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TIDAL INFLUENCE ON THE INTERMITTENT SURGING MOVEMENTS OF A COASTAL MUDSLIDE

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At West Down Beacon near Budleigh Salterton the recession of the cliff top has some control over the movements of the mudslide at its base. Originally the intermittent surges of the mudslide could all be correlated with large-scale collapses of the conglomerate which forms the upper part of the cliff. Observations of the mudslide since 1985 have shown that similar surging movements can occur without any obvious external cause: the implication is that internal changes, taking place over a period of time, are capable of producing effects similar to those resulting from cliff falls. The detailed records of instrumented displacements obtained from two of the surges have promoted discussion of the relative importance of the destabilising factors. It has been established that, in stormy conditions, the tidal cycle can influence the triggering of the mudslide and its acceleration and deceleration during a surge. The improved understanding should lead to better prediction of those surges which do not have an obvious external trigger.

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INTRODUCTION

Investigation of the landslide at West Down Beacon (Figure 1) started in 1979. Between then and 1992 there had been thirteen surges of the mudslide at the base of the cliff, each surge characteristically involving a displacement of about 10 m. Between 1979 and 1984 all the surges could be associated with obvious external causes: large-scale rockfalls which fell directly onto the mudslide. When such a fall impacts onto the mudslide there is no time for drainage and the new load represents *undrained loading* (Hutchinson and Bhandari, 1971), being at first carried almost entirely by an increase in pore-water pressure. Until the pore-water pressure can dissipate there can be no increase in intergranular contact pressure (effective stress) within the mudslide. Without an increase in effective stress there is no means of mobilising the shearing resistance necessary to counter the increased shear stresses which result from the greater load on the head of the mudslide.

In spite of a reduction in the frequency of large-scale rockfalls, surging of the mudslide has continued. It has become clear that the surges can also be triggered by factors other than rapid loading of the head of the mudslide. Two surges, which were initiated without there being any obvious external cause, occurred while the mudslide was instrumented and the records from the data loggers examined as part of a continuing investigation into the mechanics and causes of the surges.

THE LANDSLIDE AND ITS GEOLOGICAL SETTING

The landslide and its geological setting have been described in detail elsewhere (Henson, 1971; Kalaugher and Grainger, 1981; Grainger and Kalaugher,1987a and b; Hodgson, 1993) so only an outline description and pertinent details will be given here. The landslide affects a sequence of Permo-Triassic strata in the coastal cliffs at West Down Beacon, approximately 2 km west of Budleigh Salterton in east Devon (Figures 1 and 2). At their highest point the cliffs are almost 130 m high with 110 m of a predominantly non-durable calcareous mudstone (the Littleham Mudstone) overlain by a 20-m thickness of weakly cemented sandy conglomerate (the Budleigh Salterton Pebble Beds). The essential features of the landslide are that it is made up of rockfalls from the main cliffs which feed, either directly or indirectly, to a mudslide which is found to extend from the foot of the main cliffs to the storm beach. Indirect addition of material to the mudslide is through the action of mudflows derived from mudstone debris. The rockfalls, mudflows and mudslide are described below in separate sections.

Rockfalls

Rockfalls are responsible for most of the erosion of the conglomerate and mudstone from the cliff face. They are preferentially developed where there are seepages of groundwater: at these locations the rockfalls from the conglomerate are initiated by seepage erosion while those from the mudstone are also associated with gullying. The weakly cemented conglomerate is brittle but not fissured and there is little or no prior deformation at the cliff top to give warning of impending rockfalls. Blocks of intact material are almost in "free fall" as they travel down the cliff face. They disintegrate on reaching the foot of the cliff and the conglomerate-derived pebbles avalanche to form debris fans of granular material. There have been occasions when massive falls from the conglomerate have spread out onto the surface of the mudslide in the form of air-entrained debris flows (Shreve, 1968).

Rockfalls from the mudstone may be on a small or large scale and involve just a few or several hundred blocks (ranging in size up to 500 mm). These rockfalls most often occur when wet conditions, typical of the winter, are followed during early spring and summer by a period of drying which causes shrinkage and loosening of the surface layer of mudstone on the cliff face.

Mudflows

Mudflows form from the weathering and degradation of mudstone in the debris fans which accumulate at the base of the main cliff. Hodgson (1993) has shown how a certain range of plasticity index values (12.3 - 14.2%) is beneficial to the development of slurries and has described the mechanism by which mudstone remaining outside this range resists degradation and persists as clasts. The mudflows which originate in the debris fans close to the mudslide are liable to flow onto its surface from the flanking mid-cliff ledges, transporting mudstone clasts and conglomerate debris (Figure 2).

The mudslide

The mudslide consists of a mixture of mudflow debris and the relatively unaltered products of rockfalls from the mudstone and the conglomerate. It moves as a coherent unit that is about 100 m in length and between 10 and 15 m thick. It is about 30 m wide, with well-defined boundaries where it cuts through the mid-cliff ledge area, but spreads out as its lobate toe approaches the beach. A salient feature of the mudslide is that the shear zone at its base has a steeper inland section and a more shallow seaward section (Figure 3).

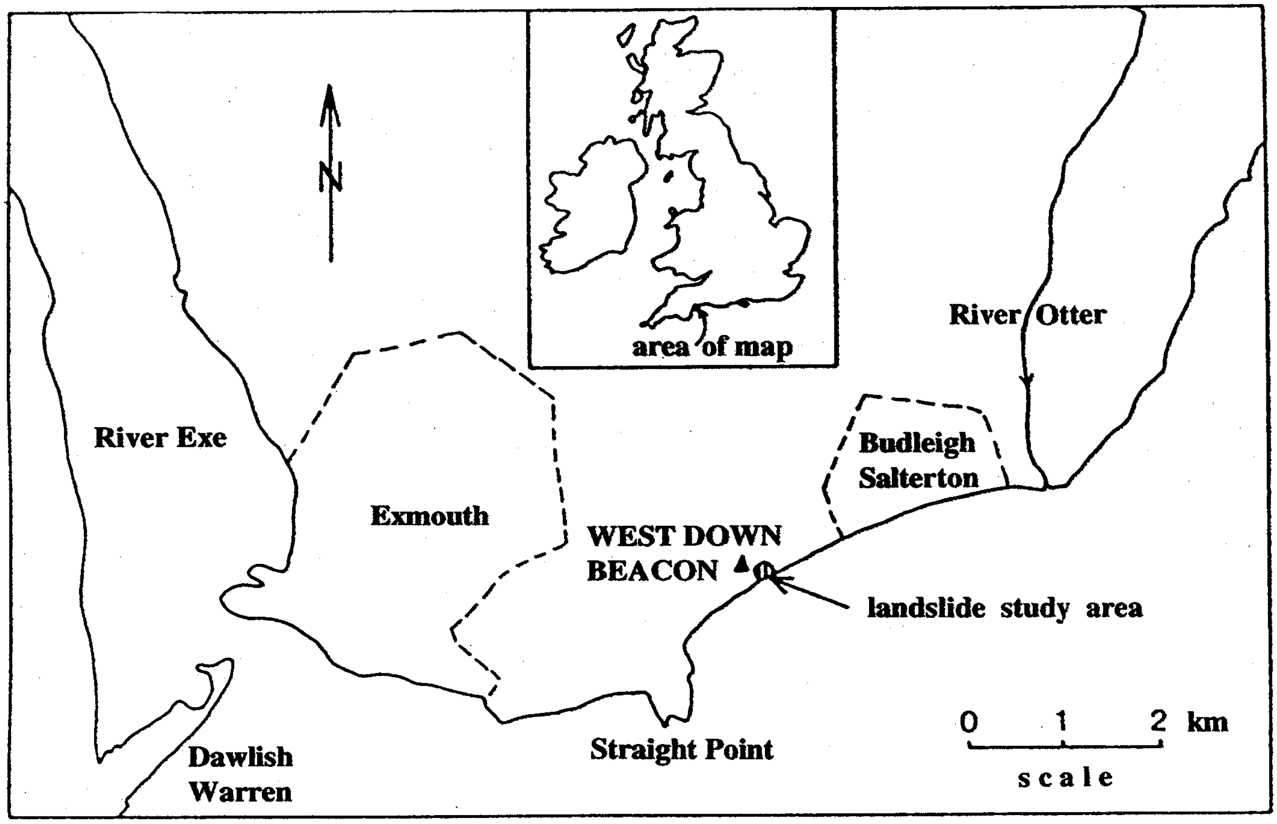

Figure 1: Location of the west Down Beacon landslide.

SELECTED FACTORS WITH VARIABLE EFFECT ON THE STABILITY OF THE MUDSLIDE

Selected factors which affect the stability of the mudslide are described together with an indication of how they vary when the mudslide is dormant and when a surge is in progress.

Progressive loss of strength

The mudstone-derived soil, while moving towards the mudslide, will have its strength reduced in response to the increases in plasticity indices resulting from weathering and degradation. During mudslide movements any local re-routing of shearing to paths not previously involved in shearing will also result in progressive loss of strength, with the residual values being reached after relatively small displacements (Hodgson, 1993). However, the greater part of the shearing zone beneath the mudslide will have been involved in previous surges and, when movement is reactivated, will already be at residual values.

The strength of the shearing zone can also be altered if the relative proportions of fine- and coarse-grained material fed to the mudslide change over a period of several years. There will eventually be changes in both the composition of the lower levels of the mudslide and the available shearing resistance which can be mobilised. If the granular component decreases to the extent that the shearing zone can readily be located entirely in weathered and degraded mudstone there will be a reduction in available resistance.

Loading of the head and neck of the mudslide

The rate of loading of the head of the mudslide by rockfalls, whether from the conglomerate or the mudstone, depends on the magnitude and frequency of the falls. Those from the cliff immediately above the mudslide fall directly onto it, the sudden increase in loading representing undrained loading on the head of the mudslide. As a result of changes in the points of discharge of groundwater from the base of the conglomerate there have been fewer large falls from the conglomerate in recent years but rockfalls from the mudstone have continued although not many have fallen directly onto the mudslide (Hodgson, 1993).

A rather slower rate of loading of the head and neck of the mudslide will result from the cumulative effects of several much smaller rockfalls and when there are mudflows from the flanking mid-cliff ledges. Under these conditions a given increase in loading will not lead to a significant increase in pore-water pressure as there will be time for dissipation as the load builds up.

Any increased loading on the head and neck of the mudslide will increase the shear stresses throughout the shearing zone. The shear stresses will diminish as the mudslide moves because weight will be redistributed from the head area with its relatively steeply inclined basal shear zone to the generally lower-angled slope of this zone near the toe.

Changes in groundwater level

A rise in the level of groundwater within the mudslide will lead to increased pore-water pressures and hence to reduced effective stresses. Groundwater levels are generally higher during the winter months and the general rise in levels is assisted by ponding and infiltration. The levels may be lowered during movements of the mudslide if drainage is temporarily enhanced by fissuring.

Suction of pore water

Effective stresses in the matrix of the mudslide are increased by suction of pore water from the matrix into the clasts. Hodgson (1993) described a state of transient moisture equilibrium which exists within a heterogeneous mixture of clasts and degraded mud. Any alterations in stress regime in the mixture readily disturb the equilibrium, and moisture will either be sucked into or expelled from the clasts. It is postulated that the local fluctuations in shear stress during a surge may

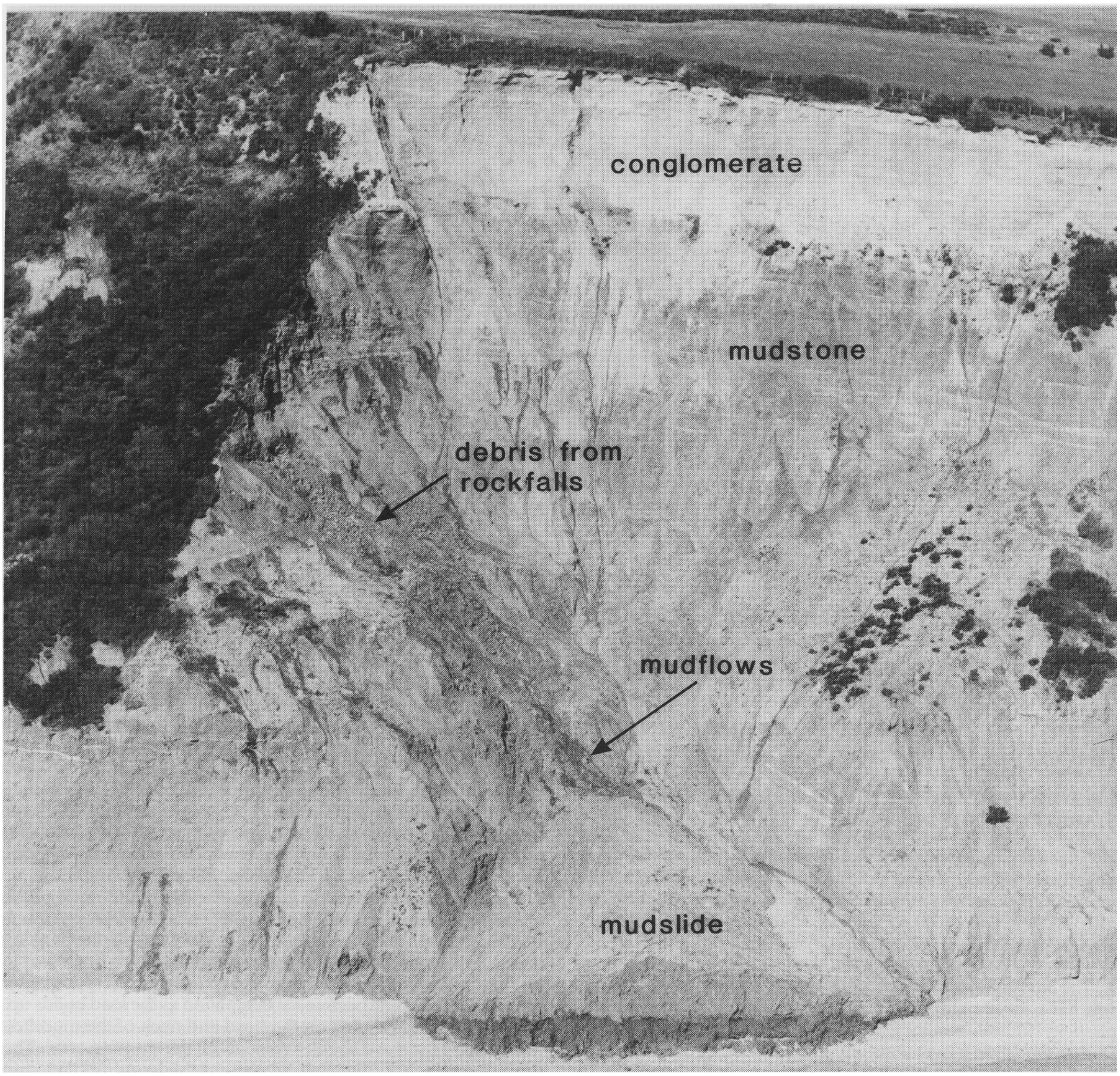

Figure 2: Oblique aerial view showing the landslide area in the middle of the picture with the toe of the mudslide extending onto the beach. Photograph by J. Saunders on 24th April, 1985, 17 days after the first of the instrumented surges referred to.

lead to stabilisation of the mudslide as transient pore suctions are exerted by the included clasts.

Wave action at the toe of the mudslide

The stability of the landslide will be adversely affected by effective stress variations in the shearing zone near the toe. These are caused by cyclic changes in pore-water pressures resulting from wave action at times when waves are able to impact against the toe of the mudslide. The pore pressures are affected directly by the varying water level and by direct impact of the breaking waves, with undrained loading both from water and from the pressure of entrapped air.

Rough seas will erode the toe of the mudslide, the release of blocks of debris being assisted by the increased pressure of water and entrapped air. Erosion has a destabilising effect on the mudslide through removal of weight from the toe area and by enabling the pore-pressure fluctuations to penetrate further into the shearing zone.

The detrimental aspects of wave action seem to dominate any stabilising action from increased hydrostatic pressure against the toe. All of the detrimental aspects will be enhanced when storms coincide with higher tidal levels and will be effective for more of the tidal cycle as the mudslide toe is pushed towards the sea during a surge.

Resistance of the storm beach

The basal shear zone of the mudslide normally terminates below the level of the storm beach (Figure 3). As the mudslide moves forward, the cobbles and pebbles on the beach are pushed up, with consequent increase in resistance as the mudslide's displacement increases.

SURGES

The main movements are best described as surges in which the

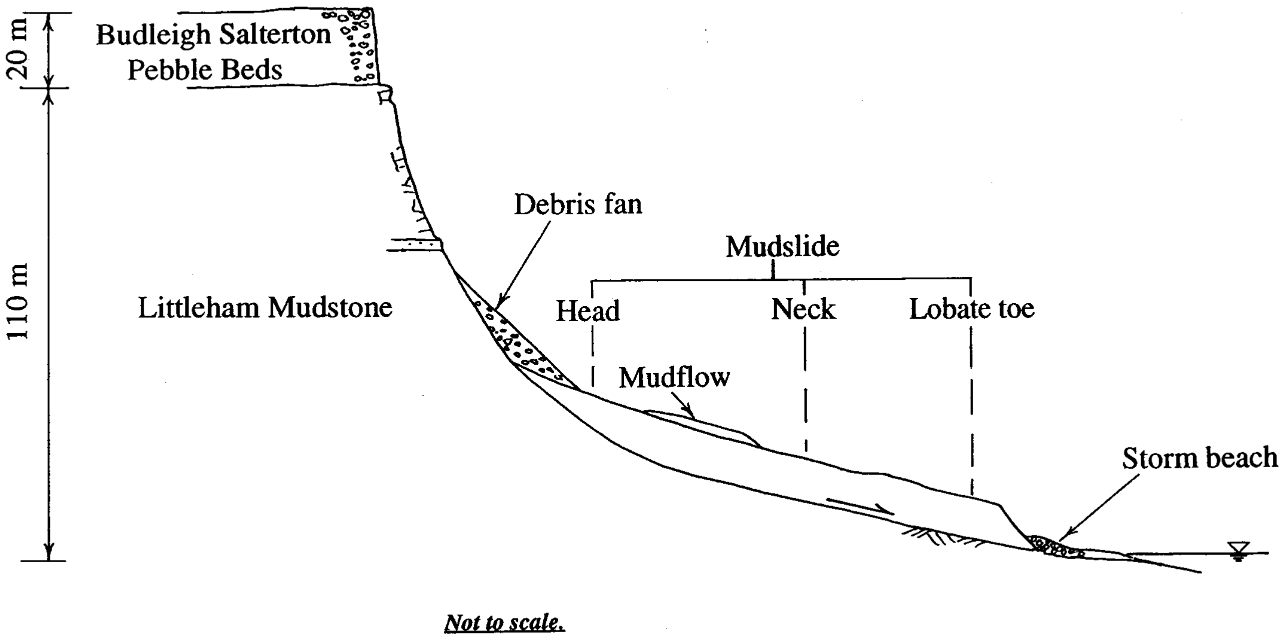

Figure 3: *Diagrammatic cross-section through the landslide to show the main features. A mudflow from a flanking mid-cliff ledge is shown on the neck area of the mudslide.*

mudslide moves characteristically about ten metres in a single event over a period of one or two days. There are occasional minor creep movements in between the main surges but almost all of the cumulative displacement of the mudslide can be accounted for by its characteristic surges. There have been fewer surges since 1985 when rockfalls from the conglomerate became rare.

The instrumented surges

Two different designs of displacement gauge linked to a data logger have been used at different times to give details of the movement of the mudslide. The data loggers were concealed on the mid-cliff ledge and actuated by a line attached to a peg on the surface of the mudslide. The withdrawal of the line from its reel was recorded and the plots drawn from the data corrected to give the displacement of the surface of the mudslide towards the sea (Figure 4). The first data logger yielded results for the whole of the surge of 7th April 1985 which was completed within a single tidal cycle (Grainger and Kalaugher, 1987b). The second data logger gave results for the greater part of the surge of 6th and 7th February 1990 which was moving for more than two tidal cycles (Hodgson, 1993). Both surges occurred during stormy weather with strong on-shore winds conducive to the formation of large waves and neither was triggered by a large-scale rockfall.

It can be seen in Figure 4 that the plot of displacement against time has a steeper slope at times of high water than at low water. The evidence for dependence on tidal and wave effects is compelling for the faster surge (1985) and enables the more subtle variations in slope of the slower surge (1990) to be recognised as also varying with the tidal cycle.

DISCUSSION

Kalaugher and Grainger (1981) established that undrained loading could be responsible for triggering surges of the mudslide. The obvious external cause was the relatively rapid loading of the head of the mudslide when a large-scale rockfall from the conglomerate occurred. It is recognised, however, that a larger but slowly accumulating load, with time for pore-pressure dissipation, could equally lead to instability and trigger a surge.

Now that rockfalls from the conglomerate are rare the mudslide consists of a greater proportion of mudstone with its reduced shearing resistance and, with fewer surges, there is time for weathering and degradation to continue in the intervals between surges.

The data logger results have given an extremely valuable extra dimension to the understanding of the mudslide. If the mudslide is known to be accelerating and decelerating in sympathy with the tidal cycle the implication is that the factor of safety is taken above and below unity (Grainger, 1990) by tidal and wave effects even in the later stages of a surge when the load at the head of the mudslide is much reduced. Tidal effects have only to be responsible for the factor of safety being taken below unity at the beginning of a surge for them to qualify as the triggering mechanism. The factors of safety can never have been very far above or below unity at any time or the influence of tidal control would not be so marked. It is noteworthy that since 1985, in the absence of replenishment by large-scale rockfalls, each successive surge has been initiated with progressively less and less build-up of debris on the head of the mudslide.

Both of the instrumented surges responded to the tidal cycle with greater velocities being achieved during the higher stages when the higher pore pressures and the wave effects were able to destabilise the toe. Both surges had overall displacements of comparable amounts indicating that after a certain displacement there was sufficient redistribution of weight and sufficient resistance caused by ploughing of the beach for the mudslide to stop moving. With its overall greater rate of displacement the 1985 surge was completed within one tidal cycle whereas, with lower velocity, the 1990 surge continued for rather longer before sufficient displacement was achieved. The increased internal disturbance during the more rapid movement would also have increased the suction of pore water from the fine-grained matrix soils, further inhibiting reactivation during the next high tide.

The surges can be predicted to some extent when undrained loading of the mudslide head is not the trigger. The large-scale rockfalls occurred at any time of year whereas the surges triggered in other ways seem to be much more likely during the winter months when groundwater levels are high and there is a greater chance of storm conditions coinciding with high tides. Because of the steady accumulation of debris at the head of the mudslide, the chances of a surge are greatly increased if there has not been a surge for several months.

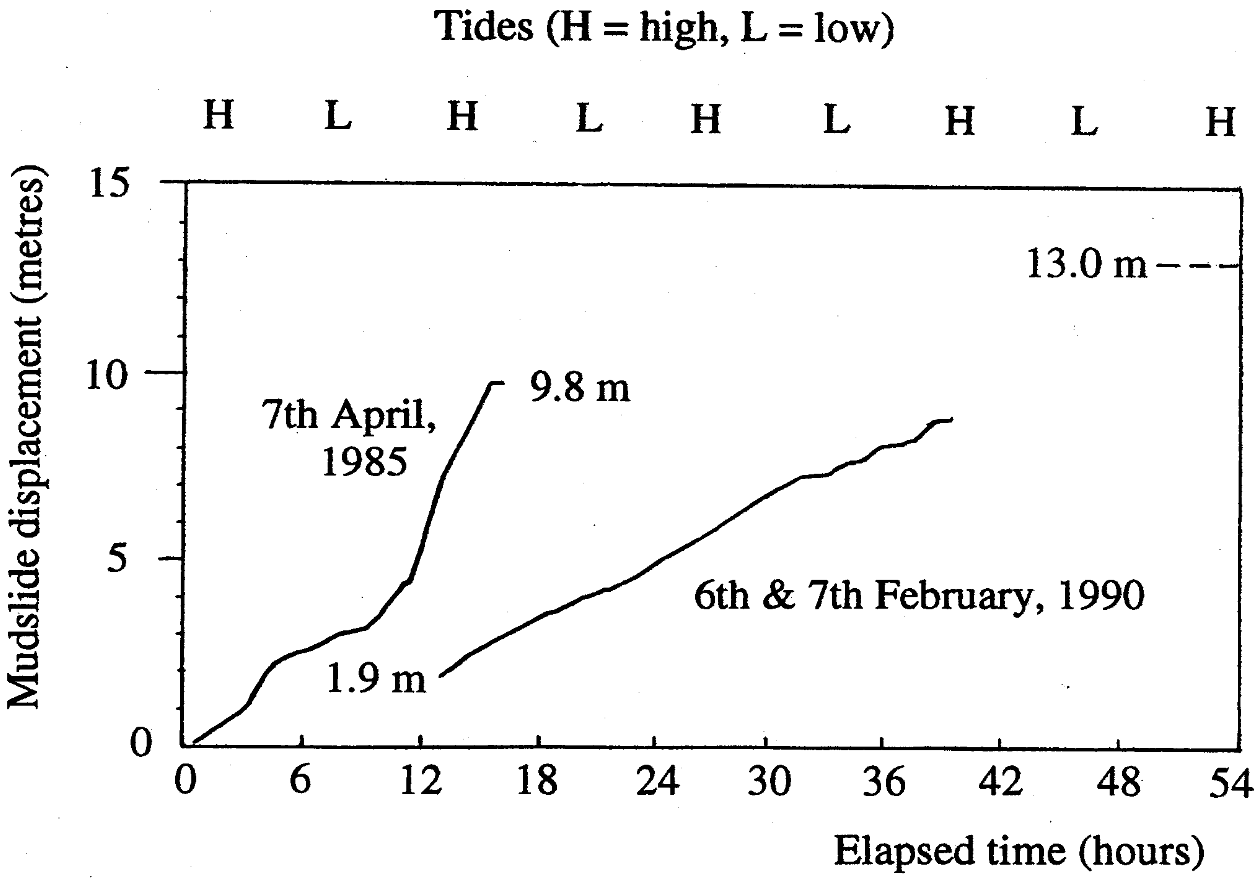

Figure 4: Plots of mudslide displacement against time for the surge of 7th April 1985 and the surge of 6th and 7th February, 1990. An indication of the position in the tidal cycle is given.

CONCLUSIONS

The influence of the tides and waves would not have been recognised without the knowledge of the dates and the timings of the surges provided by continuous data logging. Firm evidence points to triggering by high tidal levels with the assistance of storm wave action.

Since 1985 the landslide appears to have entered a phase in its history when large-scale rockfalls are much less common, possibly as a result of changes in the discharge points of groundwater from the base of the conglomerate. Between 1979 and 1984, large-scale rockfalls were more frequent than in later years and tended to dominate as the triggering mechanism, the factor of safety being lowered to below unity by the immediate and relatively powerful effects of undrained loading, apparently without significant assistance from other destabilising factors. The opportunities for tidal triggering were suppressed because the factor of safety between surges was markedly above unity, at least just beyond the ability of tidal and wave effects to lower it to below unity. The predominance since 1985 of surges that were not initiated by undrained loading indicates that, given time, the gradual reduction in strength of the shearing zone by long-term degradation can lower the factor of safety to the extent that tidal fluctuations and wave effects are able to trigger a displacement. That surges occur with less and less build-up of load at the head of the mudslide is further evidence of progressive reduction in strength of the shearing zone with time.

With regard to hazard assessment, if there has not been a surge for several months and major rockfalls from the conglomerate above the mudslide continue to be rare, surges are most likely when storm conditions coincide with high tidal levels in the winter months. There was a lesser degree of predictability when large-scale rockfalls were more frequent as they are able to initiate surges at any time of the year.

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