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Aspects of landslide mobility

Aspects de la mobilité des glissements

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SYNOPSIS

Geotechnical case histories both in New Zealand and overseas have provided more than an isolated instance where the potential for rapid acceleration of a landslide has been underestimated. Frequently, detailed survey information has been obtained but seldom have appropriate criteria been considered and pre-set for identification of a critical situation with respect to landslide mobility. While many factors may cause acceleration of a slide mass, these may be grouped as either displacement-dependent or displacement-independent mechanisms. It is apparent that the former require particular consideration when assessing the potential for a landslide to move rapidly. Laboratory evaluation of landslide materials using a ring shear apparatus operated in a stress controlled mode is an effective means of observing displacement-dependent aspects of mobility. A review of some notable landslide disasters demonstrates the enhanced predictive capacity which might have been provided through appropriate interpretation of deformation monitoring.

1. INTRODUCTION

In many landslide situations, an aspect of particular concern is not only whether movements will occur but what rates of movement are to be expected, in order to ascertain if the degree of slide mobility could present a hazard. This article attempts to collate known and conjectured mechanisms for rapid failure of slopes, to provide a rational basis for assessment of active or potentially active landslides.

2. BASIC CONCEPTS OF SOIL FAILURE

2.1 Peak and residual effective strengths.

The concepts of peak and residual strengths of soil have been discussed by Skempton (1964). Depending on the initial structure of the material, there will exist a greater or lesser separation of the peak and residual strength envelopes. Any displacement of a "first time" slide will result in a transition from the peak, towards the residual strength, leaving a net accelerating force acting on the slide mass.

Skempton (1977) suggests that movements totalling about 1 or 2 metres may be required to achieve residual strength in fine grained soils. Accordingly, the most convenient means of simulating this condition has been in a ring shear apparatus (Bishop, 1971) in which an annulus of soil may be subjected to indefinitely large displacements.

2.2 Rate dependence of residual strength.

Skempton and Hutchinson (1969) note that the strength of soils is dependent on shearing rate even when these rates are slow enough to permit full drainage. A value of about 1% increase in strength per tenfold increase in strain rate was obtained in strain controlled ring shear tests. Because landslide behaviour is stress controlled rather than strain controlled, it may be argued that Skempton and Hutchinson's data might be replotted with shear stress as the abscissa (independent variable), as shown on Figure 1.

Further results have come from stress controlled ring shear tests on schist-derived gouge from landslides in Otago. For both sands and plastic soils, strained to the residual strength condition, generally similar results were obtained, ie the nature of curve A - B (Figure 1) was confirmed. However, if the shear stress was reduced (effective normal stress being held constant) until all movement ceased (B on Fig. 1) then a significantly higher shear stress was required in order to reactivate movement (point C). Very slow creep displacement rates could then be achieved by subsequently reducing the shear stress. Obvious analogies for this aspect of soil behaviour are the thixotropy of gels and the accepted differences between static and dynamic coefficients of friction for solid surfaces.

Figure 1 gives explanation for three significant features of landslide mobility:

(i) Successive "stick-slip" movements are to be expected in a residual strength slide where the factor of safety is being slowly reduced (eg by river erosion of the toe).

(ii) If a small percentage (1 or 2%) decrease in the factor of safety occurs in a slide which is creeping slowly, the result is an

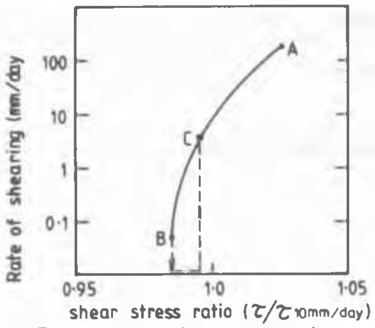

Figure 1. Rate dependence on shear stress. in stress-controlled apparatus.

acceleration until the displacement rate mobilises the appropriate higher strength.

(iii) Following from (ii), if shear stresses approach failure in a homogeneous, normally consolidated soil, greater strength will be shown by the elements through which incipient displacement is occurring thus favouring the failure of a zone of soil rather than a discrete failure surface, at least for initial movements. This aspect is discussed further in Section 4.3.4.

3. DISPLACEMENT-INDEPENDENT ACCELERATING MECHANISMS

Many external factors acting independently of slide displacement can affect the resultant force acting on a slide mass (Terzaghi, 1950). In general these factors (eg change in submergence or groundwater, redistribution of mass etc) occur slowly and more predictably than displacement dependent accelerating mechanisms (which will be discussed in detail).

4. DISPLACEMENT-DEPENDENT ACCELERATING MECHANISMS

Those factors which decrease the available resistance of a soil along a slide failure surface while displacement progresses, provide the potential for rapid movement when accelerating forces are left unbalanced. A discussion of soil characteristics which may provide displacement dependent accelerating mechanisms follows.

4.1 Reduction of effective cohesion.

Reduction or elimination of effective cohesion is the most obvious source of significant loss in strength. Failure may be very brittle with little warning, when a large proportion of available shear resistance is cohesive.

Cohesion may be present in soils previously at residual strength (with c = 0) through dessication, which has been demonstrated to create effective as well as apparent cohesion, (Allam and Sridharan, 1981).

4.2 Reduction of effective friction.

4.2.1 Peak to residual strength.

In dense sands or overconsolidated cohesionless soils, the "density component" of strength (Cornforth, 1973) can equal more than 30% of the available peak strength, allowing rapid failure after initial movements have increased the void ratio to its critical value. Normally consolidated clays can show similarly large differences between their peak and residual strengths, as platy minerals become aligned parallel to the direction of shearing.

4.2.2 Mechanical attrition.

Granular materials composed of weak rock and subjected to moderate or high normal stresses will suffer particle breakdown in shear until a sufficient matrix of fines is created to "cushion" any further degradation. Formation of such gouge invariably results in a decrease of available frictional resistance.

4.3 Increase in pore fluid pressure.

4.3.1 Shear contraction.

Excess pore pressure, resulting from densification of a soil that is above its critical void ratio, has been the mechanism involved for many catastrophic slides in both granular and cohesive 'quick' soils, eg the Aberfan disaster (Bishop, 1969).

4.3.2 Monotonic loading.

Landsliding is generally a slope reducing process which transfers load from the head of a slope to the toe. This process of slope adjustment causes a general reduction in shear stress within the soil and particularly to the soil located beneath the failure zone. If this soil is a dense granular material which was previously subjected to at least a moderate degree of shear mobilisation, the pore pressure parameter A (Skempton, 1954) would be negative, regardless of the amount of shear stress reduction (as opposed to the more common case of a reversal of the sign of A under increasing deviatoric stress). This concept was investigated in the laboratory. Figure 2 shows the stress path for a dense sand which was sheared in a drained triaxial test until a high degree of shear was mobilised and the sample was dilating rapidly. The deviatoric stress was then removed in an undrained test (to simulate rapid unloading). The resulting pore pressures were small but positive.

Skempton's B parameter also provides an explanation for pore pressure rises within a failure zone. For a typical slide, the geometry of the failing mass involves a thickening from the toe to the central regions. In the vicinity of the toe of such a slide, an element of soil close beneath the failure surface will be subjected to an increase in total confining pressure as displacements take place. Since B is always positive, any saturated or near saturated soil elements, regardless of their relative density, will incur significant excess pore pressures which can then be transmitted to the overlying failure surface.

Pore pressure responses of this nature would be most marked where failure is taking place in a low permeability soil underlain by fully saturated material.

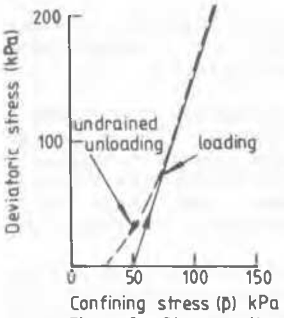

Figure 2a. Stress path

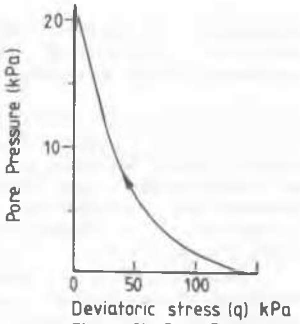

Figure 2b. Pore Pressure

Figure 2. Response of dense sand to unloading

A feature of slides which have been subjected to excess pore pressures induced during sliding is that they can only be arrested naturally by a change in slide geometry (mainly self-buttressing at the toe) which is significantly more effective than the geometry required to counter sliding in the absence of excess pore pressures. It follows that on coming to rest, the long term factor of safety of such a slide (after pore pressure dissipation) may be substantially greater than unity.

The East Abbotsford landslide (Salt et al, 1979) is a suggested example where undrained response of dense saturated soils contributed to unexpected acceleration.

4.3.3 Cyclic loading.

Pore pressure increases in both granular and cohesive soils have often been demonstrated during cyclic loading. An undulating failure surface could induce densification of either material within a slide (through cyclic shear in the vertical direction) or material beneath the failure surface (through cycling of the effective normal stress). Either case may allow transmission of excess pore pressures to the failure zone.

4.3.4 Frictional heating.

Pore pressure increase through vaporisation of fluid has been suggested as the mechanism for rapid accelerations at Vaiont, (Voight and Pariseau, 1979). However, because the coefficient of thermal expansion of water is about 8 times that of common rock forming minerals, it may be considered that even minor frictional heating without the extreme case of vaporisation could cause significant excess pore pressures.

When verifying the data in Figure 1 with the stress controlled shear apparatus, it was noticed that with low permeablility soils subject to sudden shear stress increments (of about 3% or more), acceleration from the yield state to rapid velocities (greater than lm/sec) occurred, usually within 10 seconds. The superposed shear was then removed but stable conditions could not be readily restored. Substantial reductions (30% or more) of the shear stress level were necessary to restore creep displacement. However after sufficient time the original shear stress could again be sustained. As this effect is most readily explained by frictional heating of pore fluid, this effect was examined further. The shear cell was adapted to take a heating element which for practical reasons had to be located closer to the base drainage platten than to the centre of the shear zone. Efficiency was hence in doubt but the effect of pore fluid heating could be crudely investigated. Figure 3 shows the comparative effects that can be obtained by heating indirectly (through friction) or directly with a similar quantity of energy applied through the heating element. For the saturated, low permeability clay tested, heat was applied at a very low intensity with convincing results.

The aspect of note with regard to increase in shear stress or fluid heating is that the rate of introducing energy must be short with respect to the soil permeability and boundary drainage conditions. If the velocity of a slide is made to increase gradually (Figure 3b) a new temperature differential from the failure zone to the surrounding soil will become established so that at no time do significant excess pore pressures develop. Excess pore pressure is dependent on a sufficiently rapid energy increment.

Thus it is apparent that a slide undergoing an acceleration for any reason will incur some frictional heating with accompanying pore pressure increases. These in turn create a greater difference between slide driving and resisting forces and lead to further acceleration.

It may be concluded that while some soils fail in a zone rather than a discrete surface, if

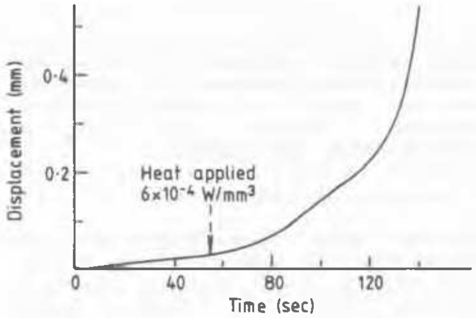

Figure 3a. Electrical heating

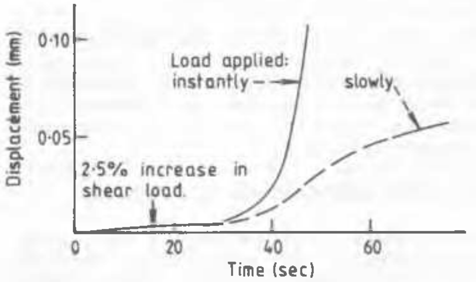

Figure 3b. Frictional heating

Figure 3. Heating effects in low permeability soil in stress controlled ring shear

the failure zone is sufficiently restricted, then frictional heat will be confined to a small volume of soil where higher temperatures and excess pore pressures will act. The worst conceivable situation for the frictional heating mechanism is in a sequence where a thin layer of low strength material lies between layers of significantly higher strength . Such layering prohibits failure of a thick zone (Section 2.2).

For this mechanism to operate, a suggested dimension for the "thin" layer is where the failure zone is about 3 or more orders of magnitude smaller than the average overburden thickness.

As well as at Vaiont, the pore fluid heating explanation may have contributed to the accelerations of the Goldau Slide (Terzaghi, 1950) and the East Abbotsford Slide.

4.4 Coalescence of multiple slides.

When a group of individual slides merge to form common boundaries, lateral shear restraint reduces giving a means for sudden increase in the resultant accelerating force. An example is given by the Lower Baker Slide (Peck 1967).

4.5 Development of internal deformations.

The concept of internal deformations required for movement of non-circular slides has been discussed by Karal, (1979). This can lead to rapid movement if the deforming slide mass is brittle or contains saturated soil exhibiting a positive value for Skempton's A parameter. A lurching response ("stick-slip") results if the material is a low permeability saturated soil with negative A value.

4.6 Unstable failure surface geometry.

A slide containing non-homogeneous material and having a general failure surface profile which is upwardly convex, can present an unstable situation where the factor of safety decreases with displacement because the average inclination of the slope increases.

4.7 Secondary accelerating mechanisms.

Various mechanisms have been postulated to explain the very rapid movement of the Vaiont Slide, eg. hydrodynamic wave pressures (Corbyn, 1982); aquaplaning (Trollope, 1980); fluid vapourisation (Habib, 1975) and fusion (Erismann, 1979).

In most cases, velocities must be substantial before the above mechanisms can operate. Primary acceleration mechanisms are therefore regarded as being sufficent to create a hazardous situation (regardless of aggravation by secondary accelerations).

5. INFERENCES FROM 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, some warning movements typically occur. Terzahgi (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".

Consideration of events preceding the Vaiont Slide and two recent catastrophic slides in New Zealand (East Abbotsford and Ruahihi) suggests that techniques for interpretation of surface deformation monitoring have not been well documented. Three aspects requiring consideration are:-

(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,
(b) whether a significant non-circular motion is occurring and
(c) whether regressive 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 earlier. Some attempts have been made (unsuccessfully) to predict rapid failure from displacement criteria (Voight and Kennedy, 1979). In general, this approach will be unreliable.

(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 permeablility of the failure zone is of particular importance). Downslope velocities of 100 mm/day were achieved by the Vaiont, East Abbotsford and Ruahihi Slides (NZGS, in prep) 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 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. It follows that adequate monitoring of landslide movement requires successive differentiation of the displacement - time record to obtain both velocity and acceleration.

This is essential in any instance where the displacement-time curve exhibits a concave upward shape. A good example of such forewarning (with the benefit of hindsight) is given by the detailed displacement monitoring carried out for the East Abbotsford Slide. Successive differentials for the latter (Figure 4) 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. The movement record of the Vaiont Slide may be differentiated similarly to reveal a concave upward acceleration record for the two weeks immediately preceding the catastrophic failure. Comprehensive survey monitoring is not available for the Ruahihi Slide (final readings were at weekly intervals). However, approximate interpolation suggests a concave upward acceleration curve may have been taking place for 10 days prior to the rapid failure

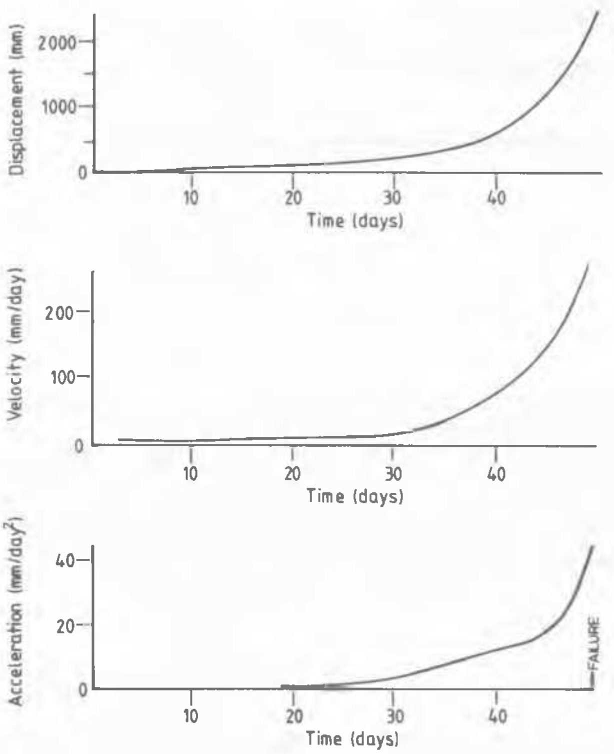

Figure 4. East Abbotsford Slide: Movement History.

(NZGS in prep.). This example highlights the need to provide sufficient survey data to determine the acceleration characteristics continuously at any stage when a hazardous slide is experiencing positive acceleration.

6. CONCLUSIONS

In establishing a policy for rational evaluation of marginally stable slopes, this discussion has endeavoured to collate known and conjectured means whereby catastrophic rates of movement could occur. While it is not possible to establish that this list of mechanisms is exhaustive, all rapid slides reviewed during the preparation of this article can be explained by conditions favouring one or more of these mechanisms.

An ideal slide which provides no attributes likely to cause rapid failure must be subject to only small increments in external forces and exhibit all of the following:-

i) thick, permeable shear zone which has no irregularities and is at residual strength;

ii) unchanged history (since the previous movement) with respect to effective stresses on the failure zone;

iii) stable failure surface geometry (concave upward) with no capacity for coalescing with adjacent slides;

iv) no capacity for development of unfavourable internal deformations.

To some extent, the potential for displacement dependent accelerating mechanisms may be quantified using standard techniques for pore pressure response under undrained loading, and by determining response to stress controlled ring shear. Further research using the latter is in progress to determine empirical criteria for predicting rapid failure from shear zone thickness, velocity and acceleration characteristics.

A review of some catastrophic slides for which deformation monitoring is available suggests that landslide mobility may be most rationally assessed through examination of all possible accelerating mechanisms, particularly those which are displacement dependent. Predicted behaviour may best be confirmed by due consideration of displacement, velocity, and most particularly, acceleration characteristics determined from downslope deformation vectors.

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