

# DRAINAGE OF THE CAIRNMUIR LANDSLIDE, NEW ZEALAND

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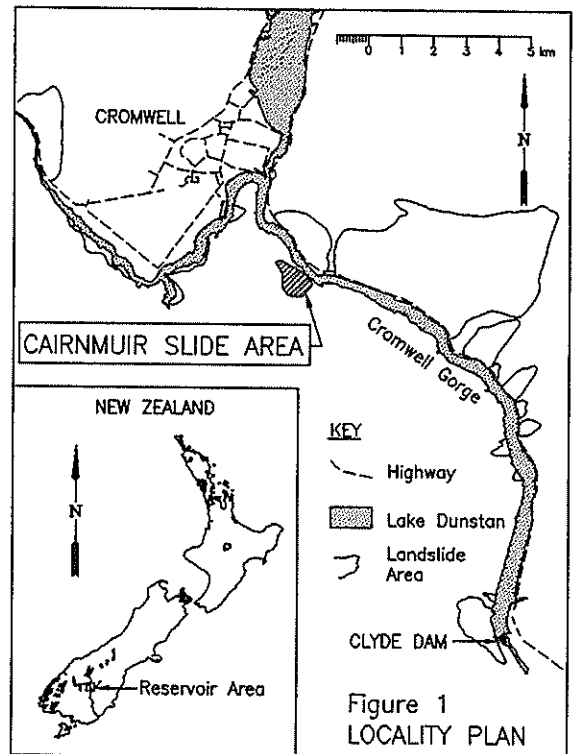
## SUMMARY

The 20 million m<sup>3</sup> Cairnmuir Landslide is located on the right bank of Lake Dunstan about 15km upstream of the Clyde Dam. Investigations and remedial works concentrated on the 8 million m<sup>3</sup> active segment, a 40-70m thick translational slide composed of schist debris. The groundwater model is a relatively simple stepped watertable below the slide but a highly compartmentalised system of aquifers within the debris. Groundwater below the slide was easily drained by drainage drives and drainholes. However, the thin compartmentalised aquifer system within the debris was difficult to drain. Prior to remedial works the active segment was moving at rates of up to 100 mm/yr. Since the completion of the underground drainage and surface infiltration protection works the slide velocity has reduced to approximately 5 mm/yr.

## 1. INTRODUCTION

Seventeen landslides are located around the 35km long reservoir of the Clyde Dam in the Central Otago region of New Zealand. Remedial works were completed on 9 landslides including the Cairnmuir Slide as part of the Clyde Power Project development [1]. The Cairnmuir Slide is not directly affected by the lake as the slide base is approximately 60m above the reservoir. However, an Active Segment of the slide has sufficient volume (8 million m<sup>3</sup>) to block the reservoir and rapid movement could cause a wave that would overtop the dam. This hazard necessitated stabilisation measures which would isolate the segment from the effects of lake filling and limit its demonstrated sensitivity to rainfall.

The Cairnmuir Slide is north facing and receives a low average annual rainfall of 400mm. Generally the climate on the slide is extreme, warm in summer and cold in winter. Consequently before remedial works the vegetation was sparse with up to 50% of the surface made up of bare ground or rock. A high rabbit population ensured vegetation was kept to a minimum.



## 2. GEOLOGY AND GROUNDWATER

The Active Segment, a 40-70m thick translational slide composed of schist debris, is 600m in length with an average width of 450m. The segment has an average slope angle of 20° which increases to more than 35° at the toe and head of the slide (Figure 2). The Active Segment occupies a generally deflated basin and fresh scarps (up to 1.5m in height) extend around its perimeter. Frontal Lobes at the toe of the slide are surrounded by a set of arcuate fresh scarps (up to 3m in height). Approximately 400 sinkholes were present over the surface of the Active Segment, generally associated with tension zones and formed in lines along active scarps.

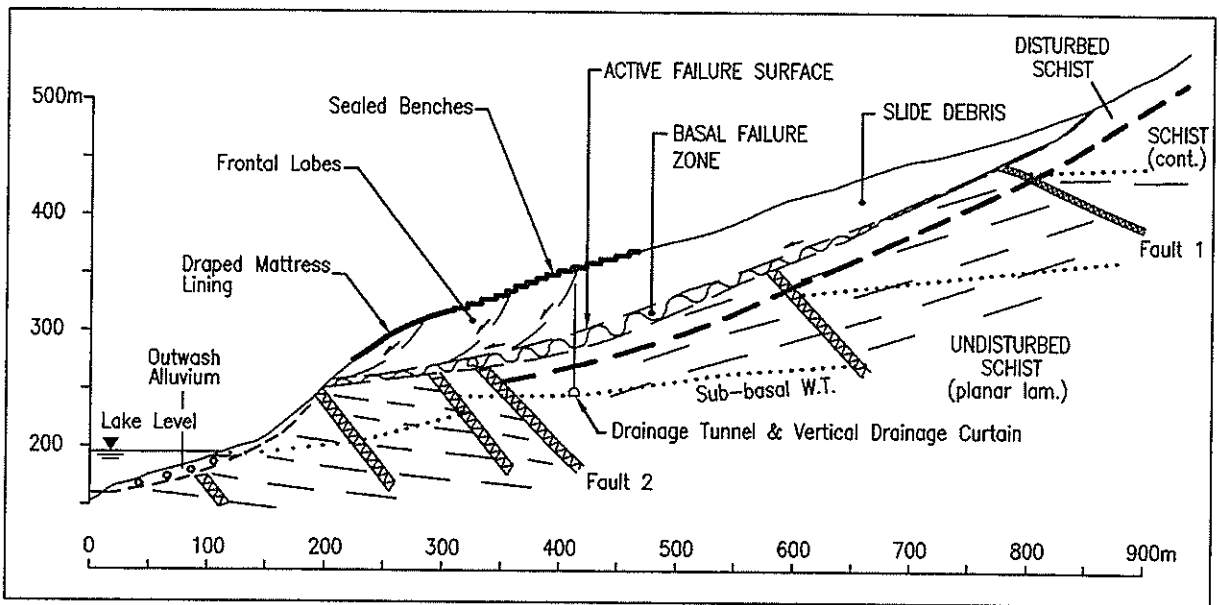


Figure 2. Typical cross section

### 2.1 Undisturbed Schist

Undisturbed schist beneath the slide comprises unweathered, strong, foliated, quartzo-feldspathic mica schist (greyschist). The predominant tectonic defects within bedrock are a series of faults which dip into the slope at 20-40°. These features generally consist of crushed, sheared and shattered schist with occasional gouge seams. The faults are up to 26m thick and traceable across the full width of the slide area.

Foliation below the majority of the slide dips out of the slope. However, downslope of Fault 2 foliation dips into the slope. At the head of the slide Fault 1 separates two lithological distinctive schist types; “planar laminated” greyschist below Fault 1 and “contorted” greyschist above.

The faults which dip into the slope act as low permeability groundwater barriers and divide the sub-basal watertable into large groundwater compartments. Head differences of up to 50m occur across the faults. Before drainage the sub-basal watertable was confined beneath the basal failure zone (BFZ) over a limited area upslope of Fault 2 and it was inferred that these uplift pressures could rise with or following lake fill.

### 2.2 Disturbed Schist

A layer of disturbed schist just below the BFZ extends from the head of the slide down to Fault 2. The material is similar to undisturbed schist but is slightly weathered and the rock mass is generally more open. It is inferred that this schist has been disturbed by stress relief processes [4].

The disturbed schist has a higher permeability than the underlying undisturbed schist. It is also likely that the faults dipping into the slope which compartmentalise the sub-basal aquifers may be disrupted in the disturbed schist zone resulting in increased leakage between the sub-basal compartments. Therefore, the disturbed schist provides a flow path for infiltration from above the headscarp to migrate beneath the slide. Monitoring has detected transient responses to significant rainfall events within the disturbed schist down to approximately the mid-slope area of the slide.

During significant rain events it was possible for groundwater pressures within the disturbed schist aquifer to pressurise parts of the BFZ and AFS for short periods. Therefore, drains drilled from the sub-basal drives were installed within this unit.

## 2.2 Basal Failure Zone

The BFZ above the disturbed and undisturbed schist is a 1-17m thick crushed and sheared zone with occasional gouge seams, shattered zones and blocks of relatively intact schist. Groundwater within the BFZ is trapped in shattered schist clasts which form local, discontinuous aquifers. The degree of interconnection between these blocks is limited or non-existent. Consequently this zone was difficult to drain but did not recharge after drainage. Typically when a shattered clast was hit in the drainage drives flows of approx. 5 l/min were evident but would dry up within a week.

## 2.3 Active Failure Surface

The active failure surface (AFS) is located at the top of the BFZ and is generally a 100-300mm thick zone of moderately to highly plastic gouge. The gouge is slightly weathered, sandy silty clay with minor gravel (CL/CH) and contains thin discrete slickensided surfaces (c. 0.5mm thick). Slickensides were generally orientated downslope, correlating with overall slide movement.

Contorted schist occurs above the gouge zone and planar schist is present below it. This marker horizon proved useful for identifying the AFS and the positioning of instrumentation. During tunnelling an attempt was made to excavate the drive along the failure surface and the lithological change was used to steer the drive. The AFS and the BFZ are effectively impermeable and act as a perching horizon for infiltrating groundwater.

## 2.4 Slide Debris

The bulk of the slide debris in the Active Segment is made up of "contorted" schist, derived from above Fault 1. This implies that the original slide volume has been completely evacuated downslope, a displacement of at least 600m [2]. Slide debris generally consists of slightly weathered, schist blocks in a sand/gravel matrix with some silt. Schist blocks vary from cobble size up to 20m in length and also vary from completely shattered to competent. Joints and fractures are common in these blocks and are usually open 1-100mm. In some locations these fractures are infilled with debris or loess. Commonly the loess was cross bedded indicating water deposition or reworking.

Gouge and crushed zones define Frontal Lobe failure surfaces. Randomly orientated gouge and crushed zones were also logged within the debris. These defects, combined with the AFS, compartmentalise the debris and make the permeability of this material highly variable. Scarps and sinkholes allow the ingress of water into the debris. Shattered boulders and tension zones provide flow paths for infiltration from the surface to the AFS. Before drainage the perched watertable was generally 2-4m thick, but up to 19m in some localised areas.

During the early stages of drainage drilling the perched watertable was modelled by contouring the head of water above the AFS both before and after drainage. The differences between these surfaces was then used to estimate the effective drainage of the perched watertable. This methodology was discontinued when the extent of compartmentalisation within the debris was realised. A piezometer within the debris reflects a groundwater level of a compartment that is typically less than 15m in width and can not be reliably used to infer the depth of perched water between piezometers.

## 3. MOVEMENT HISTORY

Outwash terrace remnants deposited during the Hawea-Mt Iron Advances (16 000-23 000 years BP) outcrop below the toe of the slide. By calculating the amount of debris on this outwash surface it is inferred that the toe of the slide has moved some 16-40m in the last 16 000 years (1-2.5 mm/year). Boulder displacement plots from comparison of aerial photos from 1949 and 1990 indicate that the main body of the slide has moved downslope 1-2m (50 mm/year) and the Frontal Lobes 4m (100 mm/year) in the last 41 years. This indicates a significant increase in the slide velocity in at least the last 40-50 years. Survey pillars located on the upper slide mass confirm the higher velocity with deformation rates of 30-35 mm/year between 1984 and 1989 (pre remedial works).

It is postulated that the increase in the velocity of the Cairnmuir Slide is related to the removal of vegetation. Approximately 150 years ago the vegetation on the slide was adversely affected by the introduction of grazing from sheep and rabbits. During the 1940's a further increase in the rabbit population occurred in Central Otago

resulting in reduced vegetation cover and increased soil erosion. This general denuding of the slide is believed to have increased the infiltration into the Active Segment elevating the perched watertable and resulting in greater deformation over the last 40-50 years.

Since detailed monitoring began in 1989 six movement events triggered by rainfall have been detected. Generally these rainfall events have been relatively small with an average recurrence interval (ARI) of 1-2 years. Total observed movements during individual episodes have been up to 100mm in the toe and up to 10mm in the head of the slide, with rates of up to 3 and 0.5 mm/day respectively.

#### 4. REMEDIAL MEASURES

The sensitivity to rainfall indicates that the general stability of the Active Segment is controlled by the perched watertable. Movement appears to be a retrogressive type of failure with the toe of the slide moving before and to a greater extent than the upper slide mass. This mechanism is consistent with the boulder displacement plots which show the Frontal Lobes moving twice the distance of the head of the slide over the period 1949-1990. Therefore the majority of the remedial works concentrated on the Frontal Lobes of the Active Segment. Sub-surface drainage was installed to drain the perched and sub-basal aquifers and isolate the slide from the effects of lake filling. Surface protection works were also implemented to control infiltration. Buttressing of the slide was not considered practical because of the height of the slide base above the valley floor (90m).

##### 4.1 Drainage Drives.

A total of 1.2km of drainage drive has been installed within and below the Active Segment. The tunnels are nominally 3.5m wide and horseshoe shaped. Approximately 800m of the tunnels were excavated within the undisturbed schist to provide both sub-basal drainage and access for perched drainage drilling. The sub-basal drives were excavated using a conventional drill, blast and muck cycle with hand held air-leg drills and ST6 Wagner muckers. Excavation rates of up to 50m per week were achieved in this competent material and no significant stability problems were encountered. Rockbolts and crown shotcrete were used to line the majority of the sub-basal tunnels. Limited use of the NATM was made when excavating through the sub-basal faults.

Approximately 400m of tunnel was excavated within the BFZ and slide debris. These drives, constructed for both investigation and drainage purposes, were excavated along the AFS to form a drainage cut off and intercept all the water perched upon the failure surface. The AFS had more relief than had been previously inferred and was only able to be followed over approximately 60% of the length of the tunnels. However, generally this method of drainage was successful, with seepage and minor flows (<5//min) from above the AFS and other crushed zones within the debris intercepted over the majority of the tunnel length.

Conventional drill, blast and muck cycle was intended to be used for excavating the BFZ and slide debris material. However, when excavating through the BFZ a possible correlation between blasting and slide acceleration was detected. Blasting was limited to 0.5kg per delay for the popping of isolated boulders. The remainder of the tunnelling within the slide debris was completed using the wagners and air picks to excavate the face. Despite this restriction excavation rates of approximately 25m/week were achieved.

Steel sets at 1m spacing and heavy to medium timber lagging with the walls prelined 1.5-2.0m high were used to support the drive during excavation. Full reinforced concrete lining was used as permanent support. A standard pattern of weep holes which included a line of holes parallel to the failure surface, was drilled through the lining to intercept any seepage. A gravel side drain was also installed outside the lining adjacent to the country to maximise tunnel drainage.

Tunnel stability problems were encountered within the debris where a water bearing shattered/sheared unit was intercepted in the crown. Flows of 10-20 //min produced some running ground and the crown became unstable developing a 5m chimney. A bulkhead was constructed and the drive terminated 2.5m short of its target.

##### 4.2 Drainage Drilling

A total of 320 drains with a combined length of 22km have been installed within and below the Active Segment. Drainage of the sub-basal compartments was easily achieved by 12 drainholes which drained the confined groundwater and accomplished widespread lowering of piezometric pressures. However, the debris was difficult

to drain due to the low head conditions and its highly compartmentalised nature. Drainage responses indicate that the compartments are less than 25m in width and typically 5-10m. Therefore, many drainholes at close spacing were required to obtain effective drainage.

Two types of drilling have been used at Cairnmuir to drain the perched aquifers; “target” drilling implemented to drain specific targets and a “drainage curtain” installed from the sub-basal drives across the full width of the Active Segment just behind the Frontal Lobes (Figure 3). The curtain, consisting of 200 drains drilled at 5m centers and extending 15-30m through the AFS, was installed to intercept groundwater migrating downslope from the upper slide mass before it could influence the more active Frontal Lobes. Most of the drainholes produced only small flows of less than 1 l/min, but a limited number flowed initially at 50-150 l/min. All high initial flows reduced rapidly (2-14 days) also indicating that the compartments are relatively small.

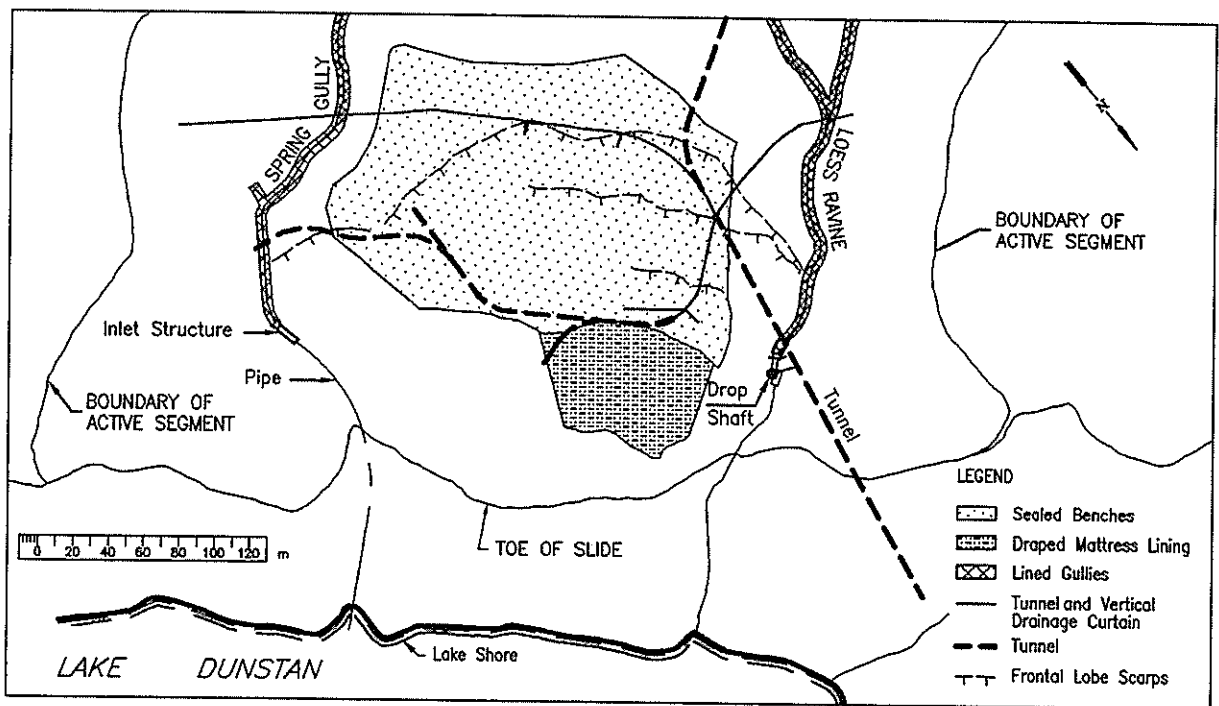


Figure 3. Plan of stabilisation measures

Drains are up to 170m long and were drilled using down the hole hammer and limited Odex type drilling. Generally the holes were drilled to total depth, the hammer and drill string extracted and a slotted 100mm diameter steel casing installed with a 50mm diameter slotted plastic liner pipe. This “open hole” method of drilling proved to be successful even in relatively poor drilling conditions within the debris. A 24 hour drilling operation enabled drilling and screen installation before the hole deteriorated and became unstable. Where collapsing or open ground were encountered the hole was typically advanced using a tricone.

During the drainage drilling cutting samples were collected and logged to determine the change from “planar laminated” to “contorted” schist and hence the location of the AFS. Logging of the cuttings proved to be a quick method of establishing if significant drillstring deviation had occurred and could help determine if the drain had hit or missed its target.

#### 4.3. Surface Works

The surface works are not considered in any detail as a full description of these is presented by Gillon and Saul [3]. Surface infiltration protection works include:

- Lining of two gullies within the Active Segment (1250m) to ensure that all water collected is transported off the slide.
- 15 reinforced earth retaining walls with sealed benches between (2.8ha) which collect water from the Frontal Lobe area and divert it to the lined gullies.
- A lower sealed slope (0.6ha) which collects water from the very steep toe of the slide and diverts it to the lined gullies.
- Vee drains located in the upper slide area which also collect run off and divert it to the lined gullies.

- Revegetation, oversowing and fertilising of the slide area. A rabbit-proof fence has been constructed around the perimeter of the slide and a rabbit control programme implemented.

## 5. SLIDE PERFORMANCE

Monitoring of the Active Segment before the remedial works indicated the upper slide area was moving at about 30 mm/year. In the toe several movement events were monitored with velocities up to 3 mm/day recorded for a short duration. Current monitoring (September 1995) suggests the upper slide is stable or creeping slowly (1-2 mm/year) and the toe of the slide is moving at approximately 5 mm/year.

From December 1993 to February 1994 the slide experienced a long period of extremely wet weather (by local standards) with 226mm of rain in 60 days. This event with an ARI of approximately 150 years occurred when the drainage works were nearly complete and during the early stages of the surface infiltration protection works. Deformation responses to the rainfall were detected, but were less than had been observed in previous movement events and were relatively limited considering the size of the rainfall event.

Only one significant rainfall (ARI of 2 yr) has occurred since the completion of the remedial works. No increase in the velocity of the slide was identified and only limited piezometric response was recorded, entirely from outside the area of the Sealed Benches. The lack of deformation and minor piezometric response to this rain event, and the relatively limited movement during the December 1993 event combined with the continued slowing trend of the slide, suggest that the stabilisation measures have been successful.

## 6. CONCLUSIONS

The Cairnmuir Slide is perched 60m above Lake Dunstan and is not directly affected by the lake. However, an Active Segment of the slide has sufficient volume to block the reservoir and rapid movement could form a wave that would overtop the dam. This hazard, combined with the sensitivity of the Active Segment to rainfall, necessitated intensive stabilisation involving drainage and surface infiltration protection works.

The Active Segment is believed to have moved more than 600m. The extent of movement is the largest of any of the Cromwell Gorge Landslides and has also produced crushed and gouge zones throughout the slide debris resulting in a highly compartmentalised internal aquifer system. Geological evidence indicates that the Active Segment has been creeping at an average rate of 1-2.5 mm/year since the last glacial advance. However, it is inferred from boulder displacement plots that the slide velocity has increased over the last 40-50 years to rates of up to 100 mm/year. This increase in movement is believed to be due to de-vegetation and increased infiltration.

Drainage of the sub-basal aquifers was easily achieved with the use of drainage drives and a limited number of drainholes. However, the highly compartmentalised nature of the slide debris made drainage of this unit difficult and many drains at close spacing were required. A total of 1.2km of tunnel and 320 drainholes totalling 22km of drilling were installed.

Limited deformation response to a large rainfall event (ARI 150 years) occurred during the later stages of the drainage works and during the early stages of the surface works. A small rain event (ARI 2 years) after the completion of the works caused no increase in the slide velocity. These results, combined with the continuing slowing trend of the slide, suggest that the remedial measures have been successful.

## REFERENCES

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