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Deformation Behaviour of Rock Slopes on Pre-Existing Shear Surfaces

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Summary: The deformation behaviour of a rock slope prior to collapse is inherently related to the failure mechanism, strength of the defects controlling the failure mechanism, and in some cases is related to the rock mass strength. This paper presents results of analysis of a selection of rock slopes whose deformation behaviour has been influenced by defects that have experienced significant shearing. The rupture surfaces of these slope failures have experienced large deformation due to either regional folding, stress relief or previous instability. Examination is made of the relationship between normal effective stress acting on the rupture surface, rock mass dilation, over-riding of defect asperities and shearing or crushing of asperities. These factors are considered in the context of slope deformation behaviour and discussion is presented on their influence.

1 BACKGROUND AND NOMENCLATURE

The deformation behaviour of a rock mass prior to collapse is related to the failure mechanism and the strength of defects within the rock mass. Skempton and Hutchinson (1969) presented the terms "first-time slides" and "slides on pre-existing slip surfaces" to distinguish between slides in unsheared ground and slides on surfaces that have experienced significant shearing. Hutchinson (1988) suggested that slides on pre-existing slip surfaces can be further sub-divided into two distinct categories:

1. Failures on surfaces which have been pre-sheared due to geological processes other than landsliding; and
2. Failures on surfaces that have been pre-sheared by previous landsliding episodes (reactivated sliding).

Geological processes responsible for causing shear along defects include rebound/stress relief, regional faulting and folding under tectonic stresses and glaciotectonic influences. This paper discusses the nature of landslides on pre-existing shear surfaces and the influence this shearing can have on the pre-collapse behaviour of a rock slope.

The present industry practice of dealing with moving slopes generally involves establishment of a monitoring system and design of stabilisation measures if appropriate. The critical questions that need to be answered include:

- Will a moving slope collapse?
- If so, will the failure be sudden and brittle?
- What signs are expected prior to collapse? and
- How far and fast will the slope move before collapse?

This paper attempts to address some of these areas of uncertainty by examining a select group of well investigated and well monitored slopes.

Numerous terms have been adopted for describing the deformation behaviour of a rock mass including rebound, regressive/progressive movement, elastic deformation and creep. No two rock slopes will behave in the same manner in terms of deformation, due to the variability in rock mass characteristics. However, the deformation behaviour of a rock slope can be shown to exhibit certain typical stages, such as decreasing displacement rate, constant displacement rate or accelerating displacement rate.

The cases presented in this study are all natural slopes and no assessment of their elastic response to load variation has been made or measured. Following the initial elastic response, plastic deformation associated with stress relief may occur. In most cases this is observed as shearing along defects and may occur as steady movement over protracted periods or as episodic (stick-slip) movement. The rock mass response to stress relief and other external changes (such as increasing groundwater level) may be short-lived and rates of displacement may reduce with time or the response may be ongoing leading to accelerating rates of displacement and eventual collapse. The term creep has been adopted in this study to describe the time-dependent "slow, more or less continuous deformation or flow of natural and excavated slopes" (Emery, 1978). Creep is generally recognised to have three main divisions, as indicated in Figure 1. These terms will be used to describe the case studies presented in the following sections of this paper.

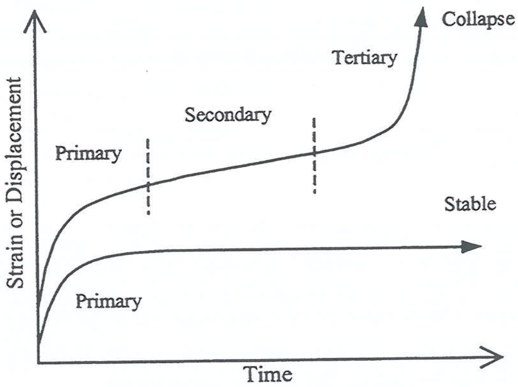


Figure 1: Diagrammatic representation of creep curves for moving slopes

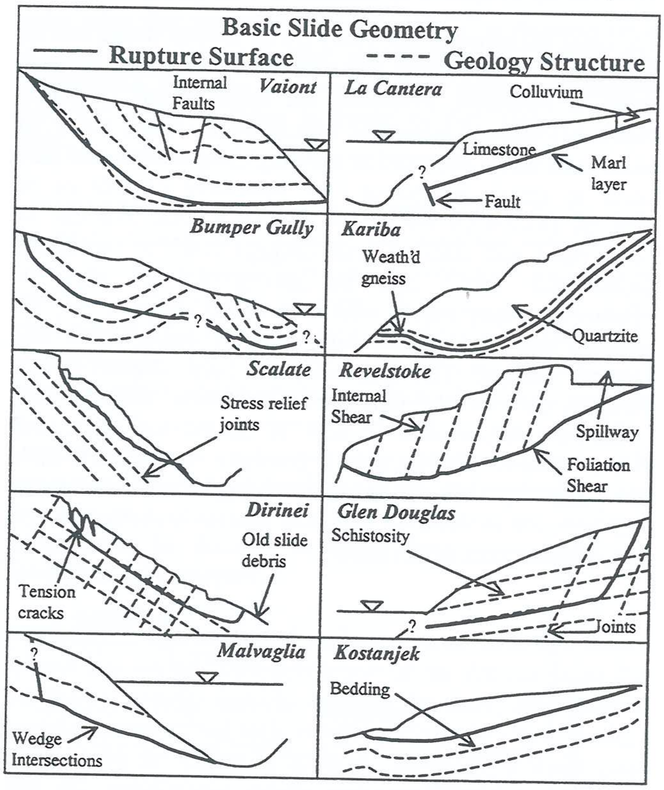
2 DESCRIPTION OF CASE STUDY DATA

2.1 Classification

Ten cases of rock slides on previously sheared surfaces were examined in this study and their characteristics are summarised in Table 1. They were categorised according to whether they were first time slides on pre-sheared surfaces or reactivated slides. They were also sorted in terms of geological environment, failure mechanism and displacement-time behaviour, with comment provided in Table 1.

In all cases, the failure mechanism is broadly described as translational sliding, using Hutchinsons (1988) classification system. On a detailed level, cases represent wedge sliding or block sliding on planar or curved failure surfaces. Diagrammatic illustration of slide geometry is presented in Table 2. Information on the cases was obtained from published literature and unpublished reports. In all cases displacement monitoring commenced after the slope started moving. Comparison of data is not straightforward due to variations in length of monitoring period and intervals between readings. Eight of the slopes presented in the database were monitored using surface survey prisms.

Table 2: Diagrammatic Illustration of Slide Geometry.



The interpreted mechanism shown in Table 2 for Bumper Gully is based on surface geology and geomorphological mapping. There is some suggestion that the failure mechanism at Bumper Gully may be a compound slide involving some internal shearing. Further assessment of the Bumper Gully case will likely confirm the failure mechanism.

Comparison of total measured displacements is difficult due to variations in size of the slope failures. It is expected that, all other things being equal, a larger rock mass will exhibit greater displacement than a small rock mass. It is suggested that failure limits in terms of strain may be more relevant than total displacements. Therefore, for the purpose of comparison, total displacements for each case have been normalised against the down-slope length of the failed mass, to give an indication of strain of the rock mass. It is considered that the down-slope length is the most appropriate parameter for normalising, as vector deformation of these sliding failures is generally in a direction parallel to the slope face.

2.2 Case Study Commentary

Two of the ten cases examined (Vaiont and Scalate) progressed through to collapse. The remaining eight cases exhibited movement of varying extent and may be considered to have failed in terms of serviceability criteria but they did not show sudden catastrophic collapse.

The mechanism of previous shearing on the rupture surface of each of the slides was examined, and is indicated in Table 1. Causes of previous shearing include regional tectonic folding of strata, stress relief due to unloading and earlier periods of sliding. Five cases had previously sheared basal rupture surfaces associated with both regional folding and earlier sliding. Two cases had previously sheared rupture surfaces derived from both stress relief and earlier sliding activity. Two cases showed no signs of folding or stress relief but were reactivated landslides and one case was likely a first-time slide on a surface previously sheared by regional folding.

There were essentially two geological categories within the ten cases examined. Four cases involved sliding in sedimentary environments (limestone, marl, sandstone and siltstone), with rupture surfaces defined by bedding. The other six cases were from metamorphic terrains (schist, gneiss and quartzite) with rupture surfaces defined by jointing or schistosity. All failures were predominantly defect controlled.

3 ANALYSIS OF DEFORMATION BEHAVIOUR

3.1 How Do Slides on Pre-existing Shears Behave?

3.1.1 General

All ten slides respond in different ways to load changes, such as groundwater rise or stabilisation works. Slides with a larger normal effective stress (on the rupture surface) generally show a more regular displacement-time response under periods of constant loading. Slides at low normal stress levels tend to show more erratic behaviour at constant loading. Many of the slides exhibited sensitivity to rainfall events, with larger slides generally showing a more delayed reaction time.

Geomorphological features on a number of the slides suggest significant movement. This movement combined with irregular rupture surfaces has resulted in disaggregation of slide masses. Vaiont and Kariba show disrupted slide masses overlying a rupture surface of complex geometry. Bumper Gully shows a highly to moderately disturbed slide mass, over what is likely to be an undulose and curved slide surface. La Cantera slide is described as highly fractured yet the rupture surface is understood to be relatively planar. The large total movement (50m+) of this slide may explain the high degree of fracturing.

Movement rates for nine of the slides were typically between 0.05 and 0.5mm/day. Vaiont had monitored rates generally above 1mm/day, with occasional peaks at about 20-40mm/day and a final displacement rate immediately prior to collapse assessed to be about 200mm/day. Distinct primary, secondary and sometimes tertiary creep stages are visible in the monitoring data for most cases, with Vaiont showing particularly distinct phases (refer to Figure 2). Many of the slides were stabilised so complete tertiary creep sequences are often not available and may in some cases not have developed.

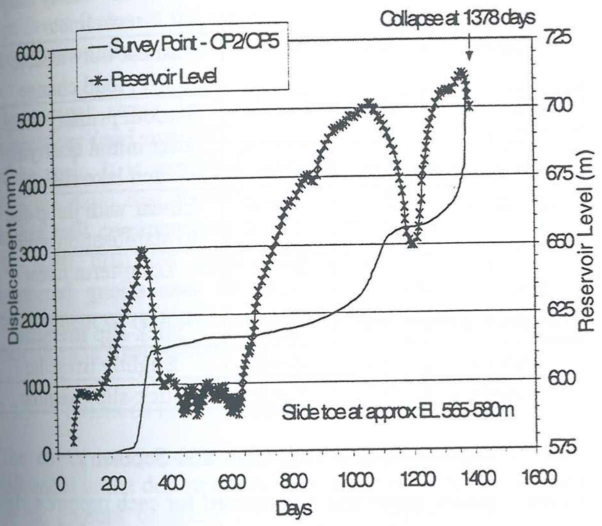


Figure 2: Displacement data for Vaiont slide showing relationship with reservoir level (Hendron and Patton, 1985).

3.1.2 Stick-Slip Displacement Behaviour

Stick-slip motion is the term used to describe sequential episodes of rapid displacement followed by periods of low displacement rate. It is associated with the sudden over-riding of asperities on the rupture surface. In many slopes this type of behaviour may be observed in association with peaks in rainfall or snowmelt. In examination of these cases, focus was on stick-slip displacement behaviour during periods of relatively consistent stress levels. Consideration also needs to be given to intensity of monitoring. If readings are made at long intervals then a smoother displacement-time curve will be produced and stick-slip motion may be unrecorded. The displacement-time data for Revelstoke slide, presented in Figure 3, suggests some stick-slip type behaviour at very low normal stress levels. This slide was described as reactivated (with some regional folding) but the extent of previous shearing is unknown. Clay gouge and breccia are known to occur along at least part of the rupture surface and the normal stress level is very low. It is possible that the slide surface is not at residual strength and this combined with the presence of breccia may cause some brittle response to shearing (and hence a possibility for stick-slip motion).

Most other slides examined in this study show more uniform displacement-time behaviour at higher normal stress levels. This is attributed to the fact that destruction of asperities has taken place to a greater extent on these other slides. The data also suggests that slides that have undergone large shear displacements exhibit a reduced stick-slip tendency.

Cases such as Kostanjek, Vaiont and La Cantera involve sliding on clay coated rupture surfaces that have experienced significant shearing during previous sliding episodes and/or regional folding. The normal stress levels on these rupture surfaces were high and significant crushing and shearing of asperities is expected to have occurred. These three slides do not exhibit any apparent stick-slip tendencies and tend to show more gradual changes in displacement-time behaviour.

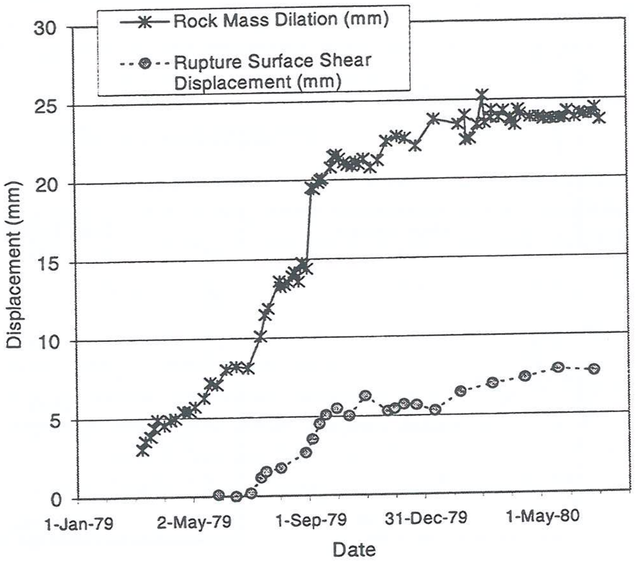


Figure 3: Displacement data for Revelstoke slide showing irregular (stick-slip) behaviour (Martin & Kaiser, 1984)

3.1.3 Radial Displacement Behaviour

Radial displacement behaviour was observed in a number of the cases examined. In all cases, it appeared that extent of radial change in displacement behaviour was related to the extent of fracturing of the slide mass. In the case of Bumper Gully, the slide mass was recognised to be very disturbed, with average RQD's of the order of 15-50%. Highest rates and greatest magnitudes of movement were observed towards the centre and front of the slide. Rates and magnitudes of movement appear to show a general decrease with increasing radial distance towards the rear and sides of the slide. Similar patterns were observed in Dirinei and Malvaglia slides, which were described as highly fractured.

3.2 Reasons Behind Deformation Behaviour

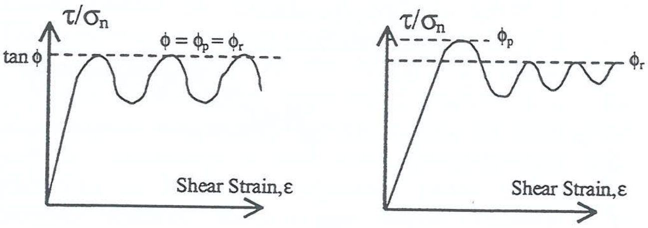
3.2.1 Overview

Translational slides may be considered analogous to laboratory direct shear tests on defects. The critical factors that determine the behaviour of a slide mass on a pre-sheared surface include:

1. the effective normal stress acting on the rupture surface;
2. rupture surface properties and geometry;
3. rock mass properties of the overlying slide mass; and
4. extent of previous shearing.

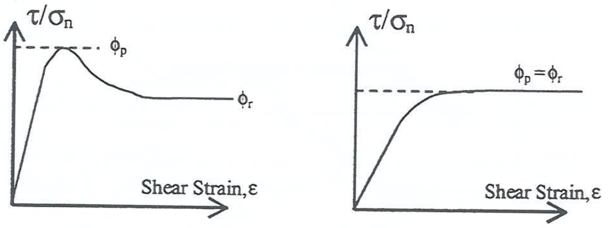
3.2.2 Normal Stress

Analysis of test data for rock defects highlights the relationships between defect roughness, normal stress and shear strength. At all but very low normal stress levels, the shear strength of a defect decreases with progressive shear strain, until residual friction angle is attained. At low normal stresses dilation of the defect and over-riding of asperities is dominant while at high stress levels shearing and/or crushing of asperities is dominant. At high normal stress levels a more rapid reduction in shearing resistance is expected (ie: the strain required to reach residual strength is expected to be lower). This is schematically illustrated in Figure 4.



Case 1 - Very Low σ_n

Case 2 - Low σ_n



Case 3 - Moderate σ_n

Case 4 - Very High σ_n

Figure 4: Diagrammatic stress-strain curves for defects at various levels of normal stress (Xu & de Freitas, 1990).

Shearing and/or crushing of asperities is likely to have taken place to some extent in all of the ten cases examined. However, some rupture surfaces are still described as rough and irregular, such as Dirinei and Scalate at low normal stress levels (following Case 2 type behaviour, Figure 4). Other slides have rupture surfaces coated with clay gouge or breccia, such as Vaiont, La Cantera and possibly Bumper Gully at relatively high normal stress levels (Case 3 or 4 type behaviour). Table 3 contains details of average normal stress levels, rupture surface infill and displacement characteristics for each of the ten slides examined in this study.

The case with the highest normal stress level (Vaiont) has long been recognised to have involved sliding on a rupture surface that was at residual strength. The extent of earlier shearing (from previous sliding and regional folding) and the low UCS of the clayey limestone layers contributed to the destruction of asperities and development of residual strength. It is therefore expected that no further strength loss on the rupture surface would have occurred and further displacement behaviour would have been essentially ductile (Case 4 type behaviour, Figure 4). The suddenness of the Vaiont failure may be attributable to brittle failure within the fractured slide mass rather than along the rupture surface. The geometry of the rupture surface was such that internal deformation was required for the slide to proceed. Hendron and Patton (1985) in fact showed that results of stability analysis were sensitive to values of internal friction angle. They also suggested that there was strong three-dimensional control on the slide, which may have also contributed to the brittle collapse.

Table 3: Normal effective stress, rupture surface infill and general displacement behaviour.

Slide	Avge σ'_n (MPa)	Infill	General Displacement-Time Behaviour
Vaiont	3.4	Clay	Smooth primary-tertiary sequences
Malvaglia	1.1	Rock	Long-term linear
Kostanjek	0.9	Clay	Not clear - likely long-term linear
Kariba	0.8	Rock	Linear but variable with load change
Bumper Gully	0.8	Gouge/ Breccia	Smooth primary creep after initial quarrying and lake filling
La Cantera	0.8	Clay	Linear with jump due to stabilisation works
Glen Douglas	0.6	Rock	Long-term linear
Revelstoke	0.4	Clay	Stick-slip irregular
Dirinei	0.3	Rock	Slightly irregular
Scalate	0.2	Rock	Stick-slip irregular

3.2.3 Rupture Surface Properties and Geometry

A basic friction angle was determined for each rupture surface by examination of direct shear test data (on smooth defects) in published literature (Einstein and Dowding, 1989). The basic friction angle is primarily a function of the rock type but is also sensitive to normal stress levels. Where laboratory direct shear test results on infill material was available these results were adopted for basic friction angle where appropriate.

Many slides in this database have rupture surfaces with large-scale irregularities that affect the overall stability of the slope. An assessment has been made of the relevant field scale asperity from descriptions of the rupture surface geometry or by analysis of the changes in vector displacement direction. This asperity roughness is considered as a dilation angle (i) which adds to the overall frictional resistance, and is presented in Table 1. In the case of large slides with complex rupture surfaces, the asperities seen at laboratory scale testing are of little relevance. McMahon (1985) has suggested that the relevant asperities are those that have a wavelength measured over 2% of the length of the rupture surface. In many cases this value served as a useful guide for assessment of dilation angle. Some behaviour differences were noticed from the data when comparing slides on undulose or irregular surfaces with those on relatively planar surfaces. It was assessed that degree of break-up of the slide mass is significantly influenced by the irregularity of the rupture surface. Vaiont, Dirinei, Malvaglia, Kariba, Glen Douglas and Bumper Gully slides all show significant rock mass disaggregation. These slides all occur on rupture surfaces with higher dilation angle values.

3.2.4 Rock Mass Properties

The extent of disaggregation of a slide mass is seen from the data to be not only a function of rupture surface geometry, but is also influenced by failure mechanism, amount of previous sliding and the rock mass strength. The extent of shearing along the rupture surface as a percentage of rock mass dilation was measured at Revelstoke, and is illustrated in Figure 3. It was observed that basal shear accounted for about 40% of the total observed deformation with rock mass dilation accounting for the remainder. It was also observed in this particular case that rock mass dilation preceded shearing along the rupture surface. It is suggested that dilation may have been required in order to over-ride asperities. The internal friction angle (and hence the rock mass strength) of the slide mass may be a significant factor in the stability of the slope, particularly for slides on complex rupture surfaces (as illustrated by Vaiont).

The normal stress level at which crushing of asperities commences (and over-riding ceases) depends on the strength of the rock. It is expected (although not readily observable from the data) that shearing and crushing along the rupture surface will commence at lower stress levels for sliding on clay marl than for fresh limestone. Similarly, slides in weathered gneiss may be expected to show yielding and development of residual strength at lower normal stress levels than slides in fresh gneiss.

3.2.5 Extent of Previous Shearing

The extent of previous shearing has been shown to be influential in the deformation behaviour of these slides. Based on the amount of shear displacement many of the rupture surfaces examined are at or close to residual strength. Slides that have undergone the greatest total displacement have a tendency for more regular deformation and the degree of stick-slip type behaviour is reduced on these slides. This is again related to progressive destruction of asperities on the rupture surface and development of residual strength.

La Cantera slide illustrates that disaggregation of the slide mass can also occur on relatively planar rupture surfaces. Disaggregation in this case is likely due to the large displacement this slide has experienced.

The type of previous shearing (ie: stress relief, sliding or regional tectonic folding) does not appear to influence the deformation behaviour in any significant manner. It is assessed that the extent of shearing and the normal stress levels at which that shearing occurred are of more influence.

4 CONCLUSIONS

The displacement behaviour of a slide on a pre-sheared surface has been shown to be predominantly controlled by:

- the effective normal stress acting on the rupture surface;
- rupture surface properties and geometry;
- extent of previous shearing; and
- rock mass properties of the overlying slide mass.

The first three factors listed above influence the extent of strength reduction from peak towards residual strength and hence the degree of brittleness remaining on the rupture surface. The fourth factor influences the ability of the slide mass to dilate and over-ride asperities on the rupture surface. The development of residual strength on a rupture surface with progressive shear displacement suggests that the likelihood of sudden brittle failure is reduced. The ten cases examined illustrate that stick-slip type motion is reduced with increased displacement. However, Vaiont illustrates that other factors (such as internal deformation) need to be considered before assessment of brittleness can be made.

In contrast to first-time slides on rupture surfaces that have not experienced shear displacement, slides on pre-sheared surfaces are expected to have a reduced stick-slip tendency. Slides on pre-sheared surfaces often show a high degree of disaggregation and following from this they often show a tendency for radial displacement behaviour.

6 ACKNOWLEDGEMENTS

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Case Name (Origin)[1]	Geology	Avge σ'_n [2] (MPa)	Rupture Surface Description	Approx UCS Category[3]	Approx ϕ_b (deg)	Approx i [4] (deg)	Total Displ (mm)	Displacement/ Slope Length (%)	Comments on Displacement Behaviour
Vaiont (R, F)	Limestone	3.4	Dip = 24 deg (avge). Defined by bedding partings in monoclinal fold. Rupture surface in clay units within marly limestone. Direct shears: ϕ_r=8-10deg. Small monoclinal folds perp to direction of shearing giving i = 9-10deg.	R2	10	10	5340+ (measured over 42 months)	0.39+ (measured)	Reactivation due to reservoir filling. Planar/curved slide with some rotational movement influenced by internal deformation of slide mass (analysis sensitive to ϕ chosen for internal deformation). Displ closely associated with reservoir level/rain. Three sequences of primary to tertiary creep behaviour. Expect some strain hardening in fractured slide mass
Bumper Gully (R, F)	Sandstone /siltstone	0.8	Dip = 24 deg. Slide base geometry affected by synclines/anticlines – follows bedding partings in most of length with joints controlling remainder of length.	R2	22	6	3800+ (measured over 480 months)	0.78+ (measured)	Reactivation due to reservoir filling. Complex translational and rotational slide. Numerous small surficial slides defined by local folds on surface of larger slide. Highly-moderately disturbed slide mass (RQD=15-50%). Variation in displ. vector behaviour suggests i=6-10deg.
Scalate (SR, R)	Schistose gneiss (weath'd)	0.2	Wedge sliding on joint sets (incl. stress relief joints) – rough & irregular – with intersection plunge=40deg. Expect some staining of joint surfaces.	R3	25	10	290+ (measured over 9 months)	0.36+ (measured)	Stick-slip behaviour seen in early displacement monitoring. Seasonal rainfall has only minor impact on slide behaviour. Slide exhibited primary, secondary and tertiary creep phases before collapse. Vector displ. plunge = 40deg.
Dirinei (SR, R)	Schistose gneiss (weath'd)	0.3	Planar sliding on 33deg dip stress relief joints – rough & irregular - with minor crushing on slide surface.	R3	25	8	1900+ (over 34 months) 5000+ (inferred from geomorph)	5.0+ (inferred)	Reactivation associated with fluvial oversteepening and rain. Sensitive to high intensity rain events. Slide shows overall primary creep trend. Radial displ behaviour observed. Vector trend parallel to rupture surface.
Malvaglia (R)	Schistose gneiss	1.1	Wedge sliding on joint sets and schistosity. No infill. Dip of 21+ deg on rupture surface.	R3	25	6	130 (measured over 65 months)	0.09+ (measured)	Reactivation due to reservoir filling. Radial decrease in displacement rates suggesting dilatant (fractured) rock mass, therefore possibly large historical displacement. Sensitive to seasonal rainfall. Approx. linear displ-time behaviour.
La Cantera (R)	Limestone/ dolomite/ clay marl	0.8	Planar slide in 5m thick clay marl layer (following bedding) dipping at 18 deg. Illite/kaolinite coating on rupture surface with ϕ_r=17-18deg. Distinct shear surface in inclinometer readings.	R2	18	0	80+ (over 10 months) 50000+ (inferred from geomorphology)	11.0+ (inferred)	Geomorphological features suggest previous sliding of the order of 50 metres. Rupture surface at residual. Slide mass is highly fractured. Expect low dilation angle on rupture surface due to shearing in clay marl layers. Slide shows near-linear displ-time behaviour with no signs of stick-slip.
Kariba (R, F)	Gneiss/ quartzite	0.8	Rotational slide along rupture surface defined by syncline along weath'd gneiss/quartzite contact. Rupture surface dips at 35-40deg out of slope at head and 20 deg into slope at toe.	R2	23	8	690+ (measured over 432 months)	0.27+ (measured)	Slide reactivated by dam works and reservoir filling. Slide mass highly fractured and sensitive to rain/spray from spillways. Previous sliding known to be significant with numerous tension features at head of slide. Internal deformation of slide mass required for movement of slide.
Revelstoke (R, F)	Quartzite/ gneiss	0.4	Translational sliding along 23deg dip foliation shear. Direct shear ϕ_r=18deg on 20-50mm clay gouge. Undulose surface due to regional folding. Clay gouge & breccia on rupture surface.	R2	18	6	34+ (measured over 18 months)	0.04+ (measured)	Slide mass has numerous steeply dipping internal shears and some fracturing. Dilation of slide mass (measured using extensometers) observed to occur before shearing along rupture surface. Displacement sensitive to rainfall. Rupture surface dilation determined by regional folding.
Glen Douglas (R, F)	Schist/ phyllite (weath'd)	0.6	Planar sliding on schistosity (up to 30 deg dip) with back release on joint set. Slide located within regional fold. Crenulation on schistosity gives large difference between peak and residual ϕ.	R2	21	8	620+ (measured over 228 months)	0.17+ (measured)	Slide mass quite broken suggesting large prehistoric movement. Crenulation on schistosity + regional folding add to frictional resistance. Dilatant rock mass, therefore likely to be more influenced by larger geometrical features on rupture surface. Approx linear long-term displ-time behaviour.
Kostanjek (F)	Dolomitic breccia/ limestone/ marl	0.9	Planar sliding on three levels. Main surface in silty schists and marls. Upper surfaces within clayey marl. Dip=10deg. ϕ_r=9deg on main rupture surface	R1	9	2	6500+ (measured over 372 months)	0.47+ (measured)	Slide activated by quarrying, blasting and high groundwater pressures. Peak shear strength measured as 20-28 deg therefore large drop to residual strength. Likely 1st time slide but previous shearing due to regional folding.

Table 1: Data on slides occurring on previously sheared rupture surfaces.

(1) R = reactivated landslide, F = folding has affected slide surface, SR = stress relief has affected slide surface.
(2) Average normal effective stress acting on rupture surface.
(3) Unconfined compressive strength category as per ISRM.
(4) Assessed relevant field scale dilation angle.