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A decade of earthflow research and inter-related studies in the North Island of New Zealand

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Abstract Research on earthflows and inter-related processes in the eastern North Island, New Zealand, is reviewed. Early studies indicated strong coherent spatial movement patterns within individual flows. Maximum surface velocities of 3.6 to 20.4 m year^{-1} were seasonally consistent. Surface movement rates on forested flows were 2-3 orders of magnitude less than those on grassed earthflows. Subsurface deformation accounted for less than 25% of total surface movement. Subsurface deformation results largely from compression flow on forested earthflows and from extension flow on grassed earthflows. Soil-water measurements indicated a shorter period of high winter soil-water content under forest stands than under clearfelled sites. Tree roots influence earthflow movement by creating a reinforced upper layer 1-2 m thick that has significant tensional strength and higher shear strength than the underlying flow material. Future research will focus on earthflow material properties, and pore-water pressure development.

BACKGROUND

Before European settlement much of the East Coast Region of New Zealand was covered in mixed podocarp-hardwood forest. During the period 1860-1920 nearly all this forest was cleared for pastoral farming. Much of this cleared land has undergone severe and extensive erosion, particularly the inland parts of the major river catchments at elevations less than 1000 m, which are underlain by uppermost Cretaceous and lowermost Tertiary sediments or are in zones of intensive fault crushing and shearing. These sediments are extremely susceptible to mass-movement processes, particularly slide-flow combinations (Pearce *et al.*, 1981). Forest removal appears to have initiated a phase of downcutting in headwater and tributary streams, eventually oversteepening footslopes and initiating slide-flow failures that have progressively regraded upslope (Pearce, 1982). The combined effects of loss of soil cohesion from tree roots and increased soil moisture content as a result of reduced evaporative losses may also have destabilized earthflow-slide complexes that were marginally stable under a dense forest cover.

Widespread aggradation of headwater river channels, apparent increases in flooding, and a recognition of long-term soil loss eventually forced a major technical assessment of the erosion problem. This resulted in a recommendation that 1500 km^2 of the headwater regions be reforested. Between 1960 and 1988 about 600 km^2 of rapidly eroding hill country were reforested with plantations of mainly *Pinus radiata*.

The earliest of these plantings is now being harvested, and earth and hydrological science data are needed to aid difficult management decisions on where harvesting should be permitted, methods of harvesting, and the consequences for slope stability.

In this paper we review a decade of research work on earthflow-slide complexes and inter-related processes. We look ahead to the next phase of research that should improve our understanding of hydrological and earth processes as cleared land is replanted and heads towards canopy closure. This research should lead to an increased ability to predict the occurrence and activity of such processes in these unstable environments.

SITE DESCRIPTION

Mangatu Forest, located in the headwaters of the Waipaoa River, has been the site for various studies carried out throughout the 1980s (Fig. 1). The forest covers approximately 120 km^2 and has extremely variable terrain ranging from fluvially dissected steep slopes (25-40°) on hard (mainly fine sandstone) rocks to near-planar gentle (12-15°) mass-movement dominated slopes on clay-rich shales.

The climate is warm temperate maritime, with warm dry summers and cool wet winters. Mean annual rainfall is about 1300 mm. The region is also prone to large, infrequent cyclonic storms, of which the most recent, Cyclone Bola, caused widespread landsliding and flooding in March 1988 (Phillips *et al.*, 1990).

Three main earthflows or earthflow complexes have been studied. Dome earthflow, Wether Run earthflow, and Wheturau Road earthflow are all located in or close to Mangatu Forest. Detailed site descriptions are given by Zhang *et al.* (1991a,b), Zhang *et al.* (in press), and Phillips *et al.* (1990).

METHODS

Surface-movement rates on earthflows were measured by repeated surveys of stake networks using both triangulation and infrared EDM methods (Zhang *et al.*, 1991a,b). Extensiometers developed from modified Belfort water-level

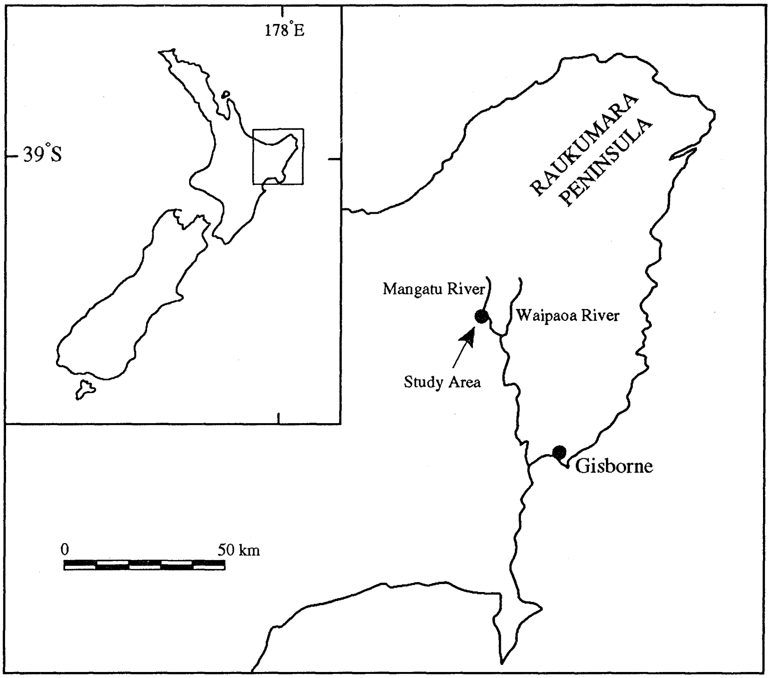

Fig. 1 Location map of the study area.

recorders have been used since 1985 to improve movement-time resolution. Vertical-movement profiles were determined with nests of tiltmeters (Zhang, 1987) in conjunction with the surface-movement measurements. Pore-water pressure distribution and development are currently being monitored in Wheturau Road earthflow using a network of tensiometers connected to a data logger. Two types of tensiometer employing rapid response pressure transducers have been installed. Rainfall and earthflow movement determined by an extensiometer are also recorded by the data logger.

Effects of reforestation on the water balance were assessed by rainfall-interception studies and soil-water content within mature (23 year) *Pinus radiata* stands. Interception losses were measured by comparing gross rainfall (measured in the open adjacent to the study stand) with throughfall under the stand (obtained by a trough-storage tank system). Transpiration from mature stands was calculated as the residual in the soil-water balance for approximately two-week periods, using throughfall data from the interception study as the soil-water recharge and net changes in soil-water storage calculated from neutron-probe measurements on 15 access tubes to a maximum depth of 2.5 m. Measurements began in 1983. In 1986 the trees on two plots containing eight neutron-probe access tubes were clearfelled and net changes in soil-water storage were compared with that on the two plots remaining in forest (seven tubes). In 1991 these plots were also clearfelled. All four plots have subsequently been replanted with *Pinus radiata* seedlings.

Root-system development and morphology were studied by excavating complete root systems of five or more trees in each of three age-classes (O'Loughlin, 1984; Watson & O'Loughlin, 1990). High-pressure water jets were used to sluice soil from around the roots. Tree-root morphology was recorded by sketching and photographing plan and profile views. Root volume and biomass were determined by cutting and dividing roots into five diameter classes.

Physical soil properties (e.g. grain-size distribution, bulk density, and cation-exchange capacity) of earthflow and adjacent non-moving ground were tested using standard procedures.

RESULTS AND DISCUSSION

Earthflow-movement characteristics

Under normal climatic conditions average movement rates on reforested earthflows (0.2-0.5 m year^{-1}) are about 10% of those in unforested flows (3-5 m year^{-1}), implying an order of magnitude reduction in erosion rate by earthflows after reforestation (Pearce *et al.*, 1987). Maximum surface-movement velocities within the transport zones of active earthflows at Mangatu range up to 3 m month^{-1} but are more typically 1-2 m month^{-1} (Zhang *et al.*, 1991b). These velocities are in the upper part of the range of movement rates observed in other earthflow studies done over 10 days or longer (e.g. Keefer & Johnson, 1983). The near-constant width, little change in surface elevation, absence of lateral influx of earth material, and near-constant ratios of velocities between any two points in the transport zone indicated that earthflow movement through the transport zone was approximately in a steady state. Data collected over a 10-year period provided a good example with which to test Iverson's (1986a,b) theories of unsteady non-uniform landslide movement. Calculated values of *Pe* (the landslide Peclet number) of 0.1-2.0 under saturated conditions indicated that the rheology of these earthflows was likely to be plastic with some viscous characteristics, and that diffusion may be more important than kinematic-wave propagation in spreading a disturbance downslope through an earthflow (Zhang *et al.*, 1991b).

Six simple models of subsurface deformation of fast-moving earthflows were proposed by Zhang *et al.* (1991a): (a) rotation over curved slopes, (b) rotation of material beneath the earthflow (e.g. a sub-earthflow slump block), (c) gravity-shearing flow, (d) extension flow or creeping, (e) compression flow, and (f) sliding. Micro-topography (features on a scale of 1-10 m) affected tilting behaviour (internal deformation), which accounted for less than 25% of the total surface movement, the remaining 75% being the result of sliding movement along the basal shear plane. Gravity-shearing flow occurs along the basal shear plane, which is thought to be not more than a few centimetres thick. Tiltmeter data showed differences between deformation profiles on grassed and forested earthflows. A rafting hypothesis (Zhang *et al.* in press) was used to explain the differences. Roots of individual trees bind the top soil to form a small semi-rigid raft or block that "floats" on more plastic material beneath. Individual raft blocks may be connected by lateral roots to blocks derived from other trees to form larger raft blocks. When the earthflow moves downslope, the raft blocks affect its motion as they push and pull each other. If the downslope motion of a raft is slower than some deeper part of the earthflow, compression flow takes place beneath the raft. If the downslope motion of a raft is faster than some deeper part of the earthflow, dragging or complex extension flow takes place beneath the raft.

Earthflow-material characteristics and pore-water pressure development

Undisturbed soil samples from boreholes located throughout the earthflow and on adjacent areas during summer and winter were used to measure soil physical characteristics. Clay content (<2 μm) ranged from 18 to 69%. Cation-exchange capacities of 16-28 m.e. 100 g^{-1} indicated a relatively high proportion of expansive clay. Dry-bulk densities of 1.20-1.85 g cm^{-3} were recorded. The higher values were for samples taken below the shear plane, and values of 1.3-1.5 g cm^{-3} were recorded for samples of the "flowing" material. Atterburg limits were high and indicate a high swelling potential. Liquid limits, plastic limits, and plasticity index were respectively 30 to 72% (mean = 46.0, s = 10.5, n = 59), 16 to 30% (mean = 22.9, s = 3.9, n = 59), and 5 to 52% (mean = 23.2, s = 11.2, n = 59) (J. Ekanayake & C. J. Phillips, unpublished data).

Three months of data from the tensiometer network installed in May 1991 indicated that the soil profile re-wetted rapidly with winter rainfall and remained at near-saturation levels throughout July (Fig. 2). Pore-water pressure values exceeded the equivalent overburden soil depth (potential in weight basis) at equilibrium when the water table was just below or at the soil surface. This indicates that expandable clays were responsible for relative localized swelling between interlayers, which increased the overburden potential component of the total potential of soil water beyond that for a rigid non-swelling soil at an equivalent depth. Pore-water pressure values for tensiometers H3 and G3 were equivalent to a 15-20 cm head of water above the ground surface (Fig. 2). No movement of the earthflow has taken place since the tensiometer network was installed.

Water balance

Annual interception losses under mature *P. radiata* averaged about 35% of gross rainfall. When soil water was not limiting, transpiration rates ranged from 30 mm $month^{-1}$ in winter to 90 mm $month^{-1}$ in summer (Pearce *et al.*,

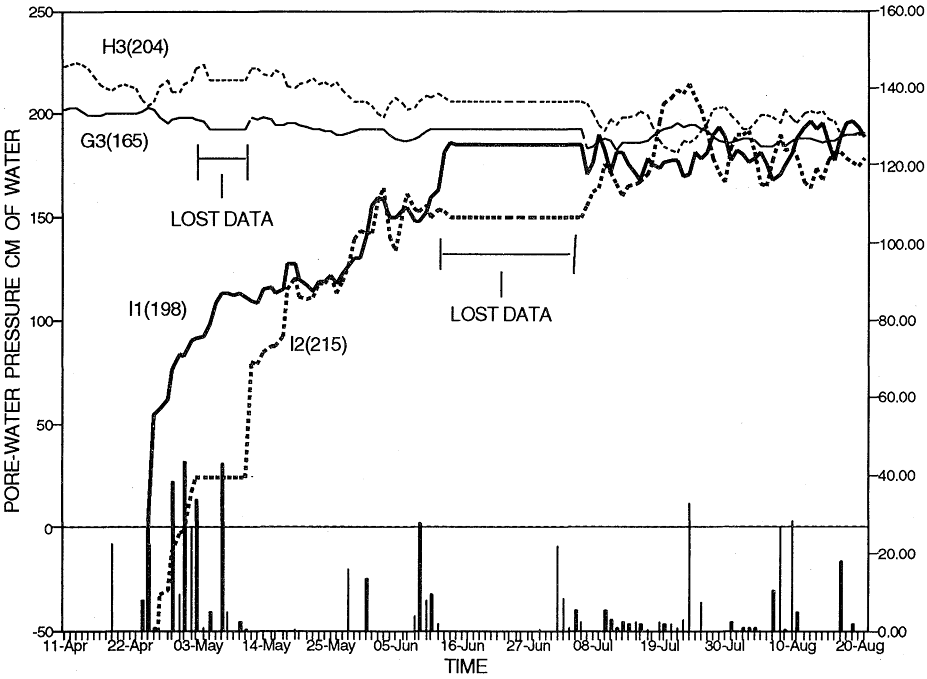

Fig. 2 Average daily values of pore-water pressure calculated from 6-h tensiometer readings from 10 April to 20 August 1991. Tensiometers I1 and I2 are located on the non-moving stable drier bank and show a gradual wetting of the soil profile. Tensiometers G3 and H3 show pore-water pressure values in excess of the equivalent overburden soil depth. The values in brackets are the depths (cm) of the ceramic tensiometer cups below ground surface. Daily rainfall amounts (mm) are also shown.

1987). The measurements of soil-water content showed that these mature forests extract up to 200-250 mm of water from storage in the soil to meet their transpiration needs during summer.

Soil-water storage is recharged slowly and often incompletely by winter rainfall, which is reduced in effectiveness because part is intercepted by the forest canopy. The two sites felled in April 1986 after a near-normal winter showed a gradual wetting of the soil for two-three months until field capacity was reached. Water rose into some access tubes on the clearfelled areas, indicating a water table 1-2 m below the soil surface. However, measurements from the plots remaining under pine forest showed that maximum water contents were not reached until October 1986, by which time the clearfelled areas had been near field capacity for four months (Jackson *et al.*, 1987). The 1986-1987 summer again gave thorough drying throughout the soil profile under forest, but on the clearfelled areas drying was concentrated near the soil surface and little water was used below 0.5 m depth. However, once a complete weed cover had invaded the clear-felled site the rates of transpiration calculated from the soil-water measurements were similar for the two sites (3.0-3.5 mm day^{-1}). Interception made rainfall less effective under forest, so that soil re-wetting was delayed until late into the 1987 winter.

Soil-moisture patterns for the sites clearfelled in April 1991 are expected to show similar trends. However, because of the influence of El Nino (Southern Oscillation), winter and autumn rainfalls were 25% down on previous years and soil moisture and water-table levels did not reach previous levels. Wet soil conditions are expected to persist for no more than one-two months before drying thoroughly during the 1991-1992 summer.

Root-network development and biomass

The morphologies of root systems and individual roots at Mangatu Forest are closely related to physical soil conditions, including stoniness, drainage conditions, and depth to groundwater table, barriers to root penetration, or bedrock (O'Loughlin & Zhang, 1986). Lateral roots of young trees were confined to the upper 40 cm of the soil profile. In 16 and 25-year-old trees, lateral roots were restricted to the upper 1 m of the profile, with 75% still occurring in the 0-50 cm zone. In all age classes, the longest lateral roots developed within 10 cm of the ground surface, i.e. they tended to follow the humus/upper mineral soil interface. The bulk of root biomass is in the root bole, which was 40% of total root biomass for eight-year-old trees, and 50% for 16-year-old trees, remaining reasonably constant for the next nine years. In a stand of 253 stems ha^{-1}, the total root biomass increased at rates of 1-2 t ha^{-1} year^{-1} from the time of planting until age 8, at 7-8 t ha^{-1} year^{-1} by age 16, and at an increased rate of 9-10 t ha^{-1} year^{-1} for at least the next nine years. These figures do not include fine root production.

Roots contribute to the stabilisation of earthflows by creating a reinforced upper soil layer 1-2 m thick that possesses relatively high lateral (tensile) strength as well as enhanced shear strength or increased apparent cohesion. In addition, the properties of the earthflow materials are changed by the presence of tree roots. Physical factors include changes to cohesion and friction angles and reduction in soil moisture in the upper layers. Chemical factors include changes in weathering regime caused by drier conditions and increased organic matter in the upper soil horizons. These changes will affect the rheological behaviour of the earthflow materials and subsequently its internal deformation behaviour. On most slopes, the upper zone of an earthflow undergoes episodes of bending, compression, and extension as concave and converse profile sections of slope are traversed. The more rigid, root-reinforced upper soil layer of forested flows resists these deformations and reduces earthflow velocities (Zhang *et al.*, in press).

Impact of Cyclone Bola on earthflow movement

The impact of large-magnitude storms on the mechanics of earthflow movement is difficult to quantify. The various threshold conditions that appear to govern the initiation and cessation of movement are not fully understood. It is considered that movement begins once the water content of the soil approaches some value less than, but close to, saturation. Whether the onset of movement is associated with rapid or slow pore-water pressure changes is not certain. Thus, when a large storm event occurs, the previous soil-moisture conditions may govern the earthflow response. Alternatively, there may be a lag of days, weeks, or months before movement is initiated.

Surface movement data collected from grassed earthflows generally show a correlation between rainfall from large storms and the movement of individual pegs on the surface of the flow. However, some pegs show large increases in movement rate after a major storm event, and other pegs show no increase. The data also suggest that some zones of the flow do not begin movement for several months after a large storm. This complicated response is obviously related to the large spatial and temporal variations in threshold conditions within the earthflow. On forested earthflows the lag time between rainfall and onset of movement was two-six weeks longer than on grassed earthflows. This may be related to drier soil conditions and a larger soil moisture deficit to overcome before the movement threshold conditions are reached. Both forested and grassed earthflows that showed increased movement rates as a result of a large storm (Cyclone Bola) returned to pre-storm rates over a time span of about six months (Phillips *et al.*, 1990).

CONCLUSIONS

Surface and subsurface movement studies of persistently active, fast-moving earthflows and allied processes have improved our understanding of the activity and motion of such earthflows and how trees affect and modify these erosion processes. Application of surface-velocity data to theoretical models of unsteady non-uniform landslide motion has enabled such models to be tested and validated. Development of new and/or improved field equipment and data-acquisition facilities have enabled real-time monitoring of such parameters as pore-water pressure development and earthflow movement and the measurement of internal deformation of earthflows.

Future work will be directed at more detailed laboratory study of earthflow materials and the role of swelling clays in modifying strength characteristics; field experiments to continue the examination of pore-water pressure development and earthflow motion and cessation; and tree-root soil-bonding strength determinations to assist with developing models of tree roots and slope stability.

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