Landslide mobility and remedial measures

Mouvements des glissements de terrain et mesures préventives

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ABSTRACT: In recent years there have been several examples of landslides associated with engineering development, where the onset of rapid failure has been misjudged in spite of prolonged periods of precursory observations. Advancement in the state of the art for the prediction of rapid landslides is essential in order to limit risks where pre-existing slides are affected by major works such as roading or reservoir impoundment. Using conventional soil mechanics, both field and laboratory characteristics of slide materials have been examined in order to allow discussion of the principles governing landslide mobility. Also, recommendations are made on the need for, and extent of, any remedial measures for activated slides.

RESUME: Depuis les dernières années, plusieurs cas d'éboulements de terrain sont apparus en association avec des travaux de gerie civil. L'évolution rapide de telles ruptures n'a pas été anticipée malgré des observations préliminaires effectuées longtemps en avance. Les progrès en matière de prédiction de glissements de terrain a évolution rapide sont essentiels. Cela permet de limiter les risques encourus par d'anciens éboulements susceptibles d'étre effectés par d'importants travaux tels la construction de routes ou la mise en place d'un réservoir. L'utilisation des méthodes traditionelles de la mécanique des sols nous a permis de déterminer les caractéristiques des matériaux d'éboulement, sur le terrain et au laboratoire. Cela permet de discutter sur les lois qui régissent la mise en mouvement des glissements de terrain. Des recommandations sont également proposees sur le besoin et l'importance des mesures à prendre pour remédier à la progression des éboulements.

1. INTRODUCTION

Large landslides, sometimes dormant but usually creeping at rates of several tens of millimetres per year on deep seated failure surfaces are common in the schist terrane of New Zealand. Where roading, submergence or other works affect landslides, assessment of their future behaviour is required. Commonly, reactivation or slight increases in present creep rates will occur when only small decreases in stability are induced. The potential for rapid landsliding has been investigated as part of a study of Otago schist derived materials, however general principles are discussed for application to other soils.

Assessment of active landslides involves:

(i) The use of precedent, using field indications of the past and present behaviour of large active and dormant slides in the area.

(ii) Interpretation of surface and sub-surface deformation surveys of present levels of movement, taking measured hydrological factors into account.

(iii) Examination of documented case histories of slides in similar materials.

(iv) Laboratory testing using stress levels corresponding to those existing in the field, together with conventional limit equilibrium methods to assess the influence of proposed works.

Combination of the above four courses is required for a full appraisal of slope stability. While all factors may indicate that any slide movement occurring should be steady, performance is usually monitored to confirm expectations. However, limits on acceptable magnitudes of velocity and acceleration should be established for each slide before any development takes place. Previously identified criteria indicative of unsteady behaviour are essential, as omissions of these appear to be principal reasons for misjudgements leading to notable landslide disasters. There are many cases where monitoring information has been diligently recorded, but the implications of the readings (interpreted with due regard to established geotechnical characteristics) have not been considered. The opportunities to be forewarned have therefore been missed.

Information on how to assess the potential for rapid mobility (unsteady yielding) of landslides is rare in geotechnical literature. Hutchinson (1977) has pointed out "the difficulties of assessing the degree of stability of existing slopes or landslides and of deciding what is an appropriate degree of improvement" and emphasised the need for further work in this field.

In order to derive relevant properties for the analysis of landslides in the schist materials studied, a simple ring shear apparatus (Bromhead, 1979) has been used with an annulus of soil sampled from the relevant gouge zone. The specimen may be sheared, by many rotations, to produce a sample which has effectively suffered a displacement of several metres. Testing may then be carried out to determine residual strength characteristics in terms of effective stresses. The modified apparatus has the facilities to impose rates of shear displacement from less than 0.01 mm/day (3 mm/year) to as high as desired. This encompasses the main rates of movement currently observed in the field (3 to 100 mm/year) and also those higher speeds likely to present a hazard. In addition to the normal strain controlled testing, the apparatus may alternatively be used in a stress controlled mode, as only the latter is directly applicable to the field situation.

This article details the inferences that may be drawn from recent laboratory testing and field observations of active slides. Quantitative answers to the following questions are suggested.

1. If an existing landslide is suspected to be marginally

stable and its factor of safety is to be reduced (eg by mass redistribution, toe submergence etc.), can the nature of any movement be predicted (particularly acceleration, velocity and total displacement likely to occur before coming to rest).

2. If a landslide is actively moving, is rapid acceleration likely?

3. If a landslide is reactivated as result of de-stabilising factors such as toe submergence (or removal of material from the toe) can reservoir filling (or cutting from the toe) be continued or must further reductions in safety factor necessarily be delayed until movement stops or reduces to a former value?

4. If landslide stabilisation is proposed, what increase in factor of safety is necessary?

Case histories found in the available literature demonstrate that where landslides present hazards, there is a marked variance in the level of caution exercised by different organisations. This is probably attributable to observations that pre-existing slides usually move only slowly and steadily, yet occasional examples of unsteady, rapid mobility exist. (For example the slide into the Vaiont Reservoir which in terms of lives lost, is one of the most notable accidental disasters in engineering history.)

Suggestions are made for the evaluation of surface and subsurface monitoring records and determination of criteria which indicate the need for any remedial action on mobile landslides. The specific data are relevant only to the area studied, but it is suggested that the approaches used may be adapted for other material types.

2. RESIDUAL STRENGTH TESTING

Skempton and Hutchinson, (1969), discuss the most readily applied method of active landslide evaluation, namely limit equilibrium analysis using effective stresses, ie residual strengths in conjunction with appropriate pore pressures. This allows confirmation of the mechanics of a slide and enables the effects of any proposed changes to be quantified in terms of a conventional factor of safety.

Residual strength has been shown to be slightly dependent on rate of shearing; Skempton and Hutchinson reported approximately one per cent increase in effective strength per tenfold increase in displacement rate. Results of comprehensive multi-stage tests on schist gouge are shown in Figure 1. The quite significant changes in shearing stress are demonstrated to be functions of effective normal stress and displacement rate. For ease of presentation, all shear strengths have been normalised with respect to the shear stress developed at an arbitrary standard shearing rate of 10 mm per day. Note that the conventional limit equilibrium factor of safety is given by the reciprocal of the normalised shear stress ratio which is plotted as the abscissa (independent variable) because in the field situation, displacement rate is the dependent factor. Strain rates cannot be accurately determined in the ring shear apparatus, but a very thin specimen (4 mm) has been used. Test data for the very slow displacement rates are limited at this stage because of the extremely long times required to obtain individual results in this region. However, from testing of various soils, the downward curvature (at low and moderate normal stresses) shown in Figure 1, tends to become asymptotic to a lower bound which for a given normal stress, gives the minimum dynamic strength. Similarly at fast displacement rates, shear stress ratios become asymptotic to the maximum strength ratio. Laboratory results show considerable variation at rates higher than about 50 mm/day in saturated low permeability soils. Frictional heating effects on pore pressures of low permeability soils have been demonstrated to be quite significant in this respect (Voight & Faust, 1982: Salt, 1985). Some variations are also noticeable at low normal stresses and these may be attributable to peripheral effects which have a proportionately greater influence in the shear apparatus at low stresses. Repeatability of the results therefore decreases at lower stress levels but further work to improve techniques in this area is in progress.

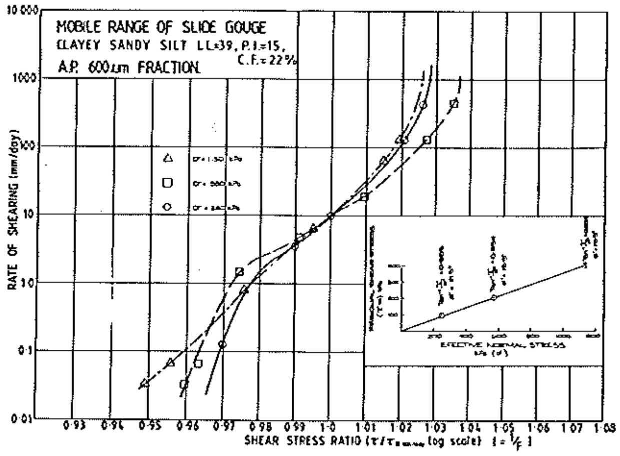

Figure 1. Mobile range of schist gouge from ring shear testing.

3. SLOPE STABILITY IMPLICATIONS

The average normal effective stress on the failure surface of a landslide may be estimated from standard limit equilibrium methods (Janbu, 1973). The highest normal stress used in the laboratory tests was 1130 kPa. Where the watertable is low, this corresponds to an average depth of slide of about 50 metres. With this normal stress it is evident from Figure 1 that the shear stress at minimum dynamic strength may be increased by about 8% before the graph ultimately begins to steepen as it approaches the maximum strength. The significance of the steep gradient is that a very small increase in shear (ie 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.

Conversely, if a correspondingly deep seated slide is initially stationary, its factor of safety may be decreased by at least say 6% without likelihood of rapid failure, providing other factors do not intervene, (Salt, 1985). The difference in shear stress ratio which can be developed over the available range in displacement rates, will here be termed the mobile range. Upper or lower bounds to the mobile range may be adopted to give appropriate conservatism, depending on the use to which this characteristic is being applied.

Figure 1 explains previous contradictory results (Hungr, 1981) on whether drained shear strengths are rate dependent: tests carried out with a limited range of variables have led to the apparently conflicting conclusions. The reason is that there is very little rate dependence at either very slow or fast shearing rates, and at very low normal stresses.

It is suggested that for a range of materials (sands, silts and clays), the dependence of residual shear strength on shearing rate is a fundamental rheological property, with significant engineering applications.

Direct implications of Figure 1 are:

1. Determination of the mobile range of a soil representative

of material from a failure surface, allows quantification of the percentage decrease in factor of safety that can safely be imposed on a pre-existing slide, before rapid mobility (unsteady failure) is likely. Provided changes are imposed slowly, mass redistribution or toe submergence of an active slide may be carried out and continued steady yielding should result. This inference is consistent with observed performance in the field. (Note this applies only to pre-existing slides. "First-time" slides cannot be analysed this simply.) If the approximate geometry of a slide failure surface is known, then the rate at which mobilised shear stresses decrease with displacement may be computed, to estimate the distance the slide will move before returning to a stationary condition (or to the steady rate of movement prevailing before imposition of the reduced safety factor).

2. If a landslide is known to move intermittently, as is commonly encountered in earthflows moving only rarely after extreme rainfall events, then the mobile range at the appropriate level of normal stress is numerically equal to the increase in factor of safety required to prevent further movement. For example, from Figure 1, slides failing in the test material, and having average depths of 10 or 50 metres, would require respective increases in safety factors of 6 and 10% to just prevent further movement in equivalent environmental conditions. This assumes conservatively that most of the mobile range was formerly utilised. However, if a record of the former displacement rates has been kept, then the appropriate lesser increase in safety factor needed to just arrest movement may be read from the mobile range curve. Any additional factor of safety deemed necessary to allow for uncertainty should be related to the risk present and recommendations on this aspect are made below.

3. The nominal rate of shearing at 10 mm/day cannot reasonably be used to define a meaningful factor of safety of 1.0, as apart from very shallow slides, the 'point of movement' of a slide (invoking the full static strength) will require a substantially higher safety factor. From Figure 1, a slide in this material with average normal effective stress of say 1100 kPa would require a safety factor of 1.0/0.94, ie about 1.06. (This assumes strength parameters had been derived from a ring shear test at 10 mm/day.) This error would be of little consequence where an absolute factor of safety is being estimated, but would usually be quite significant where a relative change in stability is being considered, as with a slide to be influenced by reservoir filling. The above neglects, for the moment, the difference between static strength and minimum dynamic strength, but this will be discussed later.

4. LABORATORY VERSUS FIELD BEHAVIOUR

The relative thicknesses of active shear bands forming failure surfaces may cause differences between laboratory and field behaviour. The 4 mm thick sample used in the laboratory is constrained by the apparatus to fail in as thin a band as possible. Preliminary measurements with intermittently dyed samples suggest that the active shear band developed during ring shear is about 0.5 mm in thickness. A significant difference between the field and laboratory samples is that in the field, multiple shear surfaces and/or thick shear bands may develop. This should not affect the mobile range or its shape, provided results are plotted on a logarithmic scale, ie it is suggested that the laboratory test produces a characteristic curve for the soil. However, assuming the displacement rate across an active shear band is a direct function of shear strain rate and active shear band thickness, the displacement rate in the field will exceed that obtained in the ring shear apparatus by the ratio of the shear band thicknesses (field to laboratory). That is, if failure does occur in a shear band rather than along a discrete failure surface, then it is strain rate rather than displacement rate that is fundamentally related to shear stress. For example, if under a given shear stress the active shear band could be increased ten times in thickness, the displacement rate would also increase tenfold.

In Figure 1, the characteristic curve would retain the same size and shape but its position would be translated to the new velocity ordinates.

If a landslide (with unknown shear band thickness) reactivates as a result of changes in safety factor and displacement rates are recorded, the match point solution (discussed in most texts on groundwater hydraulics, eg Todd, 1950 for Theis's method) will apply to the interpretation and prediction of movement. The limit equilibrium changes in factor of safety of a slide may be computed for changed field conditions, and plotted logarithmically against slide displacement rate, but the number of shear bands and their active thicknesses will not usually be known. The normalised shear stress ratios may be computed, but these cannot be directly related to the same ratios for the laboratory test data. However, translating the field data to the known characteristic curve (or 'type curve') allows quantitative estimates of:

(i) the critical field velocity (at which unsteady yielding is imminent)

(ii) the additional decrease in factor of safety that may be imposed before the critical field velocity is reached

(iii) the approximate thickness of the active shear band.

Implications of field performance prediction:

1. In situations where a pre-existing slide is being reactivated, namely where progressive toe submergence from a rising reservoir is causing increases in slide velocity, a decision may be made on whether reservoir filling may continue, or cease until a greater margin against unsteady yielding is obtained by displacement self-stabilisation (where geometry allows), or specific remedial measures.

2. The shear band thickness may be roughly estimated, allowing qualitative appraisal of the potential for rapid mobility under conditions of sudden stress change (namely rapid drawdown or earthquake).

3. If the approximate thickness of the active shear band can be determined in the field, the analysis described above may be applied in reverse to fix the translated position of the characteristic curve. Likely increases in displacement rate with submergence may then be estimated directly. This has the advantage that the behaviour of a slide can be estimated before any reservoir filling takes place, as opposed to the approach when shear band thickness is unknown, where filling must be commenced to provide monitoring data. Variations in present movement rates of active slides taken in conjunction with piezometer readings and river level observations, may allow full or partial characterisation before reservoir filling.

Reservations:

Figure 1 relates to the fine fraction (all passing 0.6 mm) of schist gouge. The effects of larger particles and soils of differing USC groups are being investigated but initial indications are that all materials tested so far show broadly similar mobile ranges at similar normal stresses.

The shape of the mobile range curve has not been well defined at low displacement rates. Further data points are being obtained as the apparatus becomes available for the necessary long term testing.

A complication when considering the mobile range characteristics is that stick-slip movement (episodic creep) is commonly observed in periodically dormant landslides.

Present indications are that the percentage increase in shear stress required to reactivate a stationary slide is small in relation to the mobile range for all except possibly very shallow slides. Further discussion is made below.

The effects of frictional heating on pore pressures developed in low permeability soils during more rapid movements is also being investigated.

Until these aspects are investigated further, the acceptance of critical field velocity predictions made using the match point method should be regarded with caution. However, the laboratory characteristic curve (Figure 1) obtained is a good qualitative guide, ie if the factor of safety of a slide is decreased and yet the log plot against velocity yields a concave downward curve, then it may be inferred that a significant margin exists before unsteady failure. Conversely, a concave upward curvature suggests that a critical situation is imminent. Until more data are available, predicted critical field velocities should be reduced by an order of magnitude for conservative assessments of landslides reactivated during reservoir filling. Where no previous monitoring is available, critical field velocities may be assessed conservatively from the laboratory curve. For example from Figure 1 for a slide with average thickness about 25 metres, a displacement rate of about 200 - 300 mm/day might be regarded as the upper range of steady yielding, therefore a limit of somewhere between 50 and 100 mm/day might be set as the maximum acceptable displacement rate for a slide which presents a significant hazard. Before maximum rates are approached, interpretation of surface and sub-surface monitoring to assess the significance of slide velocity and acceleration changes would allow confirmation of steady behaviour.

5. INTERPRETATION OF DEFORMATION MONITORING

Monitoring of surface displacements has been the traditional means of predicting future activity of an incipient slide. Apart from earthquake induced slides and some failures in steep rock slopes, warning movements typically occur. Terzaghi (1950) reports; "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". However, Terzaghi offers no suggestions of techniques for interpretation of factors relevant to rapid failure prediction. In order to develop appropriate techniques, precursory behaviour in case histories for which data are available, is shown in Figure 2. The Vaiont Slide and two recent catastrophic slides in New Zealand (East Abbotsford and Ruahihi) are examples where the opportunity to be forewarned was available. It is suggested that three aspects of deformation monitoring require particular consideration.

(1) Displacement - Examination of resultant downslope displacement vectors relative to the topographic slope and position on the slide readily provides information on:
(a) how deep-seated a slide is (to estimate average effective normal stresses)
(b) whether a significant non-circular motion is occurring and
(c) whether retrogressive segments are developing or distortion is taking place within the sliding mass.
The former allows improved evaluation of remedial measures. Implications of non-circular failure surface geometry have been discussed previously (Salt, 1985). Some attempts have been made (with questionable success) to predict the timing of rapid failure of a first-time slide from displacement criteria (Voight & Kennedy, 1979). In general, this approach will not apply to slides in which residual conditions pertain.

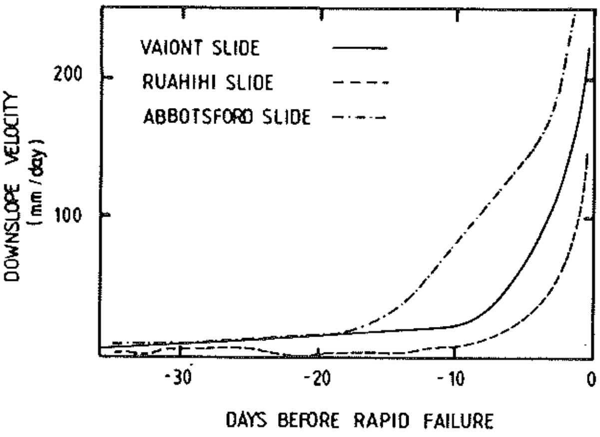

Figure 2a. Precursory velocities of slides

(2) Velocity - Creep rates preceding catastrophic failures have been documented for several notable landslides and give some measure of their future movements (although thickness and permeability of the failure zone is of particular importance). Downslope velocities of 50 to 100 mm/day were achieved by the Vaiont, East Abbotsford and Ruahihi Slides (Figure 2a) some days before their final rapid movements. This leads to the suggestion that large slides in relatively low permeability materials should be regarded with particular caution if velocities approach about 50 to 100 mm/day. However the significance of acceleration is considered more relevant.

(3) Acceleration - In terms of catastrophic potential, ultimate slide velocity is of particular relevance, and foresight into this aspect requires appreciation of accelerations. Clearly, until negative acceleration occurs, a slide cannot begin to slow down. Rational interpretation of landslide movement requires successive differentiations of the displacement - time record to obtain the acceleration history. This is essential in any instance where the displacement-time curve exhibits a concave upward shape.

With the benefit of hindsight, good examples of forewarning given by acceleration curves can be seen from the detailed displacement record kept prior to the East Abbotsford Slide, and to a lesser extent (because sufficiently regular monitoring records have not been procured) by the Ruahihi and Vaiont Slides. Successive differentials for the East Abbotsford Slide (Figure 2b) show linearly increasing acceleration for 2 weeks followed by concave upward (clearly unstable) curvature of the acceleration record for 5 days prior to rapid failure. For the Ruahihi Slide, readings in the final stages were made only weekly, in spite of significant displacement rates, so some interpolation has been necessary to develop the downslope velocity and acceleration curves. However, a concave upward acceleration curve was apparently experienced for 10 days prior to the rapid failure. This example highlights the need to provide sufficient survey data to determine the acceleration characteristics continuously whenever a hazardous slide shows increasing displacement rates. Detailed records were taken of the Vaiont Slide and in this instance velocity (but not acceleration) was plotted (Selli & Trevisan, 1964). Although there is some difficulty estimating acceleration data from the scale provided, this has been attempted in Figure 2b, revealing a concave upward acceleration record for the two weeks immediately preceding the catastrophic failure.

Clearly, additional case histories of well monitored landslides would be desirable before making generalisations

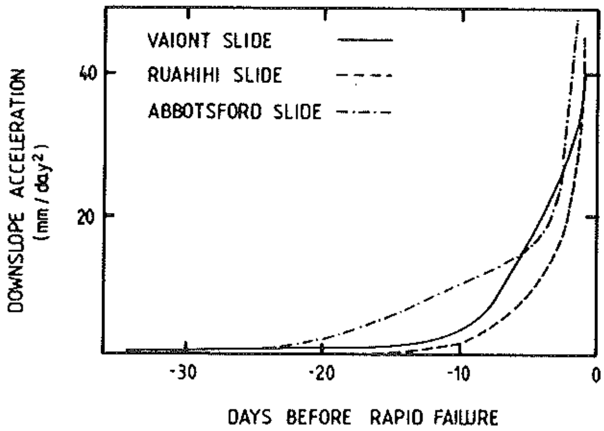

Figure 2b. Precursory accelerations of slides

from the limited data in Figure 2. However, taken in conjunction with other case histories with less detailed movement records available and Figure 1, the following are suggested as critical limits for any local schist derived slide:

Downslope velocity	50 mm/day
Downslope acceleration	5 mm/day/day

Before either one of the above is reached, specific assessment of the damage potential should be made and remedial measures taken if appropriate. (Slope deflation and self buttressing should often suffice where the hazard is low and only small reductions in safety factors have been induced.)

6. SEISMIC STABILITY

Rate dependence of strength has implications with respect to earthquake deformation analyses of the Newmark type. Effective strength tests require consideration of strain rate at failure to assess the additional strength that will be developed at the rapid strain rates induced during earthquake deformation. An additional complication is that even though residual strength conditions pertain, the higher available shear strength will result in either increased or decreased strength under undrained loading depending on the sign of the pore pressure coefficient A (Skempton, 1954) of the failing soil. At high normal stresses, predicted displacements may be altered significantly.

7. THE EXTENT OF REMEDIAL MEASURES

Design of stabilisation measures for an existing slide, which has established a form of equilibrium with its environment (ie where only creep movements are being recorded) presents a more simple problem than the determination of an appropriate geometry for a newly constructed slope. The latter requires the provision of an absolute safety factor which reflects the uncertainty in available strength and future peak pore pressures. However, the precedent conditions established for an active slide which has existed for many years, allow stabilisation measures to be assessed in terms of a percentage increase in safety factor, rather than as an absolute value. Appropriate safety factor increases will be determined primarily by:

(i) whether complete arrest of all movements must be accomplished,
(ii) allowance for the accuracy of the analysis where both adverse and favourable changes have been inflicted
(iii) the potential for damage.

In the first case, the appropriate mobile range curve may be used to determine the increase in factor of safety required to reduce displacement rates. Where no movement is acceptable, an additional increase of 5 or 10% may be added, depending on the potential for damage. An example of the second case is where a slide is to be adversely affected by submergence and this is to be countered by buttressing. To allow for inaccuracies in this instance, a reasonable approach might be firstly to ensure that the restraint just restores the original factor of safety and then apply further buttressing equivalent to say 50% of the adverse component. This amounts to a partial safety factor of 1.5 on the unfavourable effect, although the total safety factor would be only slightly greater than 1.0. Attempts to provide total safety factors similar to those used for first time slides as in the design of retaining walls or earth dam slopes (1.5 or even 1.2) are impractical and unnecessary for large existing slides where relative rather than absolute safety factors are appropriate.

8. FURTHER WORK

Testing is in progress at present to determine the mobile range of previously unsheared schist materials, ie investigating the characteristics of 'first time' slides. This requires the additional consideration of the reduction of strength with shear displacement, particularly at high normal stresses as gouge is developed.

Stick-slip behaviour (episodic creep) is also being investigated. This type of movement appears to be a characteristic of most slides for which detailed records are available. The explanation is now evident from testing of materials sheared to residual strength. If the shear stress is reduced, the mobile range curve is followed directly as given by Figure 1 until movement ceases entirely at the minimum dynamic strength. However on increasing the shear stress again, no movement occurs until the shear stress exceeds the minimum dynamic strength by about 1 or 2%. This difference between static and dynamic coefficients of friction has commonly been reported for various materials, and it appears soils are no exception. The strength difference is a function of time of stationary contact (Dieterich, 1978) and probably other factors such as soil type, normal effective stress and rate of change of shear to normal stress ratio. However, preliminary work indicates that this effect is small compared to the mobile range of large active slides. Those slides which have average depths of several hundred metres do appear to be moving more steadily (usually about 5 mm/year), ie stick-slip is evidenced less in the field at high normal stresses. This is possibly explained by the absence of downward curvature at slow rates, noticed in the laboratory mobile range curve at the highest normal stress (Fig. 1).

The behaviour of soils sheared in a stress controlled rather than strain controlled manner also appears relevant. In the laboratory, strain (or rather displacement) rates are customarily imposed and the resulting shear stresses measured. Conversely, in the field, gravitational stresses act and displacement rate is therefore the observed parameter. To consider this effect, stress controlled tests have been carried out on schist gouge. Strain controlled shearing was imposed until residual strength conditions pertained. Control was then reversed, applying constant shear and effective normal stresses. Unless initial rates were high, displacement rates always reduced slowly and finally ceased altogether. A possible explanation is that this behaviour may be attributable to secondary consolidation. The average measured shear stresses will normally show some variations in magnitude as different particles interlock, break or slide, although this effect is very small. However, once stress control is imposed, then during a period of increasing interlock, displacement rates will reduce, allowing particles within the shear band more time to adjust to more favourable positions (as experienced in secondary consolidation). This better packing will produce a marginal increase in shear strength, causing further slowing and so the process continues. In the field, the effect of larger scale is likely to minimise this type of behaviour but there is very little information available from case histories.

Scott (1978) cites an example where the failure surface of an active rockslide was accurately monitored with a continuous recorder. Displacements of 0.25 mm were observed to be occurring regularly at 15 minutes intervals. Each movement event took place within 2 minutes, starting abruptly with a velocity of several hundred mm/day but reducing asymptotically to zero in about 2 minutes. A second recording station 15 m further upslope from the first, consistently showed the same behaviour except that it lagged by 1 minute, ie the slide 'shuffled' down the slope with a displacement wave speed of 15 m/min. It appears reasonable to conclude that stick-slip may be normal behaviour in most landslides where sufficiently accurate monitoring is available, and this is consistent with the laboratory observations of both strain and stress controlled tests. To support this point, other obvious examples of the same phenomenon may be cited, eg: crustal faulting, squeaking machinery and the violin string-bow interaction (Rice & Ruina, 1983).

9. CONCLUSIONS

1. At present little information is available on procedures to adopt when pre-existing landslides are activated. A set of guidelines has been recommended (a) for assessment of the potential of landslides to move rapidly, and (b) to determine the need for and extent of remedial measures.

2. Testing of landslide gouge has established a clear relationship between residual strength, shearing rate, and effective normal stress. A family of characteristic curves which show the mobile range of a soil may be determined with a simple ring shear apparatus. Rate dependence of shear strength clearly explains the observations that pre-existing landslides usually move in a steady manner. Conservative limits to steady failure may be predicted.

3. Determination of the mobile range of gouge from an existing landslide allows straightforward quantitative assessments (using standard limit equilibrium analysis) of the following situations.

a) If an existing landslide is suspected of being marginally stable and its factor of safety is to be reduced (eg by mass redistribution, toe submergence etc), the nature of any movements can be predicted. (Namely acceleration, velocity and total displacement likely to occur before coming to rest). In particular the likelihood of rapid acceleration can be assessed.

b) If a landslide (previously recognised or otherwise) is reactivated as result of de-stabilising factors such as toe submergence (or removal of material from the toe), a decision can be made on whether reservoir filling (or cutting from the toe) may continue or if further impoundment (etc) must be deferred until movement stops or reduces to a former value.

c) If landslide stabilisation is proposed, the appropriate minimum increase in factor of safety may be determined, depending on whether movements must be entirely arrested or if a specific creep rate is acceptable.

4. Independently of landslide behaviour predicted from mobile range characteristics, appropriate interpretation of deformation monitoring can provide forewarning of rapid landsliding. Recommendations have been made for limits to downslope velocity and acceleration of the large existing slides in local schists. Instances of significant rates of movement will require regular review of monitoring data to provide assurance that any process which de-stabilises a landslide (eg reservoir filling) may continue safely, or alternatively, to indicate the appropriate extent of any counter measures.

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