Fifth Australia-New Zealand
Conference on Geomechanics
Sydney, 22-23 August 1988

Predicting Landslide Mobility
An Application to the East Abbotsford Slide, New Zealand

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1 INTRODUCTION

Landslides which develop unexpectedly rapid movements have occurred sufficiently frequently to indicate that a much improved understanding is required of the geotechnical properties governing landslide mobility. The development of standard techniques that will provide a means of predicting whether an actively creeping slide could accelerate catastrophically is a research priority being conducted jointly by the Geotechnical Group of the N.Z. Geological Survey and the Civil Engineering Department at the University of Canterbury. Also under investigation is the prediction of both the onset and expected steady velocity of a landslide activated by changing external conditions (triggering mechanisms). This paper considers the mobility of the East Abbotsford Slide which occurred in Dunedin in 1979, to show how application of techniques currently being developed can account for previously unexplained phenomena. Considerable promise is therefore indicated for the future application of the methods to the analysis of unstable slopes.

2 GEOTECHNICAL BACKGROUND

The East Abbotsford Slide accelerated unexpectedly on 8 August 1979 after more than 10 years of incipient deformation (Commission of Inquiry into the Abbotsford Landslide Disaster, 1980) and several months of creep displacement. The sliding block, covering an area of about 20 hectares and involving more than 60 houses, moved in a predominantly translational manner down a thin plastic silty clay bedding plane, which dipped at 7 degrees. Classical active and passive Rankine zones developed in the head and toe areas, respectively, where the failure surface passed through dense silty sand. Index properties of the bedding plane were LL: 60, PI: 38, and 35% clay fraction. It was highly overconsolidated and about 20-30 mm in total thickness although this contained multiple very thin lenses of silty fine sand. The depth of the failure plane averaged about 25 metres, while the watertable was located about 10 m above the slide plane and approximately parallel to it.

The slide was extensively investigated and instrumented (both during the creep phase and after the ultimate failure), allowing relatively straightforward modelling by conventional limit equilibrium analysis. Input parameters were the measured piezometric levels and frictional strength of the silty sand forming the head and toe portions (effective friction angle of 33 degrees and zero cohesion, Millar & Turnbull, 1979). Back-analysis then indicated that an effective friction angle on the clayey bedding plane of about 8 degrees (assuming no cohesion) was mobilised at failure, this being consistent with the residual shear strength measured in the laboratory (Section 4.2).

A plan with typical section is shown in Fig. 1, and detailed accounts of the slide geometry, geology and precursory events are reported by Hancox et al. (1979), Bishop & Norris (1986) and numerous submissions to the Commission of Inquiry into the Abbotsford Landslide Disaster (C.o.I., 1980). Accordingly, this article addresses principally those aspects that relate to mobility.

3 TRIGGERING MECHANISMS

Several triggering mechanisms have been suggested for the Abbotsford Landslide. This section will quantitatively analyse the effects of each phenomenon to assess their plausibility.

All of the possible triggering mechanisms, with the exception of toe excavation, affect stability by acting on pore pressures within the slope. For any quantitative analysis of groundwater changes, a realistic aquifer model is required. In this paper, in light of the groundwater geometry in the Abbotsford area, a 2-D unconfined aquifer model is developed, which uses the conventional groundwater flow equations and a finite difference numerical system. The fundamental equations that apply are Darcy's Law and Continuity used in conjunction with given boundary conditions. That is, the theory follows that used for the basic construction of flow nets, although the numerical method has the added advantage of flexibility and can readily accommodate non-steady as well as steady state conditions.

To utilise this model, the parameters of effective porosity (storage coefficient) and permeability (hydraulic conductivity) need to be estimated. Using the bulk and solid densities measured for the silty sand, and the in situ moisture content above the watertable (Hancox et al, 1979), the effective porosity can be estimated as 0.185. Data assembled by Peck & Williamson (1987) have been adopted for this infiltration model because the climate and relevant soil characteristics reported in those studies are not unlike those at Abbotsford. Firstly, infiltration reaching the groundwater system may be crudely approximated as about 15% of the measured rainfall in a deforested area, and secondly, the effective infiltration for forested terrain would be expected to be about 75% of that for the same land in a deforested state.

Taking present infiltration on the largely pastoral land as 15% of the mean annual rainfall at Abbotsford, the numerical model was used empirically to find a permeability that produced a steady state watertable with the same profile as that asse sed for the slide before its ultimate movement. The required permeability was 7E-7 m/s, a value which is consistent with laboratory measurements (Hancox et al, 1979).

3.1 Deforestation

The land contributing infiltration to the Abbotsford Slide aquifer was cleared for pastoral use prior to 1894 (Bishop et al, 1979). At the time of the inquiry into the slide little information was available on the quantitative effects of deforestation on infiltration rates.

Assuming the validity of applying Peck & Williamson's (1987) data to Abbotsford and using the aquifer model already discussed, it is possible to determine the changes in the level of the watertable from the time of deforestation. This effect is illustrated in Fig. 2A in which a deforestation date of 1890 has been assumed.

3.2 Antecedent Rainfall

Natural variations in rainfall will cause the watertable to continuously oscillate about the mean level. This effect can be analysed using the aquifer model if the rainfall record is known and an infiltration model assumed.

Hancox et al (1979) suggest that the Burnside rainfall station, for which monthly records date back to 1917, provides a good approximation of the rainfall at Abbotsford. If the infiltration rates suggested by Peck & Williamson (1987) are again assumed, the level of the watertable history can be estimated (Fig. 2A and 2B).

This assumes that the watertable responds instantaneously to the rainfall, although in reality the watertable reaction will be delayed. To determine this delay time an estimate of the flow rates in partially saturated conditions would have to be made, but to the authors' knowledge, is not calculable from the known data. However, this effect would simply shift the estimated curve to the left by a finite time.

3.3 Watermain Leakage

Leakage from a watermain has been suggested as a possible contributing factor in the Abbotsford failure (C.o.I., 1980). The leakage has been estimated to have been 18 l/min and initiated in 1976 (Hancox et al, 1979), which can be input into the aquifer model as a 2-D flow using an estimate of the likely plume width. The results of this analysis are presented in Fig. 2B.

3.4 Borrow Pit Excavation

More than 10 years prior to the ultimate failure, a borrow pit was worked in the toe of the slide. About 300,000 cubic metres of sand were removed (a significant proportion of the slide volume of about 5 million cubic metres).

3.5 Discussion

To assess the relative significance of each of these suggested triggering mechanisms, conventional limit equilibrium analysis was used. For the first 3 factors discussed, the sensitivity of the slope to movements in the watertable is required. This was found to have been about 1% change in the factor of safety per 0.3 m rise in watertable for the range of movements under consideration (C.o.I., 1980). As expected for a predominantly translational slide, the change in safety factor resulting from the borrow pit excavation was small - slightly less than 1% if the failure surface materials are assumed to have negligible cohesive strength (C.o.I., 1980).

The watertable sensitivity determination allows the effects of deforestation, varying rainfall and watermain leakage to be transferred into a change in the factor of safety. Adopting a factor of safety of 1.00 at failure, and including the effect of excavation at the toe with the data from Figs. 2A and 2B, the history of the factor of safety may be back-calculated as presented in Fig. 3.

Because the factor of safety at no date prior to 1979 approached the critical value of 1.00, the figure suggests that the combined mechanisms proposed do form a plausible triggering mechanism. However, whether the magnitude of the stress changes was sufficient to cause the observed displacement history cannot be determined until the concept of mobility is addressed.

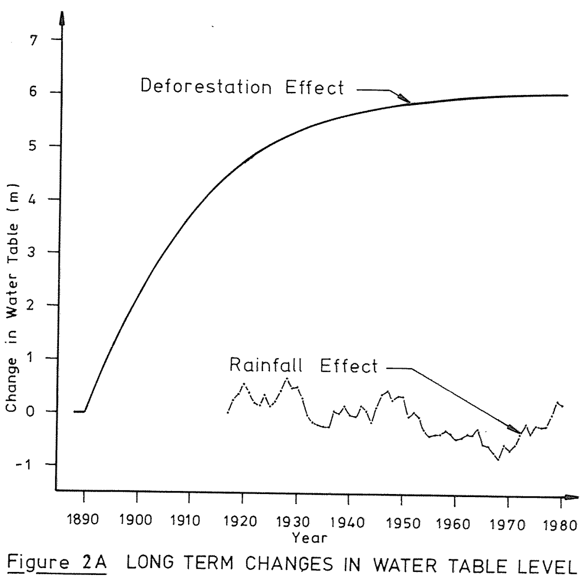

Figure 2A LONG TERM CHANGES IN WATER TABLE LEVEL

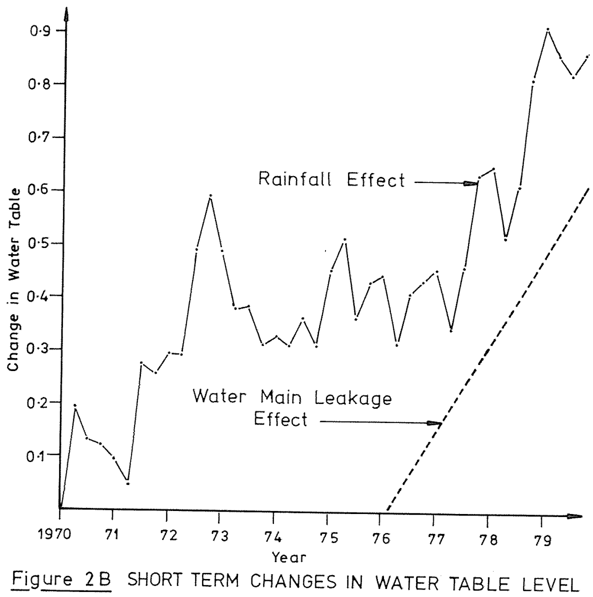

Figure 2B SHORT TERM CHANGES IN WATER TABLE LEVEL

Figure 2 Changes in water table level

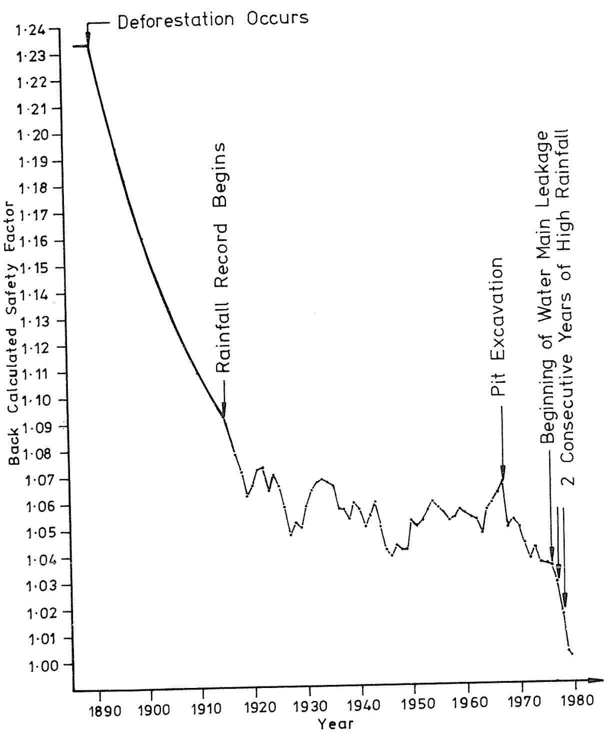

Figure 3 COMBINED CHANGES IN FACTOR OF SAFETY FROM TRIGGERING MECHANISMS

4 MOBILITY

Mobility, the disposition of a slope to accelerate rapidly, is often the principal concern of engineers and geologists attempting to assess the hazard potential of an active landslide.

In this section, the movement record of the Abbotsford Slide will be considered in light of the displacement and velocity dependence of the failing soil's shear strength. This will enable some conclusions to be drawn regarding the stress changes acting on the slide and the likely causes of its sudden acceleration.

4.1 Movement Record

Although essentially regarded as a first-time slide, movement totalled about 3 metres before the ultimate failure on 8 August. The majority of this displacement occurred in the preceding 12 months, although there was evidence of incipient deformation in the preceding 10 years (C.o.I., 1980). The sudden acceleration at about 9 pm on 8 August resulted in an estimated maximum velocity of 3 metres per minute over a period of 30 minutes and a total displacement of 50 m.

Successive differentials of the displacement record are shown on Fig. 4, which includes velocity and acceleration records from other notable landslides.

4.2 Displacement - Shear Strength Relationship

The displacement dependence of the shear strength of soils has long been recognised. An intact clay when sheared will typically show a peak strength at a displacement of a few millimetres followed by a gradual reduction to its residual value. Skempton (1977) suggests that the distance required to achieve residual strength is a function of clay content, but most soils will be close to residual after about 1-2 metres displacement. Additionally, at any displacement larger than 100 mm, the rate of change of strength with displacement will be very gradual, ie no sudden changes in movement rate are likely under constant effective stress conditions.

A sample of the bedding plane clay was recently tested for residual strength in a ring shear apparatus. The first sample attempted was remoulded with all particles coarser than 38 microns removed. Residual strength of 7 degrees was achieved by the stage that 100 mm of displacement had occurred. A second sample was prepared without screening, but all visually obvious lenses of sand were removed. This required much greater displacement (about 2 m) before yielding a steady residual strength of 7.1 degrees.

Prior to any of the detected movements, a mechanism would have been required to cause the initial strength reduction of these overconsolidated materials from peak to almost residual, and the concepts developed by Bjerrum (1967), on the development of progressive failure through recoverable strain energy, may well have been applicable in this case.

4.3 Velocity - Residual Strength Relationship

A number of researchers have recognised the small but significant dependence of the residual strength of soils on the velocity of shearing (Skempton,

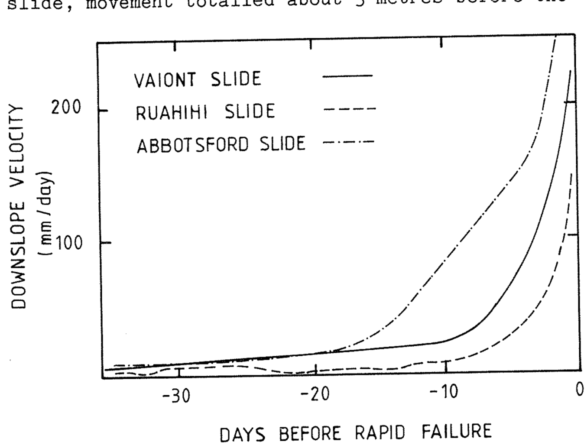

Figure 4A PRECURSORY VELOCITIES OF SLIDES

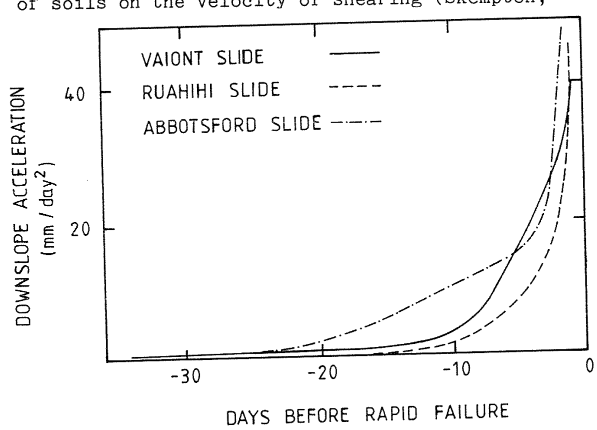

Figure 4B PRECURSORY ACCELERATIONS OF SLIDES

1985). Ring shear tests used to quantify this dependence for a moderate range of creep rates yield typically between 1 and 4% increase in strength per tenfold increase in velocity.

Superficially, such a small change may be considered negligible, and this is true for the estimation of the factor of safety for a design slope. However, for assessing landslide mobility, this relationship is useful for an active slide subjected to a known change in safety factor.

Testing to determine the mobile range of the Abbotsford bedding plane clay was carried out by measuring the shear stress mobilised at various displacement rates. All values were determined at 500 kPa normal effective stress after residual conditions were demonstrated. Table 1 gives the results where stresses are expressed as proportions of the residual shear stress mobilised at a standard rate of 10 mm/day (as adopted by Skempton & Hutchinson, 1969). Steady conditions were clearly established for results up to 1000 mm/day but at faster rates, sample extrusion from the apparatus may have begun to distort results.

TABLE 1

RESIDUAL STRENGTH MOBILE RANGE OF EAST ABBOTSFORD CLAY

Rate of shearing (mm/day)	1.0	10	100	1000	10000
Shear stress ratio	0.998	1.000	1.014	1.042	1.080

These results give no suggestion of anomalous characteristics that would lead to unstable yielding within the range of displacement rates experienced, at least until the time of sudden movement.

4.4 Frictional Heating Effects

A number of researchers have suggested that excess pore pressures may develop in a landslide as a result of pore fluid expansion from frictional heating eg: Anderson (1985), Davis & Salt (in prep.), Voight & Faust (1982) on theoretical grounds, and Salt (1985) in the laboratory.

To analyse the viability of this phenomenon as a landslide-accelerating mechanism it is assumed that all the gravitational potential energy lost with the downslope movement is transferred by friction into heat energy along a discrete failure surface. This heat is then assumed to dissipate equally in both directions away from the failure plane which, with the first assumption, forms a boundary condition for the general heat equation. Assuming an isothermal boundary exists at some distance from the failure surface, this enables the temperature profile to be determined as a function of time. Noting that the coefficient of thermal expansion of water is about 8 times that of common rock-forming minerals and using the basic principles of mass conservation, a partial differential equation can be written which relates temperature change to pore pressure change. Consolidation theory can then be used to analyse the dissipation of these pore pressures which, with a finite difference numerical procedure, allows excess pore pressures to be calculated as a function of time (Smith, in prep).

Qualitatively the effect of pore fluid heating will become significant when the energy input from the sliding mass cannot be dissipated quickly enough, causing increased temperatures and excess pore pressures if insufficient drainage can take place. This results in a decrease in the effective stress, a loss of strength and a decrease in the factor of safety. In these conditions, the slide will accelerate and the process will cascade, giving a sudden loss of stability.

To apply the analysis to the East Abbotsford Slide, reasonable numerical values must be substituted into the model. Table 2 lists the required data, the ranges of values that would be expected for this case, and the values used in the analysis to follow. Properties have been assessed from Hancox et al (1979), Clark (1962) and specific laboratory tests.

In addition to the above data, a reasonable velocity-time history must be input into the model. By considering the 95% consolidation time for the clayey layer, it can be shown that negligible pore pressures will develop in the slope until a few hours before the ultimate failure, and therefore the velocity-time function will be required for 8 August only. Although the exact form of this curve is not known, an approximate curve for this time period can be developed from the field observations. In this analysis a hyperbolic curve with the appropriate constants required to give a realistic displacement function was used to approximate the slide velocity.

The results of this analysis show the development of significant excess temperatures (up to 75 degrees C) and accompanying excess pore pressures within the clayey band, as shown in Fig. 5 (which also shows displacement of the slide with origin at the beginning of the day of ultimate failure). This suggests that the frictional heating mechanism could well have contributed to the marked acceleration of the failing slope.

TABLE 2

DATA FOR FRICTIONAL HEATING ANALYSIS OF EAST ABBOTSFORD SLIDE PLANE

Variable	Probable range	Value adopted	Units
Thermal conductivity	2.5-3.7	3.3	J/s m degree C
Specific heat capacity	840-1000	940	J/kg degree C
Soil density	1800-2200	2000	t/cu m
Fluid density	1000	1000	t/cu m
Porosity	0.2-0.4	0.3	
Depth to drainage bdy	5-25	10	mm
Depth to isothermal bdy	10-30	20	m
Total vertical stress	200-600	400	kPa
Thermal expansion coef.	0.0002	0.0002	
Young's modulus (rebound)	50-200	100	MPa
Residual friction angle	7-8	8	degree
Permeability	1E-12 4E-11	1E-11	m/s

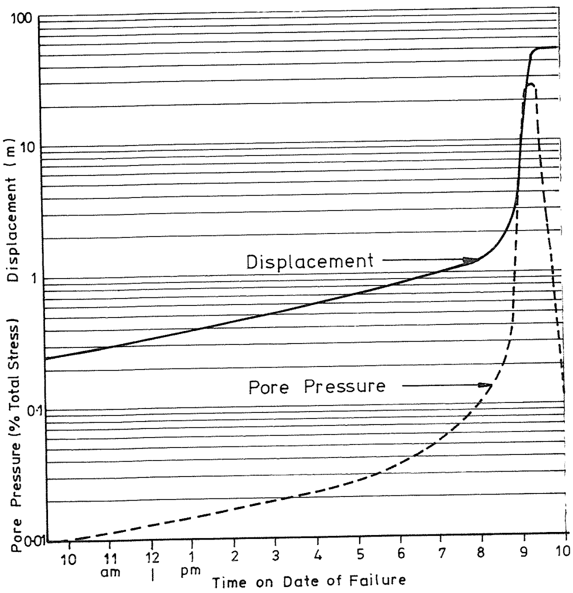

Figure 5 EXCESS PORE PRESSURES FROM FRICTIONAL HEATING

Frictional heating could also be modelled in the laboratory by imposing the observed velocities on a ring shear sample. However, there are difficulties achieving 100% saturation in conventional equipment. Small inclusions of air will diminish the pore pressure response greatly. Clearly, additional laboratory testing is required to refine the parameters listed in Table 2, and to measure directly the proposed strength loss. However, these preliminary calculations suggest that the pore fluid heating mechanism is worthy of further consideration to explain, at least in part, the sudden unpredicted acceleration of the East Abbotsford Slide.

4.5 Mass Redistribution Effects

Hancox et al (1979) note that the final failure caused a total displacement of 50 m within 30 minutes. This time and the relatively low permeabilities of all soils involved suggest that the undrained characteristics of these materials may indicate a logical mechanism for the development of excess pore pressures. Undrained triaxial testing (Millar & Turnbull, 1979) has shown that the sandy soils both above and below the clayey bedding plane displayed typical pore pressure responses of dense sands during undrained shear.

It appears likely that the stress changes (namely unloading) associated with mass redistribution during sliding would have induced excess pore pressures within the dense sand immediately underlying the clay layer (Salt, 1985). These pressures would have been transmitted directly to the failure surface, reducing the available shear resistance and thus contributing to the unexpected mobility.

5 DISCUSSION

A possible mechanism for sudden acceleration of a slide could be the reduction from peak to residual strength with displacement. However, for the Abbotsford Slide, displacements totalled about 3 m before 8 August and residual conditions would then have applied. This is supported by a calculation of the mobilised strength of the failure surface clay which yielded a low value only 1 degree greater than the laboratory residual. This difference can be accounted for by the gentle undulations in the bedding plane.

From Section 4.3, the velocity dependence of the residual strength would assist stability upon acceleration and thus can also be discounted as a source of the final failure mechanism.

Together, the mobile range curve and the movement record suggest that some long-term process had taken place to trigger significant movement by December 1978, and that this effect gradually worsened to a point in August 1979 when one or more secondary mechanisms caused sudden acceleration and failure of the slope.

In light of the mobile range for the East Abbotsford clay, it is interesting to compare the theoretical changes in velocity that would result from the triggering mechanisms discussed in Section 3. With the change in the safety factor from 1976 to 1979 of 3%, and assuming an initial velocity in 1976 of 10 mm/yr with residual conditions, the theory would predict a 1979 velocity of 250 mm/day. This compares well with the maximum daily velocity prior to frictional heating effects of 300 mm/day. There is some uncertainty regarding the displacement at which fully residual conditions applied. However, it appears that the proposed triggering mechanisms do have a combined effect of sufficient magnitude to cause the observed acceleration.

The development of excess pore pressures has significant implication with regard to expected future behaviour of the slide. The factor of safety at the time movement ceased must have been close to 1.0 since comparison of the frictional energy dissipated with the rate of change of kinetic and potential energy indicates any "overshoot" from the F = 1.0 condition would amount to only a few millimetres of downslope travel. Analysis of the slide in the deflated position in which it came to rest (50 m downslope) indicates a safety factor in excess of 1.1 if the pore pressures on the failure surface and soil strengths are considered unchanged from those determined just prior to the ultimate acceleration. The above leads to the inference that continued creep movements (after dissipation of the excess pore pressures) would be quite unlikely, and this has been confirmed by subsequent monitoring.

6 CONCLUSION

The mobility concept and consideration of triggering mechanisms have been applied to the East Abbotsford Slide. The combined effects of deforestation, antecedent rainfall, watermain leakage, and borrow pit excavation do form a plausible explanation for the triggering of the landslide. The mobile range characteristics of the failing soil explain the accompanying movement history from barely noticeable rates of creep to significant daily displacements. However, an additional accelerating mechanism such as excess pore pressures produced from frictional heating and mass redistribution is required to explain the final catastrophic movement.

It would be unwise to conclude that the processes by which landslides accelerate are well understood. However, the application of these techniques to case histories such as Abbotsford is important in that it confirms the potential usefulness of these concepts to mitigate hazards where pre-existing slides are affected by major works such as earthworks or reservoir impoundment.

7 ACKNOWLEDGEMENTS

The contributions of Dr. R.O. Davis (University of Canterbury), financial assistance of the University Grants Committee and support of the New Zealand Geological Survey are gratefully acknowledged.

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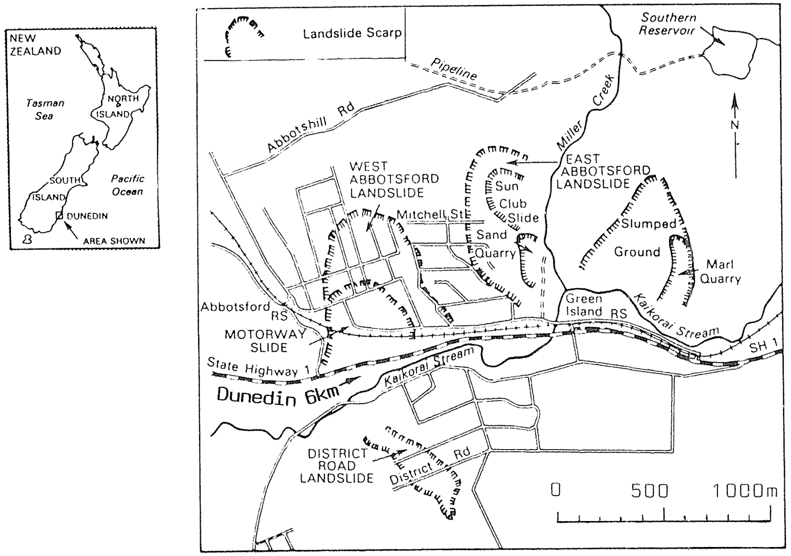

Figure 1a Locality map of the East Abbotsford Landslide

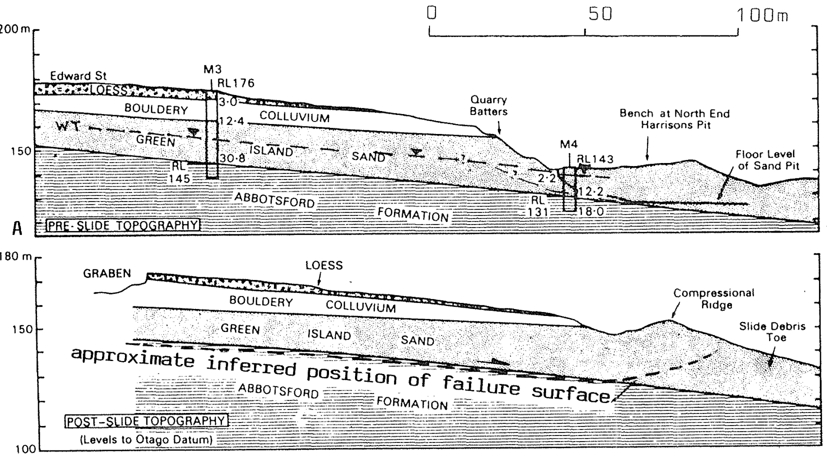

Figure 1c Generalised cross section of East Abbotsford Landslide

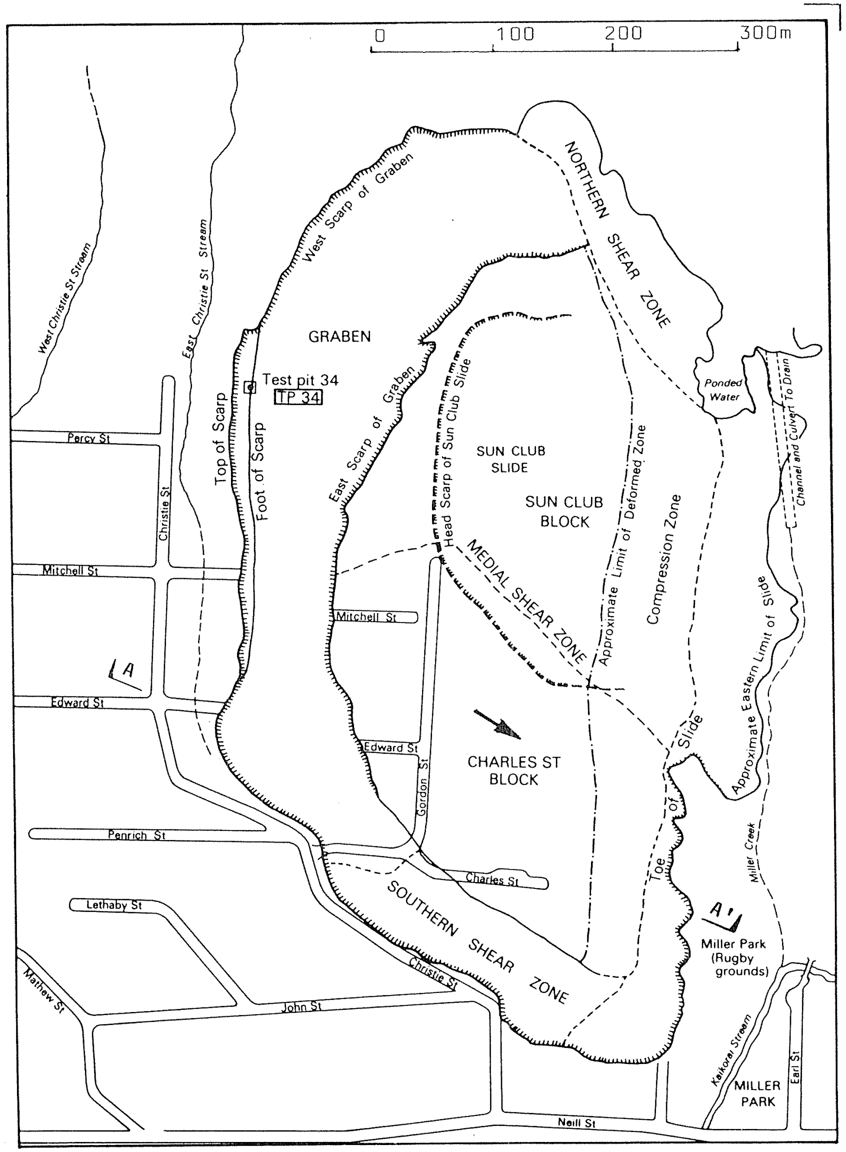

Figure 1b Map of East Abbotsford Landslide showing main features

(after Commission of Inquiry Report 1980)