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Movement History and Sensitivity to Rainfall of part of Brewery Creek Slide, New Zealand

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Summary The highway through the Cromwell Gorge was reconstructed above reservoir level as part of the Clyde Power Project. On the basis of geomorphological evidence, the 80M m^3 Brewery Creek Slide was inferred to be dormant prior to highway reconstruction. Renewed movement of approximately 1 million m^3 of the slide was caused by construction of an 80m high, 460m long cut along part of the toe. Eight discrete movement events have been monitored in varying detail since 1983. The two largest movement events are directly attributable to road construction activities. Close monitoring of the slope has allowed detection of movements as little as 6mm caused by rainfall. A clear relationship between certain rainfall events, increased piezometric levels in the slide mass and accelerated movements has been demonstrated. The largest movements attributed to piezometric rises have occurred after prolonged wet periods. The installed remedial works control, but are unable to prevent, the landslide movements.

1. INTRODUCTION

During the 1980's, the highway through the Cromwell Gorge upstream from the 102 m high concrete gravity Clyde Dam was reconstructed above reservoir level as part of the hydro development project. This 20 km section of highway crosses the lower slopes of eight large landslides along the true left margin of the reservoir. Highway design was constrained by a requirement for large radius curves, the need to provide a reasonable balance of cut and fill, and the requirement to keep the existing highway operational. Wherever possible, the highway was placed on fill to buttress known landslides.

On the basis of geomorphological evidence, the 80M m^3 Brewery Creek Slide was inferred to be dormant prior to highway reconstruction. To ensure that the slide was not reactivated, most of the new highway across it was constructed on fill. However, as Bryant *et al* (1992) report, movement of part of slide was caused by construction of an 80 m high, 460 m long cut along part of the toe between June 1982 and October 1983. At this location it had not been considered practical to construct the new highway on a fill embankment for space reasons. No field investigations had been undertaken prior to construction of the cut.

The reactivated area (Figure 1) became known as the "Active Portion". It has an estimated volume of one million m^3.

Major stabilisation drainage works were later undertaken to ensure that the main slide remained stable after reservoir filling (Gillon *et al* 1992, Brown *et al* 1993).

The Active Portion is not considered to be a reservoir hazard. Failure would block the highway and restrict (but not prevent) access to the drainage tunnels beneath the main Brewery Creek Slide.

1.1 Climate

Central Otago is one of the driest areas in New Zealand. Long term records from the towns of Clyde and Cromwell (at either end of the Cromwell Gorge) show a mean annual rainfall of 348 mm and 405 mm respectively. The highest mean monthly rainfall at the weather station closest to the Brewery Creek slide (Cromwell), is recorded in summer (average 41 mm/month); the lowest rainfalls occur in the late winter months (which average about 28 mm/month).

1.2 Geological Setting

Brewery Creek Slide is located on a south-facing slope underlain by mica-schist which generally dips into the slope behind the slide mass. An antiform axis is inferred to lie under the slide toe area. Development of the landslide is believed to have been controlled by low angle defects dipping towards the valley (Gillon *et al* 1992). Tectonic and gravitational movements have resulted in the formation of a thick zone of sheared and crushed rock, termed the Basal Failure Zone (BFZ).

2. GEOLOGICAL MODEL

Between 1983 and 1994, both the geological model and the hydrogeological model for the Active Portion were systematically developed as new investigations and monitoring data were obtained.

The model is summarised by Figures 1 to 3. The slide mass consists of chaotic schist debris and the failure surface for the Active Portion is a narrow clay gouge located within the 11 metre thick sheared and crushed zone forming the Basal Failure Zone (BFZ) of the main landslide. The active failure surface is difficult to identify from drillcore but has been modelled from inclinometer data and surface evidence. Failure occurs along a comparatively shallow (maximum depth 27m below present ground surface) curvi-planar surface bounded by steep lateral margins and the headscarp.

The toe is exposed in the highway batter at the downstream margin and thrusts up into the highway at the upstream end. The Active Portion failure surface coincides with the base of the BFZ in the downstream (shallowest) section of the slide mass and is higher within the BFZ in the central part of the slide. Near the upstream lateral margin, the Active Portion failure surface diverges from the BFZ.

Six ring shear and direct shear tests indicated residual shear strength parameters for the failure surface of $c' = 0$, $\phi' = 22.5–27.2°$.

3. GROUNDWATER MODEL

The Active Portion contains thin, highly compartmentalised perched aquifers, predominantly within the sheared and crushed rock of the BFZ and the lower part of the slope (Figure 2). The aquifers are fully above reservoir level and were not affected by lake filling. The sub-basal aquifer and aquifers within other parts of the main slide mass, which were affected by lake filling, do not affect the Active Portion.

The base of the perched aquifer is close to the base of the BFZ. Both permeabilities and piezometric levels within the aquifer are highly variable, making it difficult to confidently determine the head acting on the Active Portion failure surface. Higher permeabilities are inferred to occur in areas of shattered rock.

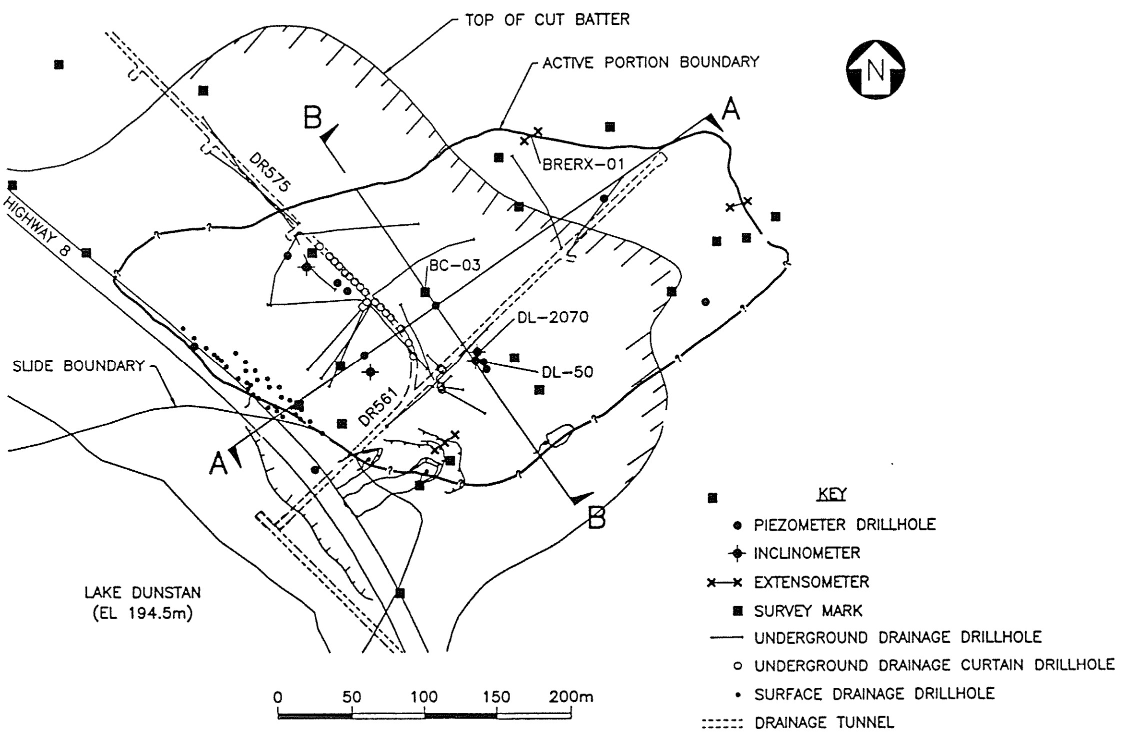

Figure 1. Layout and instrumentation of Brewery Creek Slide 'Active Portion'.

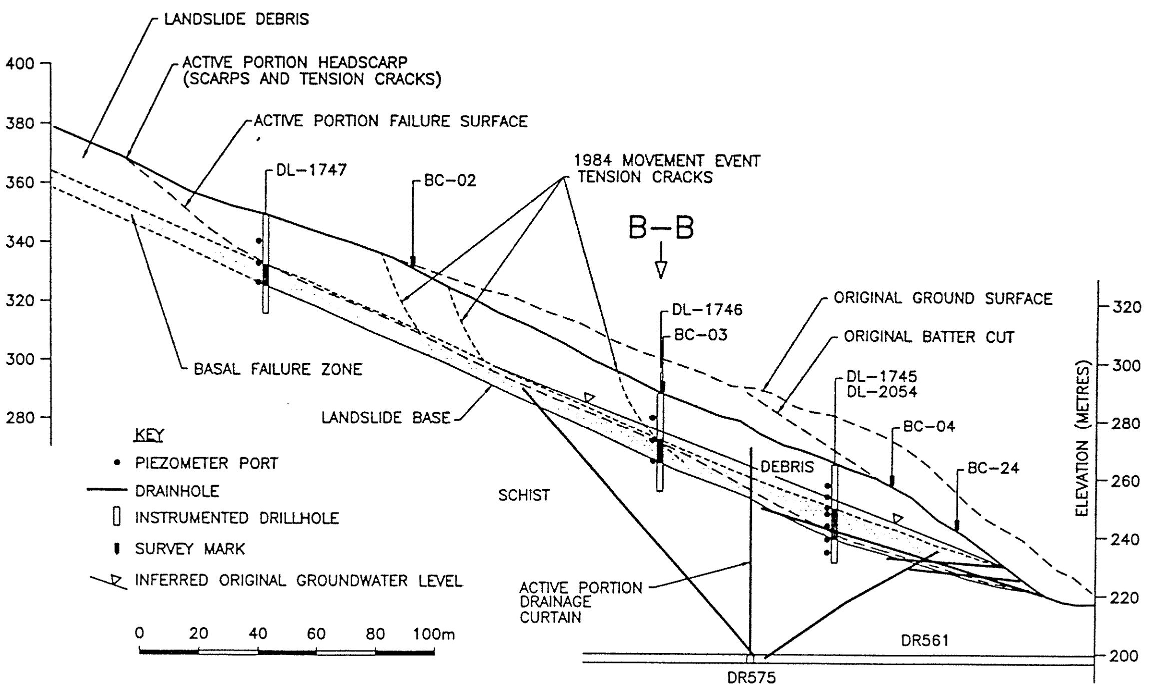

Figure 2. Cross section AA, looking down valley.

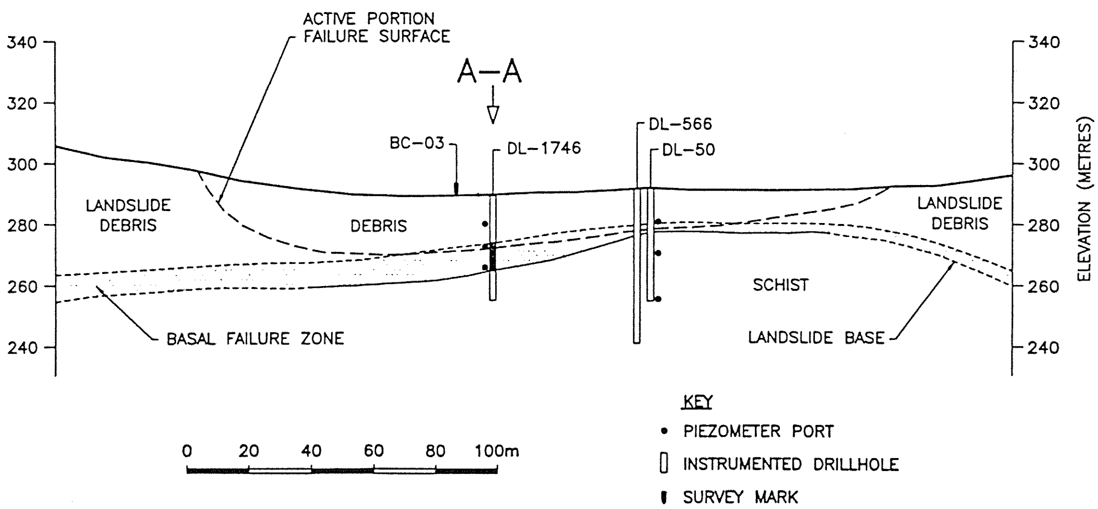

Figure 3. Cross section BB, looking upslope.

4. SLOPE BEHAVIOUR HISTORY

Geomorphic evidence made it clear that the reactivated slope was part of a large, complex landslide, but prior to highway re-construction the slope exhibited no tension cracks, well-defined scarps or other geomorphic evidence to suggest that it was active.

As described below, and summarised by Table 1, eight discrete movement events have been monitored in varying detail since 1983. Instruments installed for monitoring have included survey marks, inclinometers, extensometers and piezometers. Many of these have been destroyed during the monitored slope movement events. In addition, various remedial works have been implemented over the monitoring period, as noted below.

4.1 Movement Event 1

Failure of a 200 metre wide zone occurred in September 1983 when the 1.4H to 1V batter was nearing completion and the excavation exposed a 1.5m thick sheared zone containing a sandy silty clay gouge (Bryant *et al* 1992). Tension cracking developed at EL 300 m, up to 100 m behind the head of the cut slope, and approximately 0.5M m^3 of material was activated. Little water was inferred to be present in the slide although minor seepages were observed on the cut slope just above the BFZ. Surface survey monitoring indicated quite consistent movement rates of up to 25 mm/day. Approximately 4 m of movement was measured between September 1983 and March 1984 (Figure 4).

4.2 Movement Event 2

Back analysis, assuming a dry slope, was used to design remedial measures involving removal of 0.6M m^3 of material from the head of the active area. This work was implemented in two stages between April and October 1984. The initial earthworks caused accelerated movements (reported as up to 700 mm/day on 5 April) as a result of localised head loading but the rate reduced to a reported 60 mm/day by 8 April as the material was removed.
The total movement caused by head loading is not known, but is estimated as about 1 metre (Figure 4).

Following completion of the earthworks, ten 40m long drains were installed just above the highway between December 1984 and February 1985. They were inclined upwards at about 10° to intercept water perched on the BFZ. Little seepage was observed after initial flows. There were no piezometers installed to demonstrate drawdown.

4.3 Movement Event 3

The remedial works appeared to arrest the movement, but 6 months after completion of the earthworks, new tension cracks developed up to 100 m behind the crest of the remedial excavation. Survey monitoring of 5 permanent deformation marks commenced in April 1985. From April to August 1985, Pillar BC-03 (Figure 4) indicated a movement rate of 0.14 mm/day (50 mm/yr). A further 6 marks were added in September 1985.

In late 1985, two cored drillholes (DL-50, DL-51) were used to investigate the unstable area. Piezometers installed in them identified a relatively thin water table perched on the failure surface.

4.4 Movement Event 4

The movement rate increased to 0.88 mm/day (320 mm/yr) by December 1987. Piezometric rises of 1.4 m were recorded over the same period. There is no survey monitoring data and only limited piezometric data for the period September 1986 to September 1987. Rainfall records indicate that February 1987 was one of the wettest months recorded since 1983. Piezometric levels appear to have increased from February and peaked in September 1987. This combination of factors suggests that most of the movement occurred after February 1987.

Table 1. Summary of movement history since 1983. See also Figures 4 and 5.

Event	Dates	Trigger	Total Event Displ.	Maximum Rate	Remedial Action
1	Sep 1983 to Mar 1984	Toe excavation	4 m	25 mm/day	Head unloading
2	Apr to Oct 1984	Head loading	?1 m	700 mm/day	10 x40m long toe drains
3	Apr to Aug 1985	Unknown	>30 mm	50 mm/yr	
4	Sep to Dec 1987	Rainfall	180 mm	320 mm/yr	16 x55m long toe drains
5	Aug to Oct 1991	Rainfall	6 mm	12 mm/yr	14 targeted drainholes from tunnel
6	Sep to Dec 1992	Rainfall	12 mm	90 mm/yr	23 hole drainage curtain from tunnel, 8 x80-100m long toe drains, surface works to control runoff, tension crack treatment
7	Feb to Nov 1994	Rainfall	55 mm	130 mm/yr	Tension crack repairs
8	Dec 1995-Oct 1996	Rainfall	160 mm	850 mm/yr	Tension crack treatment and repairs

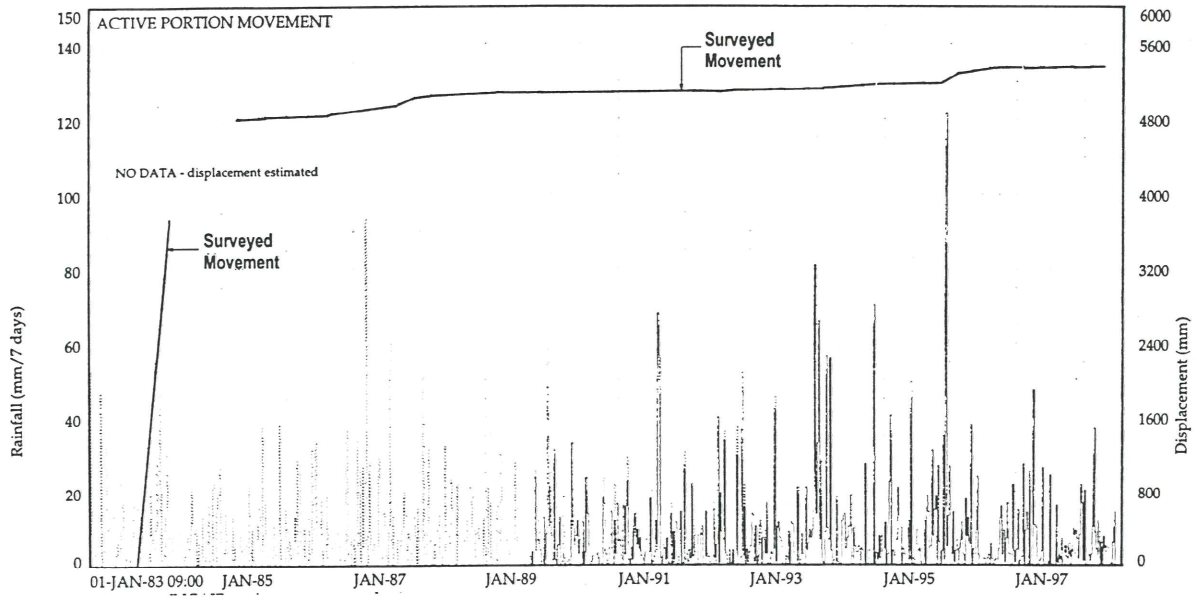

Figure 4. Active Portion movement history since 1983 compared with weekly rainfall.

Between September and December 1987, sixteen further horizontal drainage holes up to 55 m long were drilled from just above highway level to intercept the perched aquifer. The piezometric level was lowered by up to 1.5 m and movements ceased (Bryant *et al* 1992).

4.5 Movement Event 5

Between December 1990 and April 1991 drainage tunnel DR575 was driven across the slope beneath the Active Portion. Fourteen drainholes were drilled up into the Active Portion from the tunnel between May and July 1991. Following rain over a 10 day period, piezometric rises of up to 0.6 m were recorded in August 1991. The creep rate increased to about 12 mm/yr between August and October. About 6 mm of movement occurred (Figure 5).

4.6 Movement Event 6

Piezometric rises of up to 0.6 m followed a series of moderate rainfall events in June, July and August 1992. Increased movement rates (up to 60 mm/yr) were recorded from September to December. The total movement in this event was 12 mm.

To help reduce movement, two more targeted drainholes were drilled from the tunnel in November 1992, and 8 low angle toe drains 80–100 m long were drilled from the surface in November-December 1992.

Surface works involving the repair of tension cracks and runoff control at the head of the slide were carried out in February-March 1993. In addition, from April to August 1993 a vertical drainage curtain (23 holes) was installed from the tunnel to provide more positive control of infiltration into the slide mass (Figure 2).

4.7 Movement Event 7

The total rainfall in a series of events between December 1993 and February 1994 had a return period in excess of 150 years. Piezometric rises of up to 0.5 m were measured and the Active Portion was reactivated. Movement velocities increased from zero to 130 mm/yr for a short time, then reduced steadily (Macfarlane & Gillon 1996). Movement ceased by November 1994 (Figure 5). Drainage flows increased from 15 to 45 litres/minute during the wet period, and showed further increases in response to winter rainstorms, but had decreased to about 38 l/min when movement ceased. Flows continued to decrease until late September 1995, during which period monitored creep rates remained below 5 mm/yr.

4.8 Movement Event 8

From July to December 1995 a steady increase in creep rate was monitored through a wet spring period. Rates were initially below 5 mm/yr but increased sharply (to 80 mm/yr) in October. At this time piezometer levels were rising and drainage flows had increased to above 30 l/minute.

In mid-December 1995 there was a very sharp rate increase (up to 850 mm/yr) in response to a 50 year ARI rainfall event (123 mm in 2 days). Piezometric levels were already high but rose another 0.3 m within a few days. Peak drainage flow rates in excess of 200 l/min were measured during the storm and flows showed an overall increase of about 50 l/min. Inclinometers and some piezometers were sheared off by this event. Movement continued at a rate of about 130 mm/yr for several months (Figure 5) with a slight increase when piezometric levels again rose during the winter. The movement rate slowed from August when piezometric levels fell below EL 280.9 m in indicator piezometer DL-50C and the total drainage flow reduced below about 30 l/min. Movement ceased in October 1996.

Slow creep recommenced in March 1997, apparently in response to a piezometric rise of about 0.3 m. There was no associated flow increase detected.

5. FACTORS AFFECTING BEHAVIOUR

5.1 Construction Activities

The initial reactivation of this section of the Brewery Creek Slide was clearly caused by earthworks for the highway. As shown by Figure 4, almost all of the monitored movement of the slide occurred as a result of the construction activities. The head unloading carried out in 1984 reduced measured movement rates from 25-30 mm/day (approx. 10 metres/year) to creep rates less than 25 mm/year.

The batter has not been successfully revegetated and remains a relatively bare slope of broken rock. Consequently, infiltration can be very rapid and little run-off is observed during rainstorms. The pattern of flow from the drainage curtain holes indicates discrete flow paths through the debris. These are most probably along tension cracks associated formed during movement events.

5.2 Rainfall

Since 1983, there has been only one occasion that the monthly rainfall has exceeded 100 mm without an associated increase in the movement rate of the Active Portion being detected. As shown by Figure 6, since 1990 there is a clear relationship between certain rainfall events, increased piezometric levels in the perched aquifer and accelerated movements.

Four piezometers used as indicator instruments generally record minor water level rises (typically 0.3 to 0.6 m) following those rainfall events which lead to accelerated movement of the Active Portion. Other piezometers are located in lower permeability materials and show no clear pattern of response to rainfall. Since construction of the drainage curtain, DL-528D (an indicator piezometer downslope from the curtain) has not responded to rainfall events.

Initially the piezometers were generally read too infrequently to enable accurate determination of response delay times. However, short duration, high intensity rainfall events generally caused a rise in the "indicator" piezometers about 10 days later (Event 5, 1991; Event 7, 1993/94). In Event 6 (1992) it is difficult to attribute piezometric rises to any particular rainfall event and in 1995 there was a general rise over a period of several months. This initiated creep and a subsequent large rainfall event triggered more rapid movement (Event 8) almost immediately.

There is an apparent increase in the magnitude of movements induced by individual rainfall events in the period between 1990 and 1996. However, the two extreme rainfall events which occurred in 1993/94 and 1995 can be expected to have induced abnormal responses. Consequently, the apparent increase in movement with each subsequent event cannot be considered indicative of increasing sensitivity to rainfall at this time.

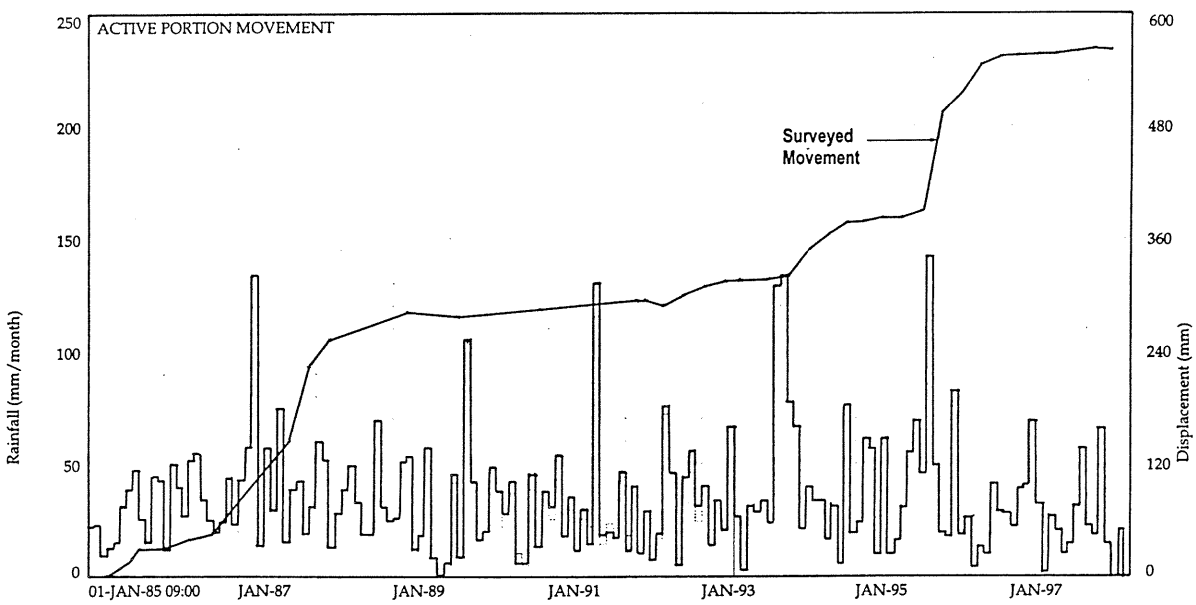

Figure 5. Active Portion movement history since 1985; cf. monthly rainfall.

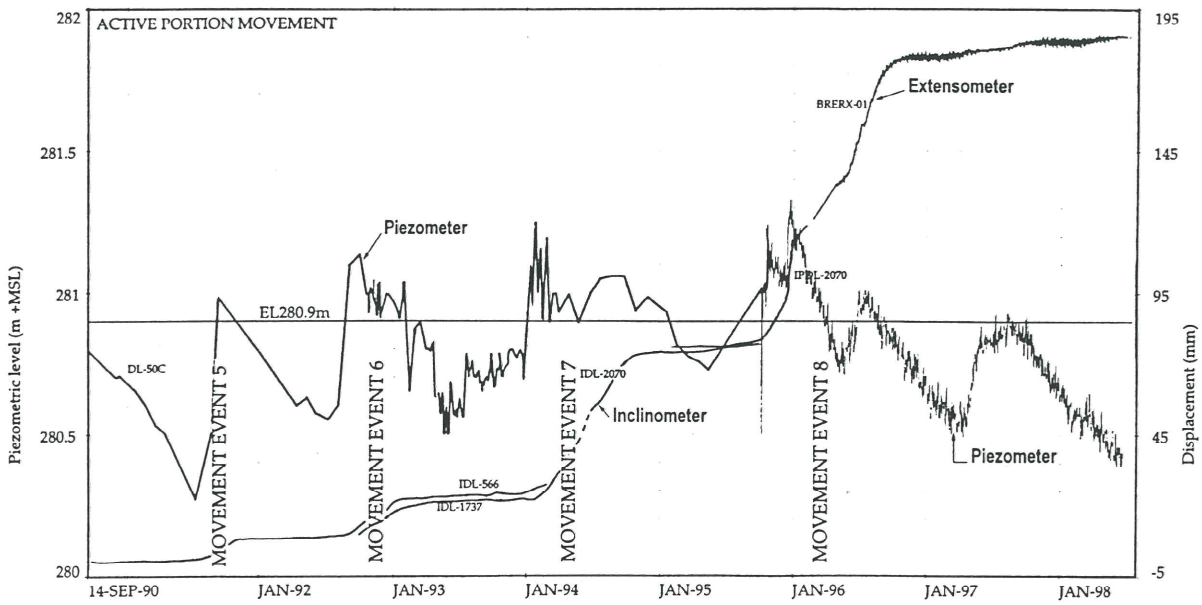

Figure 6. Active Portion movement history since 1990 compared with DL-50c piezometric level.

6. CONCLUSIONS

Re-activation of the "Active Portion" of Brewery Creek Slide in September 1983 was caused by earthworks for highway reconstruction. Almost all of the movement recorded since 1983 occurred as a result of the construction activities.

Close monitoring of the slide has subsequently allowed detection of quite small movements (as little as 6 mm) caused by rainfall events. A clear relationship between certain rainfall events, increased piezometric levels in the slide mass and accelerated movements was demonstrated in 1991 and 1992, 1993/94 and 1995. The largest movements attributed to piezometric rises have occurred after prolonged wet periods in 1993/94 and 1995 (Events 7 and 8).

There is a reasonable correlation between slide movement episodes and the piezometric level in the indicator piezometer DL-50C, with movement generally occurring when it rises above EL 280.9 m.

Movement rates decrease as the slide dries out and the slide does not move while dry conditions prevail. The established pattern of acceleration and deceleration with variation in piezometric levels within the slide mass is expected to continue.

The installed remedial works control, but are unable to prevent, the landslide movements.

The apparent increase in displacement with each subsequent rainfall event between 1990 and 1996 cannot yet be considered indicative of increasing sensitivity to rainfall because of the extreme rainfall events which occurred later in this period.

7. REFERENCES

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