Alarm Criteria and Monitoring for Hazardous Landslides

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"If a landslide comes as a surprise to eye witnesses, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide" - Terzaghi (1950)

Abstract

Where hazardous landslides have been identified, case histories show that prediction of the onset of any rapid movement has not always been successful. Studies have been made of the precursory movements for a number of notable landslides and relevant geotechnical characteristics examined. Guidelines are provided for effective monitoring and improved evaluation of the potential for rapid landsliding of a hazardous slope.

Introduction

Alarm criteria are required for two basic categories of landslide hazard:

(i) Limited hazard, ie readily evacuated situations such as open pit mines or small slides where lives would not be threatened if alarm systems provide forewarning, an hour or so before rapid failure.

(ii) High hazard, ie where residents must be removed from dwellings or public facilities in the hazard area. A day or more may be required for effective evacuation. Examples are landslides (usually triggered by sustained rainfall, earthquake or earthworks) threatening inhabited areas either directly or indirectly (via effects on dams and reservoirs).

This article addresses both categories with emphasis on the latter, and discusses two large landslides, which occurred in New Zealand, because they are considered particularly instructive with regard to the selection of alarm criteria.

These are the Abbotsford Slide, a natural slope failure; and the Ruahihi Slide, a fill slope failure. Both failures had been monitored for many weeks before catastrophic movements developed. In neither case, was sudden acceleration predicted. The opportunity for timely action was missed.

Factors Related to Alarm Criteria

The likelihood of rapid movements occurring without adequate forewarning can be minimised by:

(i) Consideration of the geometry of the slide (particularly the curvature of the failure surface).

(ii) Establishment of pre-set alarm criteria, which are determined from geotechnical properties of the slide materials. In the event that specified thresholds are met, then it must be acknowledged that the slide is out of control and all measures necessary to mitigate damage from rapid movements should be taken immediately.

(iii) Ensuring that monitoring intervals are appropriate to the rate of development of the slide. The possibility that a slide may accelerate unexpectedly between surveys must be addressed continuously, using standard geotechnical procedures.

Pre-set Alarm Criteria

Empirical curve fitting approaches

Several investigators (Saito, 1969; Fukuzono, 1985; Varnes, 1982; Azimi et al, 1988) have addressed the prediction of time of failure.

Saito (1969), suggested an empirical creep law which implies that slide velocity will be inversely proportional to the remaining time to failure. This method has been applied to both first time and residual strength slides, but has two limitations. Firstly, as Saito points out, creep laws should not be used where displacement independent accelerating factors apply. Secondly, a small proportion of cases have been found where the time to failure would have been seriously overestimated. Creep laws appear better suited to predicting failure when the remaining time is only a few hours, rather than days.

Azimi et al (1988) proposed an advancement on the Saito method, in that velocity may be inversely related to an exponential function of the remaining time to failure, and trial and error solutions are not involved. The proposed method to estimate remaining time to rapid failure is graphical. However from the proposed empirical relationships, it can be shown that the remaining time, t(r) is estimated simply by:

$$ {}_t(r) = {}_t(n) \times {}_t(n) / ({}_t(n-1) - {}_t(n)) \tag{1} $$

Where ${}_t(n-1)$ and ${}_t(n)$ are successive time intervals corresponding to the two latest successive displacements of equal magnitude. In other words, the latest portion of the displacement versus time curve is divided into two equal intervals for displacement, to produce two successive time intervals. The data may be smoothed if appropriate and the distance interval selected should give due regard to survey accuracy and trends in the acceleration record.

Zavodni & Broadbent (1980) and Cruden & Masoumzadeh (1987) investigated empirical creep laws to provide a basis for predicting the timing of rapid movements. An inference from the former article is that rapid failure of a first-time slide can be expected if the acceleration increases linearly with respect to the velocity. (The constant of proportionality is likely to be in the range of 0.1 to 1.0/day.) Rapid failure is reportedly unlikely to occur within 24 hours if the velocity is less than 15 mm/day. Methods for extrapolation of displacement records, using monitoring criteria have been investigated by Voight & Kennedy (1979): an alarm criterion of 6m displacement; and Vibert & Arnould (1987): a criterion of 90 mm/day velocity. One disadvantage of such predictions for timing of rapid failure is that wide ranges of possible failure times often result, depending on the curve fitting approximation used. Much of this work has been directed towards the more difficult fields of pit slope management and first-time slides (rather than those where residual strength conditions apply). However, little work has been done to derive creep laws based on effective strength characteristics determined from direct shear or ring shear tests using variable displacement rates.

Empirical threshold criterion approaches

Empirical alarm criteria are rarely reported in case histories. Johnson (1982) states that acceleration should be used as "the basis for predicting failures" but no specific threshold limits are recommended. Macrae (1982) gives examples where downslope velocities in the range of 30-35 mm/day were used for evacuation of open pit mines.

Geotechnical - Empirical approach

This section will attempt to integrate the use of empirical alarm criteria (usually obtainable from deformation monitoring) with geotechnical characteristics of the relevant materials.

Velocity - Creep rates preceding catastrophic failures have been documented for many landslides. Downslope velocities of 50 to 100 mm/day were achieved by the Vaiont, Abbotsford and Ruahihi Slides (Fig. 1a) some days before their final rapid movements (Salt, 1991).

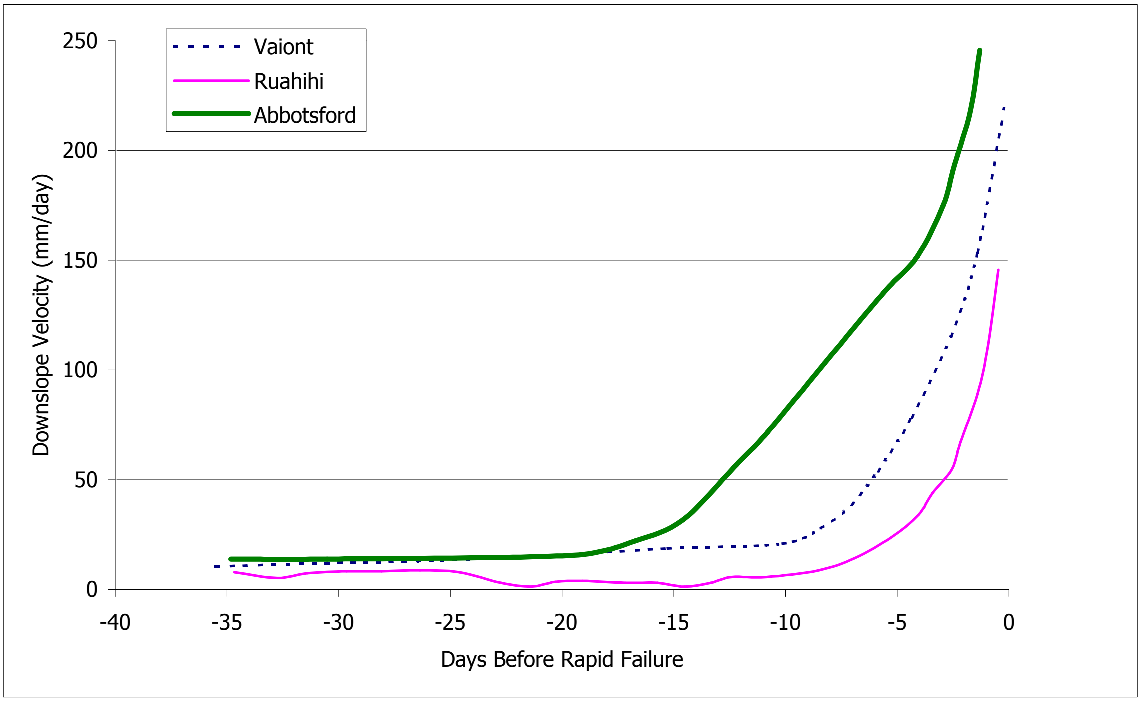

Figure 1a Precursory Velocities of Slides

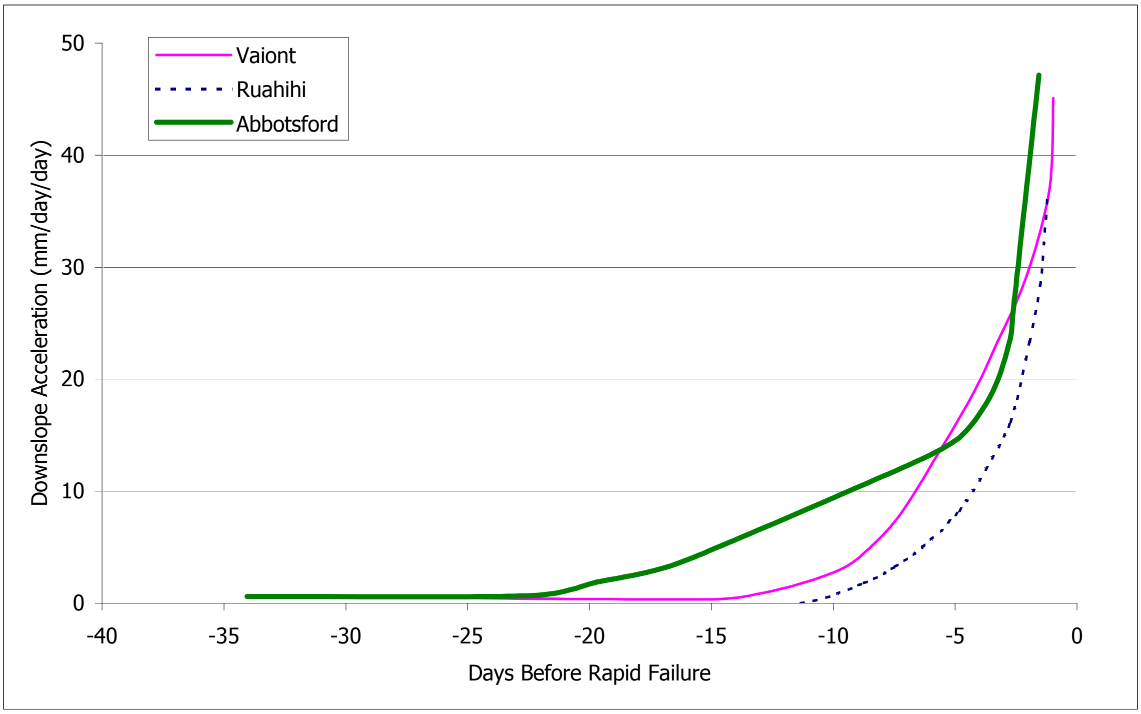

Figure 1b Precursory Accelerations of Slides

Acceleration - Where appropriately regular monitoring has been obtained, rational interpretation of landslide movement requires successive differentiations of the displacement-time record to obtain the acceleration history. This must be carried out in any instance where the displacement-time curve exhibits a concave upward shape. Examples are shown in Fig. 1b, where acceleration is shown to be increasing above 5 mm/day/day, either linearly or exponentially for 5 to 10 days prior to rapid failure.

Clearly, additional case histories of well monitored landslides would be desirable before confirming generalisations from the limited data examined. However, taken in conjunction with other case histories with less detailed movement records available, and including suggestions made by Johnson, Macrae, Zavodni & Broadbent (op cit), the following are suggested as critical limits for landslides where shearing (rather than toppling etc) is occurring.

(i) Where residual strength conditions pertain, in a wide (but probably not exhaustive) range of materials:

Downslope velocity 50 mm/day

Downslope acceleration 5 mm/day/day

(ii) For first time slides where displacements are small, a factor of ignorance (often about 5 but maybe up to 10) should be applied to the above values for residual strength slides, eg:

Downslope velocity 10 - 5 mm/day

Downslope acceleration 1 - 0.5 mm/day/day

Depending on the hazard being considered, remedial measures or other actions may be appropriate long before the above limits are reached. The point in specifying alarm criteria is that at some stage it must be acknowledged that the time for debate is over, the situation is out of control and evacuation must proceed directly. The limits proposed above are intended to be sufficiently conservative to provide several days forewarning in the case of residual strength slides, or at least 24 hours warning in the case of first-time slides with long monitoring records. However, these criteria may be too optimistic in some instances, particularly where a displacement-dependent accelerating mechanism (Salt, 1985) is operating, or an additional displacement-independent accelerating mechanism is imposed (eg rainfall).

The situation may arise where a slide velocity exceeds its critical velocity while its acceleration is less than the threshold and decreasing. In this case there may be arguments in favour of accepting velocities up to, but not exceeding 10 times the critical velocity where site specific investigations confirm that accelerating mechanisms are clearly absent. Applying this factor to the above limits indicates that it is quite unlikely that movement rates exceeding 500 mm/day could be considered acceptable for any hazardous landslide.

Although the criteria already discussed have been derived primarily from examination of case histories, they also have geotechnical bases, these being residual strength testing and frictional heating concepts, which require consideration.

(a) Residual shear testing

(Fig 2b) Residual strength testing has clearly demonstrated that the strength of soils is dependent on rate of shearing (Skempton & Hutchinson, 1969). Rates and times of testing are appropriate to allow complete pore pressure dissipation, so the findings do relate to effective stresses. Residual strength testing in the laboratory is usually a rate controlled test, that is, stress is measured as the dependent variable and plotted as ordinate. In the field, gravity imposes a stress controlled 'test' (Fig 2b). In small scale laboratory tests, there are a number of factors that limit stress controlled testing, such as the difficulty in achieving steady state conditions. Nevertheless for a large slide at residual strength, it is suggested that stress controlled behaviour can be estimated from rate controlled laboratory tests.

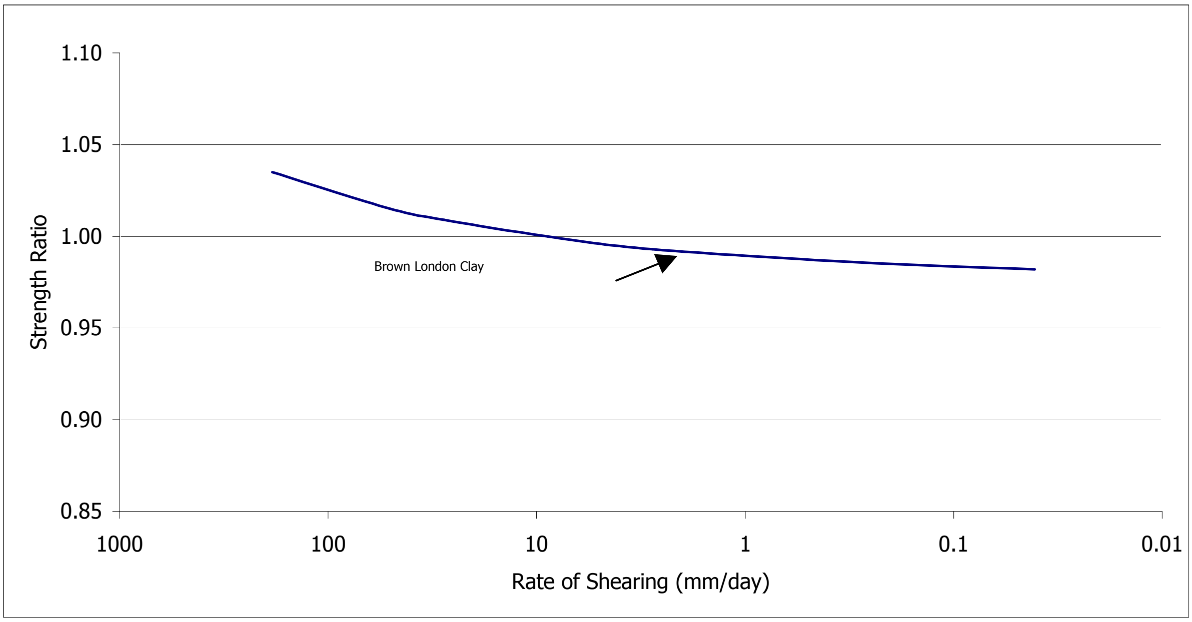

Figure 2a Rate Dependence of Residual Strength

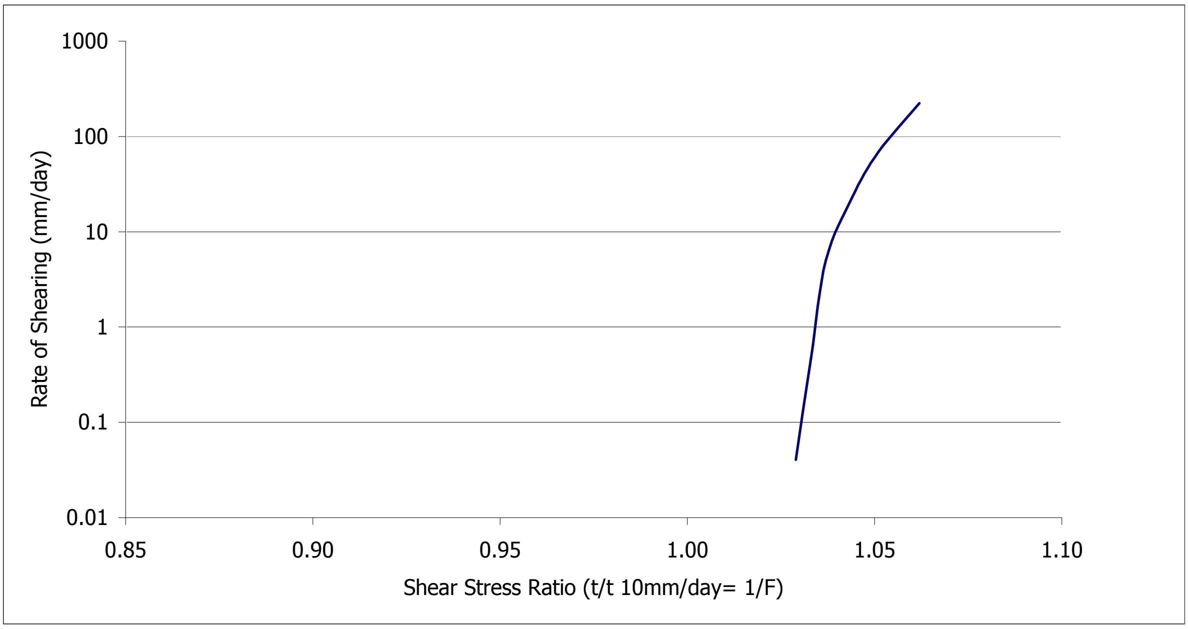

Figure 2b After Skempton and Hutchinson

Fig. 3a shows a limited number of residual strength tests on clays and silts. One feature of note is the trend for soils with low clay contents to have somewhat steeper curves, ie the change in velocity of slides in these materials is more sensitive to small changes in safety factor. Soils with high clay contents tend to be more tolerant. Regardless, determination of the rate dependence of strength allows the maximum velocity of steady yielding to be estimated. As shown on Fig. 3a, some of these curves appear to steepen, becoming asymptotic to an upper strength limit. The significance of a steep gradient is that a very small decrease in safety factor will induce a disproportionately large increase in slide velocity. A slide in this state will yield in an unsteady manner with rapid acceleration imminent. Unsteady yielding may be expected in at least some soils at shearing rates in the region of about 50-500mm/day.

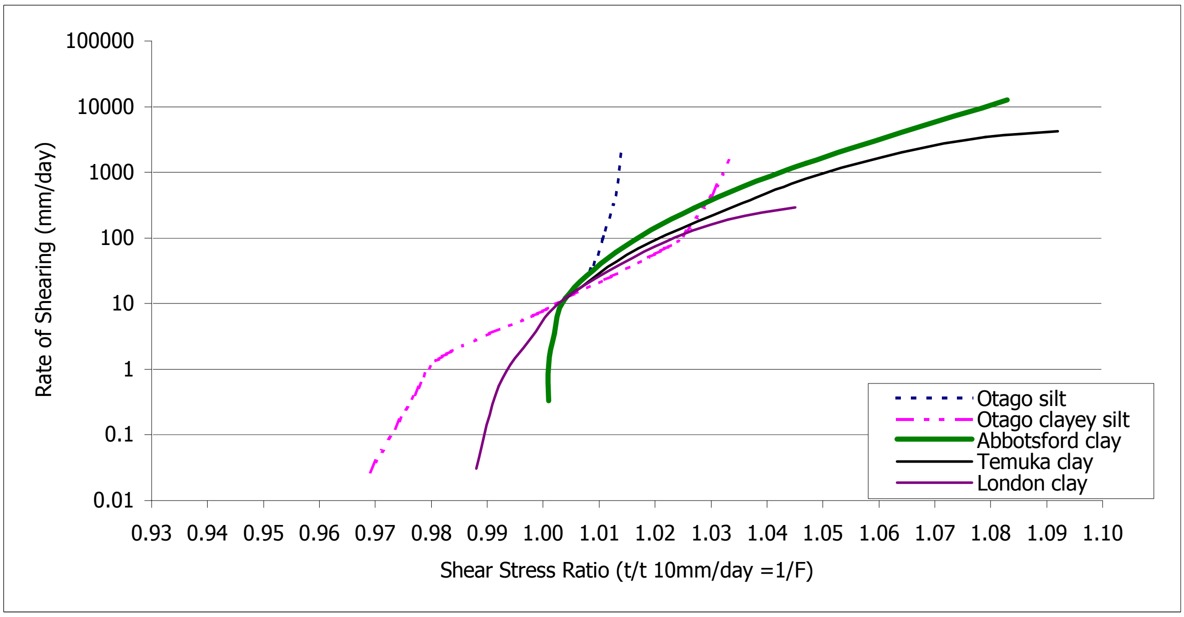

Figure 3a Residual Strength Dependence on Shearing Rate

Most soils show increasing effective strength with increasing rates of displacement, although anomalous strength properties have occasionally been reported, eg Cowden till (Lemos, Skempton & Vaughan, 1985), see Fig. 3b. If this type of characteristic can be confirmed with a stress controlled test, it indicates a soil that will shear more rapidly if the driving forces are reduced. A landslide in this material would surely fail with extreme rapidity.

(b) Frictional Heating

Pore fluid expansion from frictional heating has also been shown to be relevant to slide acceleration in specific soil types. Numerical methods are now available to demonstrate the conditions which will induce significant pore pressure rises, that is, geotechnical characteristics can be used to set critical velocity and acceleration for a given situation. It appears that pore pressures are likely to be affected by frictional heating, only in highly overconsolidated saturated soils of low permeability, subject to moderate or high normal stresses where velocities exceed about 50 to 500 millimetres per day, and accelerations are positive. Some other mechanism is usually required to initiate substantial velocity and acceleration before the effect becomes significant.

From both (a) and (b) above, therefore, it is apparent that the geotechnical characteristics of the failure surface soils are very relevant to the selection of threshold movement rates for alarm criteria.

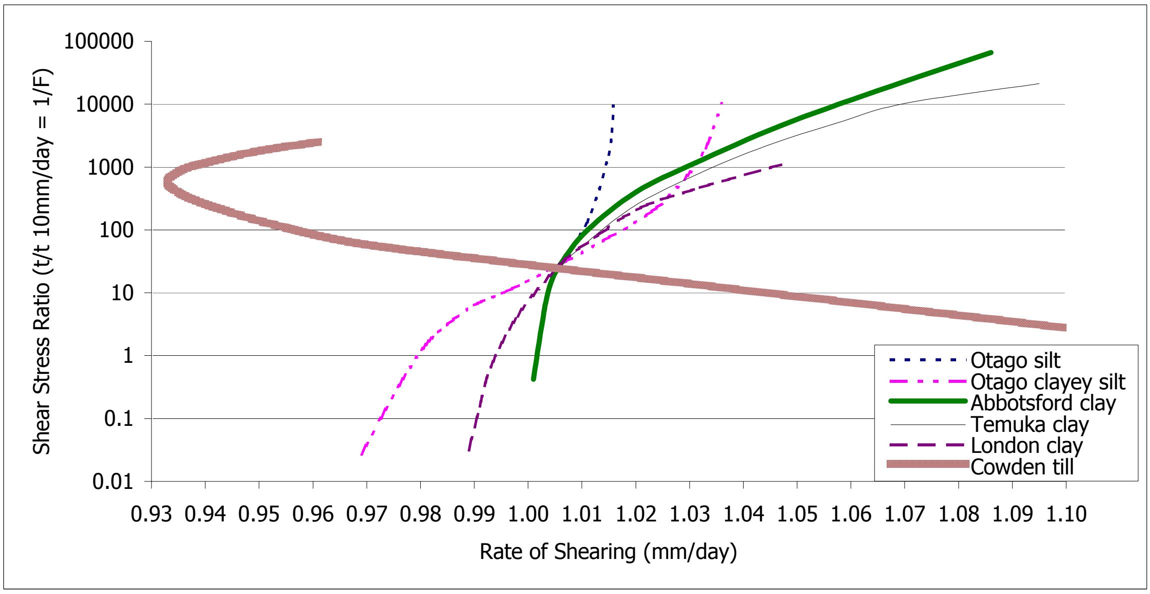

Figure 3b Residual Strength Dependence on Shearing Rate

Monitoring Frequency

Background

Case histories have demonstrated that in spite of monitoring, catastrophic failures have occurred without prior recognition simply because no procedures have been followed to determine whether a formerly adopted survey interval should be continued. Often, conditions will change so that more frequent surveys are required.

In a slide, which has been monitored for a long period, there is a danger of over-familiarity. Ruahihi is a prime example: initial surveys were carried out daily, but intervals were gradually increased in spite of obvious acceleration. By the time of failure, readings had been extended to weekly intervals!

Procedures are suggested herein, in order to lessen the likelihood of rapid movements developing between monitoring surveys. Modifications will obviously be required for specific cases, by the application of engineering judgement, and giving due regard to the geotechnical characteristics of the slide materials. The proposals relate primarily to slides at residual strength, ie where displacements at the toe are sufficiently large to discount a major strength reduction from peak to residual. To satisfy this criterion downslope displacements at the slide toe should exceed 100 mm in non plastic soils, grading to about 2m in highly plastic clays. First-time slides may be treated similarly but a much higher level of caution is clearly required.

Monitoring Recommendations.

Specific recommendations for determining landslide survey intervals where high hazards are involved (ie risk to life) are as follows:

(a) Plot displacement versus time. If velocity exceeds 0.5 mm/day then plot velocity and acceleration curves. If the acceleration is increasing, use the method described in 'Prediction of Accelerating Slide Movement.'

(b) Determine the time rate of change in safety factor expected from any displacement-independent accelerating mechanisms (eg removal or addition of material to the slide head or toe, rising reservoir, other changes in piezometric levels etc). Using conventional limit equilibrium methods.

(c) Determine the distance rate of change of safety factor for any displacement-dependent accelerating mechanism (eg decline from peak to residual strength, slope deflation or self buttressing, pore pressure changes resulting from mass relocation, pore pressure changes from frictional heating etc). Methods are described by Salt (1991).

(d) Compute the expected change in downslope velocity caused by the predicted changes in safety factor from both types of accelerating mechanisms. This is done from laboratory tests to determine the strength-displacement rate relationship for the failure surface soil (or correlations from test on soils with similar index properties).

(e) From the extrapolation of the displacement curve (together with the velocity and acceleration curves if appropriate) determine the time interval which will satisfy the following criteria:

(1) Displacement. For first time slides, the change in downslope displacement should be no more than 5 mm (less if practicable). Slightly greater displacements are acceptable for slides where residual conditions clearly apply. However, the change should always be less than 50 mm and a value of 10 mm is often appropriate.

(2) Velocity. If any precedent velocity exceeds 0.5 mm/day, the extrapolated change in downslope velocity should be small compared with its latest value, say a change of no more than 10%. Where velocity is very low, this criteria may be extended to allow for survey accuracy, (usually 0.5 mm for inclinometers or 5 mm for surface deformation marks). If the velocity is approaching the specified critical limit, the time interval should be decreased to ensure the limit is not exceeded.

(3) Acceleration. Where movement rates are sufficient to enable meaningful determination of accelerations, the extrapolated change in acceleration should be no more than 10%. If the acceleration is approaching the critical limit, time intervals should be decreased accordingly.

(4) Time. If the acceleration is positive, the time interval should be a small percentage (say 10%) of the estimated time remaining to rapid failure, ie the time interval should not exceed 10% of ${}_{t}(n)\times{}_{t}(n)/({}_{t}(n-1)-{}_{t}(n))$. (Symbols as defined above.)

The smallest of the time intervals determined above should be adopted unless precedent plus geotechnical reasoning clearly justify a longer interval. Additional surveys should be carried out after any rare event particularly seismic loading or sustained rainfall (giving due regard to infiltration delays in the latter case).

Prediction of Accelerating Slide Movement.

(After Azimi et al, 1988).

The following procedure will tend to linearise the movement record of an accelerating slide and hence is useful for extrapolation. It may also be used to estimate time of rapid failure provided no displacement independent accelerating mechanism (eg reservoir filling) is operating. Note that the 'window' of accuracy of the prediction may be very large, and unconservative. (An overestimate of up to 400% for the time remaining to failure was found in the first example for which the method was proposed.) Accordingly it is suggested that any estimate of the remaining time to failure, should be divided by a factor of ignorance of at least 5.

(1) Plot (a) the raw data for the displacement versus time curve and (b) the same curve smoothed with regard to survey accuracy. Carry out the following steps with each curve.

(2) Divide all of the accelerating section into equal distance intervals which give due regard to the accuracy of the survey (about 3-10 times larger than the standard error), and read off the corresponding series of times; T(0), T(1), ... T(i) .... T(n), using the beginning of the accelerating portion as origin (T0 = 0).

(3) Plot T(i-1) versus T(i) on natural graph paper. Draw on the line T(i) = T(i-1). The projected intersection of the two lines gives the predicted time of failure. The raw data curve gives some indication of likely error limits. The smoothed curve may provide a more accurate prediction, but grossly unconservative estimates must still be anticipated. Extrapolated movement patterns may best be estimated from the smoothed curve.

(4) The graphical method is preferred because error limits may be crudely estimated. However, direct solutions are available from any selected data points:

Time of failure

$$= (T(i) \times T(i) - T(i+1) \times T(i-1)) / (2T(i) - T(i+1) - T(i-1)) \tag{2}$$

or,

Remaining time interval to failure

$$= t(n) \times t(n) / (t(n-1) - t(n)) \tag{3}$$

where,

$$t(i) = T(i) - T(i-1) \tag{4}$$

(5) Repeat steps 2, 3 and 4 to determine sensitivity with respect to selected distance interval.

(6) Use the most conservative extrapolation to estimate (a) the future displacement, velocity and acceleration for determination of the appropriate time interval to the next survey, and (b) the remaining time to failure assuming a factor of ignorance of at least 5.

Practical Application of Alarm Criteria

Steady Creep.

Table 1 lists velocities (and accelerations where appropriate) for a number of active slides where creep has not been the forerunner to rapid movements. Many of these slides have suffered considerable displacement and most are located in reservoirs. All show consistency with the proposed limits (50-500 mm/day) for residual strength conditions. It is possible in some instances for faster movements to occur without catastrophic acceleration (particularly where normally consolidated clays are moving on relatively shallow failure surfaces, or movement causes significant self-buttressing). Nevertheless, it is suggested that for potentially hazardous slides, threshold limits which exceed the above, should not be set without detailed laboratory and field studies.

Table 1. Landslides with historic records of steady creep failure (Mostly in reservoirs)

Slide	Downslope speed (mm/day)
Downie (Active toe)	<0.03
Mica Reservoir	0.1
Needle Rock Slide	0.3
Morrow Point (Slide A)	1
Dirillo Reservoir	3
Futase Reservoir	3
Ankhangaran Reservoir	6
Fort Peck Dam	8
Waiomao	20
Vaiont (1960 filling only)	36
Wind Mountain	40
Jeffery Mine	60
America Mine	110
Minnow	450
Hochmaiss	50 (a=0.5)
Hochmaiss	190 (a=2)

Note: Acceleration (a) in mm/day/day.

Catastrophic Failure Records

At least 5 days forewarning would have been available if the proposed limits were adopted for Vaiont, Abbotsford or Ruahihi slides. Since producing these recommendations, additional raw data has been sought, but little obtained. One example received is the monitoring for the Jizukiyama Slide, where a disaster occurred, because neither the acceleration nor the sustained movements were predicted (Sassa, 1988). The monitoring data reported for this slide, are such that adoption of the above policy for threshold velocity and acceleration would have led to evacuation about 7 days before the final rapid advance.

Concluding Remarks

This review has been prepared after a brief literature review, to provide a discussion document on alarm criteria. Undoubtedly, a more comprehensive search for field data and appropriate laboratory testing will lead to recommendations for more reliable alarm criteria than those identified so far. However, the reasons for suggesting limits at this stage are that failures continue to inflict unmitigated damage because appropriate limits (and procedures for assessing them) have seldom been considered. Further research will improve the state of the art for the prediction of rapid movements. Meanwhile it is suggested that two aspects which are generally overlooked (pre-setting of alarm criteria and selection of appropriate monitoring intervals) should be addressed through examination of geotechnical characteristics. An understanding of the nature of the governing materials, together with adequate interpretation of monitoring data will substantially diminish the risk of unexpected acceleration of an incipiently moving slope.

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