen for detailed testing because the available sample was much larger than that of the "P" layer.

TABLE I

Erosion indices for Takahe and Scarborough soils

	Undisturbed	Compacted
Takahe		
"S" layer*	0.3 - 0.5	
"C" layer	2.2 - 2.3	8 - 8.9
"P" layer	10 - 19	32 - 38
Scarborough		
"S" layer		† 0.02(?) - 0.6
"C" layer	1.1 - 2.1	9.3 - 11
"P" layer	4.5 - 20(?)	15 - 23

* "In most places the top two metres of soil comprise three layers which have been designated by Hughes (1970) as -

(1) The S layer comprising about 170 mm of topsoil and 200 mm of friable pale yellow silt.

(2) The C layer which is very firm, dense and compact. This varies in thickness from about 400 mm to 1.5 to 2 metres. In some places this layer shows extensive and deep shrinkage cracking and in other places cracking is less noticeable.

(3) The P layer or 'parent material' which is generally less dense than the C layer and also tends to erode more readily."

Evans (1977)

† Data from Scarborough "S" layer at another site.

Mean values from this table are plotted in Fig.2.

Hydrated lime was added as a dry powder to wet soil, the treatment level being expressed in terms of dry soil mass.

Reagent grade phosphoric acid (H_3PO_4, S.G. 1.75) was added as a 20% solution to soil previously dried by an amount equal to the water added to the H_3PO_4. The treatment level is expressed in terms of concentrated H_3PO_4 and dry soil mass.

In the SCS laboratory dispersion test (cited in Sherard et al., 1972) the particle size distribution is measured in two ways - firstly using the standard hydrometer test, (e.g., NZS 4402 1980) in which the sample is dispersed with strong mechanical agitation and a chemical dispersant, and secondly with mild agitation and no chemical dispersant. By definition -

$$\% \text{ dispersion} = \frac{\% \text{ passing } 0.005 \text{ mm without dispersant} \times 100}{\% \text{ passing } 0.005 \text{ mm with dispersant}}$$

Saturated extracts were prepared by mixing distilled water with the soil and extracting under vacuum (Fig.16 Sherard et al., 1972).

The extracts were analysed for Na^+, K^+, Mg^{++}, and Ca^{++}. Results are expressed as -

$$\Sigma = Na^+ + K^+ + Mg^{++} + Ca^{++} \text{ all in me/}\ell \text{ (milliequivalents/litre)}$$

and
$$Na\% = Na^+ \times 100 / \Sigma$$

RESULTS

Erosion resistance of undisturbed and remoulded (compacted) soil

Fig. 2 is a plot of erosion indices for undisturbed lumps against erosion indices for the same material, compacted and cured 7 days prior to testing. Erosion indices for undisturbed lumps were available for only about 25 samples. In the remaining samples, either the soil when sampled was too friable for lumps of adequate size to be obtained, or the sample was tested before the procedure for undisturbed lumps had been developed. Thus Fig.2 represents data for only about a third of the samples tested.

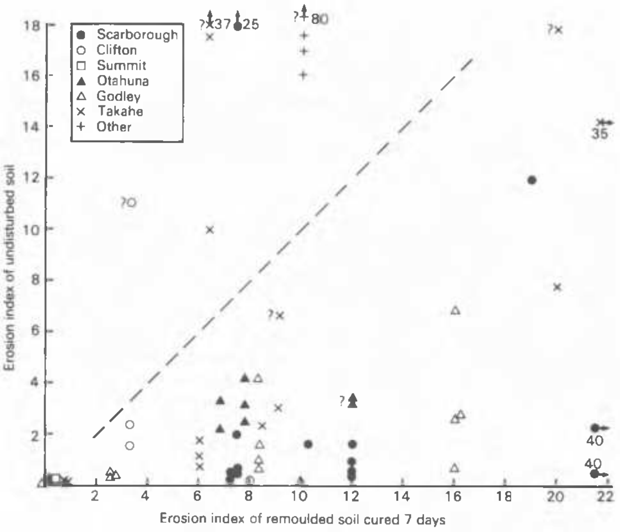

Fig.2 Erosion index of undisturbed soil versus erosion index for remoulded soil cured 7 days after remoulding and prior to pinhole testing.

Usually the erosion resistance of undisturbed material was equal to or greater than that of compacted, and the difference was sometimes quite large. (In the present context, differences of erodibility are best assessed in terms of ratios of indices. Erosion indices of 1 and 10 represent a much greater qualitative difference of behaviour than erosion indices of 10 and 20). Thus a pinhole test result from compacted material can be taken only as an upper limit indication for erosion resistance of the undisturbed material. Conversely, pinhole test results indicating good erosion resistance of undisturbed material cannot be taken to indicate good erosion resistance of compacted soil.

In a few cases where erosion resistance of compacted soil exceeded that of undisturbed soil, the material was very erodible in either state. It seemed possible that low water saturation associated with slaking or collapse during test might be factors causing very low erosion resistance of undisturbed soil, but it was not possible to demonstrate convincingly any large effects attributable to these factors.

Erosion resistance and saturated extract composition

Fig.3 shows a plot of erosion resistance of compacted soil against % Na in saturation extract (Na%) and total dissolved cations in saturation extract (Σ). Arbitrarily, materials exhibiting erosion indices >1 were considered erodible and plotted as open circles (O) while indices <1 (plotted as ●) were considered erosion resistant. Soils showing decrease of erosion index from >1 to <1 with time (see below) are represented by plus signs (+). It should be noted that the boundary between erodible and erosion resistant materials would occur in different regions of the diagram if undisturbed material rather than compacted was considered, because compacted material is generally less erosion resistant than undisturbed. However, the data for undisturbed material were not presented here because there were approximately three times as many data for compacted material, and because a comparison with the data of Sherard _et al._, (1976b) is possible only for compacted soil.

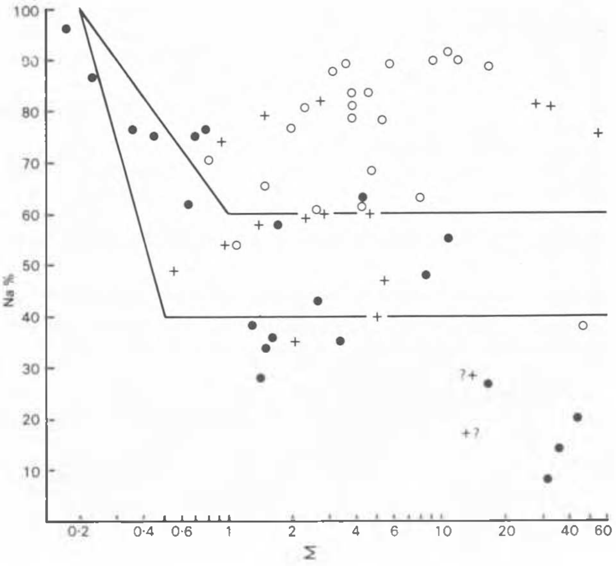

Fig. 3 Relationship between total dissolved cations ($\Sigma = Na^+ + K^+ + Ca^{++} + Mg^{++}$ all in me./ℓ, % sodium in saturation extract ($Na\% = 100 \times Na+/\Sigma$ all in me/ℓ), and erosion indices of remoulded soil. ● and O represent soils with erosion indices below and above 1 respectively. + represents soils whose erosion indices decreased from >1 to <1 during storage or after curing. Lines delineating regions of differing dispersibility (after Sherard _et al._, (1976b)) are included to aid comparison with previous work.

Fig.3 shows zones of erosion susceptibility apparently very similar to those of Sherard et al., (1976b). In particular, the non-erodible behaviour of soils having high Na% values coupled with low Σ values is confirmed. Also a few soils with Na% <40% were found with apparently anomalous low erosion resistance. However, in the present work it is shown that nearly all these anomalously erodible materials become more resistant to erosion when cured prior to testing. It seems possible that some of the six apparent anomalies in zone B, Fig.2 of Sherard et al., (1976b) might have been rationalised by curing the specimens after compaction and prior to testing.

The SCS laboratory dispersion test

Fig.4 shows a plot of SCS laboratory dispersion test results against erosion indices for compacted specimens cured before testing. There is little relationship between the SCS test result and the erosion index. Below 20% dispersion and above 80% dispersion the SCS test results give good indications of erodibility, but between 20% and 80% it can only be said that the soil probably has low erosion resistance.

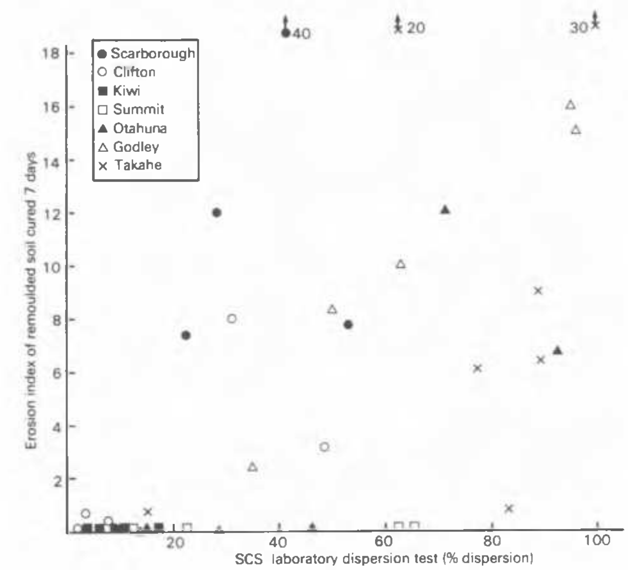

Fig.4 Na% and % dispersion (SCS laboratory dispersion test) and erosion index for remoulded soils cured 7 days before testing.

Changes of Na% with depth

There is a marked increase of Na% with depth in all the Port Hills profiles studied (Fig.5). This is probably a reflection of the particular regime of wind-blown salt and leaching on the Port Hills. Soils on the Port Hills (Summit soil excepted) are weakly leached, but the leaching regime may nevertheless be sufficient to translocate elements down the profile while not removing them completely. Hence, the increase of Na and other soluble salts with depth. The increase of Na% with depth is not a necessary condition for tunnel gully erosion because such erosion can occur whenever rainwater is able to enter vertical cracks and subsequently move horizontally in an erodible soil horizon.

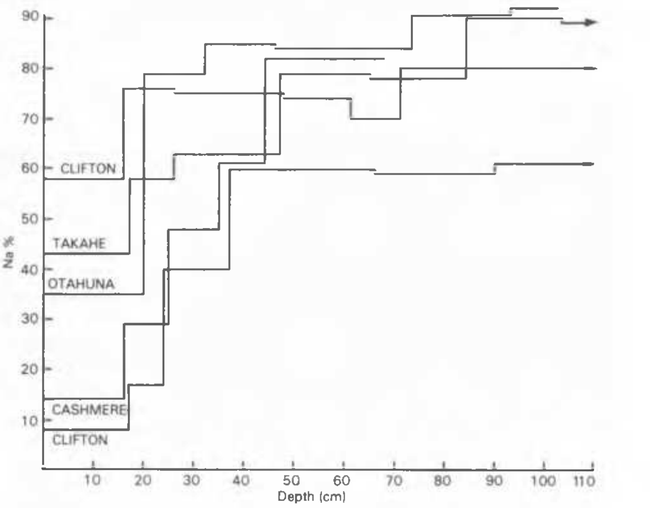

Fig.5 Na% versus depth for some of the soil profiles from the Port Hills. Maximum depth sampled or represented on the diagram is not necessarily depth to bedrock.

Topography

To investigate the influence of topography, corresponding materials from Takahe and Scarborough profiles were compared. The Takahe samples were taken from a ridge site considered potentially subject to tunnel-gully erosion, but exhibiting only minimal actual erosion of this kind. The Scarborough samples were from a site where tunnel-gully erosion was very evident, downslope from the Takahe site.

Curing for 7 days prior to pinhole testing had no discernable effect on erosion indices of compacted material, so the results are not separately reported.

For both sites, both undisturbed and compacted erosion indices progressively increase with depth (Table I), and this is in accord with the observed usual initiation of tunnels in the "P" layer of the Scarborough profile. The small number of tests made on undisturbed lumps, and the large variability of results, prevents any difference to be discerned between the undisturbed soil from equivalent horizons at the two sites. The potential for erosion is therefore apparently similar and the difference in actual performance is presumably attributable to topography or some other unidentified influence.

Stabilisation Studies

The effects of lime and phosphoric acid stabilisation treatment are shown in Table II. Immediately after treatment, phosphoric acid reduced the erosion index more than lime. However, if the treated material was cured and then broken up and compacted, lime treatment gave more consistent results and lower erosion indices than phosphoric acid treatment. There

TABLE II

Some effects of hydrated lime and phosphoric acid treatment on erodibility of Scarborough "C" layer

Specimen No.	Treatment	Erosion index
	Comparison of undisturbed with compacted. No chemicals.	
441-3	Undisturbed lumps	1.1 1.4 2.1
444	Broken up, compacted, cured 0 days	11
458	Broken up, compacted, cured 7 days	9.3
	Effect of 0.3% H_3PO_4, curing, and remoulding	
463	H_3PO_4 added, compacted, cured 0 days	1.7
464	No. 463 broken up, recompacted, cured 7 days	0.01
471	No. 464 broken up, recompacted, cured 0 days	11
472	No. 471 broken up, recompacted, cured 7 days	0.03
476	No. 472 broken up, recompacted, cured 0 days	9.2
	Effect of 0.5% H_3PO_4, curing and remoulding	
465	H_3PO_4 added, compacted, cured 0 days	1.3
466	No. 465 broken up, recompacted, cured 7 days	0.05
473	No. 466 broken up, recompacted, cured 0 days	3.1
474	No. 473 broken up, recompacted, cured 7 days	<0.01
477	No. 474 broken up, recompacted, cured 0 days	6.0
	Effect of 0.5% $Ca(OH)_2$, curing and remoulding	
459	$Ca(OH)_2$ added, compacted, cured 0 days	4.5
460	No. 459 broken up, recompacted, cured 7 days	0.09
467	No. 460 broken up, recompacted, cured 0 days	3.8
468	No. 467 broken up, recompacted, cured 7 days	<0.01
475	No. 468 broken up, recompacted, cured 0 days	3.7
	Effect of 1% $Ca(OH)_2$, curing and remoulding	
461	$Ca(OH)_2$ added, compacted, cured 0 days	3.3
462	No. 461 broken up, recompacted, cured 7 days	<0.01
469	No. 462 broken up, recompacted, cured 0 days	<0.01

NOTE: Exploratory tests on Takahe "P" layer using 0.5% $Ca(OH)_2$ gave results similar to the 0.5% $Ca(OH)_2$ treatment above.

was some indication that the erosion resistance immediately after compaction tended to increase from one cycle to the next with lime, but tended to decrease from one cycle to the next with phosphoric acid. However, a more extensive testing program would be needed to confirm this.

It appeared from the tests performed that it might be difficult to obtain a phosphoric acid-treated soil which was more erosion resistant than undisturbed soil under all test conditions. On the other hand, the prospects for an acceptable level of lime treatment to render the treated material consistently more erosion resistant than the undisturbed soil appeared good.

Influence of curing time on erosion susceptibility

It has been shown (Schafer, 1978) that curing for 7 days after remoulding markedly reduces the erosion susceptibility of some soils. A number of the soils tested in the present program exhibited this property. They are represented by + signs in Fig.3. A few cases of an apparently different phenomenon were also observed. In these cases, also represented by + in Fig.3, specimens made from the same sample and subjected to the same curing regime exhibited increased erosion resistance when retested some months after being tested for the first time. It seems possible that accelerated weathering by increased access of atmospheric gases and higher mean temperature in the laboratory, could have caused some changes in these soils, but there is no really satisfying explanation.

In its untreated state, the soil used for stabilisation studies exhibited no significant change of erosion resistance when cured 7 days after remoulding and before testing. However, after the addition of 0.3% or 0.5% phosphoric acid, or 0.5% lime, the erosion resistance was markedly increased by curing, and this behaviour was repeated through several cycles of remoulding and curing (Table II). It is not known whether this property of the stabilised soil would be retained indefinitely, with repeated remoulding and curing. When 1% lime was added, erosion resistance was increased so much that this behaviour was no longer observable, though it may still have occurred. It is assumed (perhaps wrongly) that an untreated soil exhibiting increase of erosion resistance when cured after remoulding would continue to possess this property indefinitely.

Influence of Clay

Clay content (% <2 μm) did not appear to correlate with erosion susceptibility. In the Scarborough and Takahe profiles the clay content was conspicuously low in the very erodible "P" layer materials. However, no similar effect was present in the Godley profile which also contained an erodible horizon. It may be that the type of clay is more relevant than the quantity, but this aspect has not been examined.

CONCLUSIONS

Erosion resistance of undisturbed material is often much greater than that of the same material after remoulding. Treatment with hydrated lime is generally effective for increasing erosion resistance. Phosphoric acid treatment also appears to be effective but displays some unpredictable effects immediately after remoulding.

The relationship between % Na in saturation extract, total dissolved solids in the saturation extract, and erosion resistance appears to be similar to that demonstrated by previous workers.

Neither % Na nor the SCS dispersion test correlates completely with the pinhole test. Erosion susceptibility as measured by any of the laboratory tests is only an indication of erosion potential. For tunnel gully erosion to occur, other factors must also be favourable for that type of erosion.

APPENDIX

In order to quantify the pinhole test, a series of tests were made on specimens of the same erodible soil under a variety of conditions. The initial 'pinhole' through all specimens was approximately 1 mm diameter. The variables studied were the specimen length, rate of water flow, and diameter of the inlet by which water entered the specimen. Effluent was collected over successive measured time intervals. The mass of effluent at assumed unit density yielded the flow rate, and the mass of dried solids at measured dry bulk density of the specimen yielded the eroded volume for each time interval.

It was found that inlet diameter was the most important variable influencing erosion rate, and an empirical scaling equation was developed so that tests performed under different conditions could be compared.

An erosion index was arbitrarily defined as the increase in volume (ml) of the cavity which would be formed in a 50 mm long specimen by distilled water flowing at 3 ml/sec from a 1.0 mm diameter inlet, after 5 litres has flowed. The scaling equation enables results from tests done with inlets of different sizes at flow rates greater or less than 3 ml/sec to be corrected to the standard conditions.

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