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THE RELATION BETWEEN COASTAL LANDSLIDE ACTIVITY AT PINHAY, EAST DEVON AND RAINFALL AND GROUNDWATER LEVELS

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Part of the water supply for Lyme Regis is abstracted from a spring at Pinhay in the zone of coastal landslides (undercliff) to the west of the town. This source is at risk from movements of the landslide and the supply was interrupted during the winter of 1993-94 (Grainger and Kalaugher, 1995). Further landslide activity of similar scale occurred during the 1994-95 winter, again after abnormally high winter rainfall. A high level of groundwater in a nearby borehole was reported and it later became clear that the main landslide displacements had both occurred at times when the groundwater level in the borehole was rising at its most rapid rate.

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INTRODUCTION

Increased landslide activity affecting the water supply from a spring source in the undercliff at Pinhay, Lyme Regis (Figures 1 and 2) was reported in Grainger and Kalaugher (1995). In the first significant reactivation of landsliding here since 1961, the extensive slipped masses which form the slope above the pumping station sustained relative movements of up to 400 mm and these movements were consistent over scarp lengths of up to 1 km. The landslide movements were likely to have been triggered by the very high rainfall on the night of 22/23 February 1994, which followed a very wet autumn and winter period (in the previous six months the rainfall totalled 856 mm compared to a long-term average for those six months of the year of 533 mm). The high rainfall was assumed to have raised groundwater levels, resulting in high pore pressures on the basal sliding surface and reducing shearing resistance to the point of instability. After presentation of those findings further extensive movements were recorded in February 1995, again after abnormally high rainfall in the autumn and winter period of 1994-95 (776 mm in the previous six months, that is 146% of the long-term average). A record of groundwater levels in a borehole has enabled the timing of the landslide activity to be related to changes in groundwater level a short distance inland from the coastal slope. The use of electronic distance measuring (EDM) equipment has allowed the overall displacements of the landslide in 1995 to be quantified.

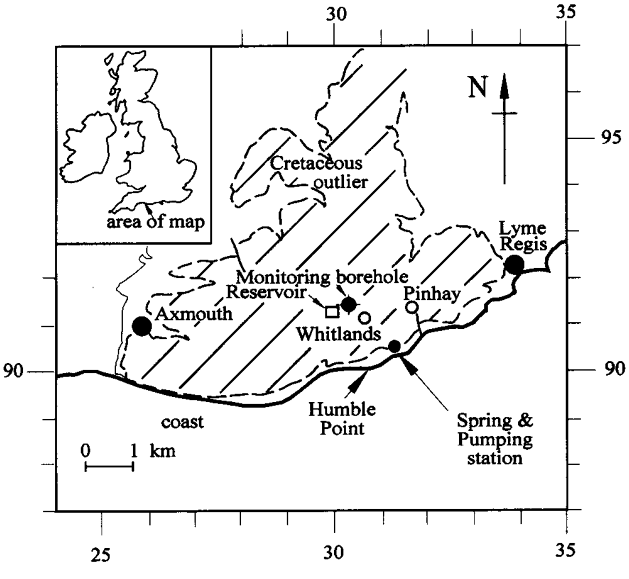

Figure 1: Location of the Pinbay landslide.

OUTLINE OF THE GEOLOGY AND LANDSLIDING

All the geological formations in the area are virtually horizontal where undisturbed by landsliding. The succession of formations from sea level to the plateau at the top of the cliff is shown in the cross-section of the landslide (Figure 3). The individual formations are mentioned in more detail in the description of the landsliding.

Between Seaton and Lyme Regis there are deep-seated landslides along most of the 9 km length of coast. For part of the length there are steep, and relatively stable, sea cliffs of Lias or Mercia Mudstone, above which there is landslipping of the Cretaceous strata creating a series of scarps extending back to the edge of the Chalk plateau forming the immediate hinterland. The remainder of the coastline has only minor sea cliffs, mantled by landslide debris, or no sea cliffs where landsliding has involved the Liassic as well as the Cretaceous rocks. Around the Pinhay area the plateau is fronted by a coastal slope which, for descriptive purposes, can be divided into an upper steeper zone and a lower flatter zone (Figure 3). The upper zone, between the plateau and the spring just upslope from the pumping station, is referred to as the "deep-seated landslide" and is formed of extensive slipped masses, the products of multiple rotational retrogressive landsliding. Seaward of the deep-seated landslide the lower zone, extending down to the beach and including the spring and the area around the pumping station, can be thought of as part of the toe of the main landslide. The lower zone forms in its own right a landslide within the landslide complex and is referred to as the "shallow debris slide".

The debris slide, which fronts the deep-seated landslide over only a limited part of its width, moves over a stepped surface eroded into Blue Lias bedrock and contains a relatively thin layer of landslide debris from the Chalk, Chert Beds, Foxmould and Gault (Figure 3).

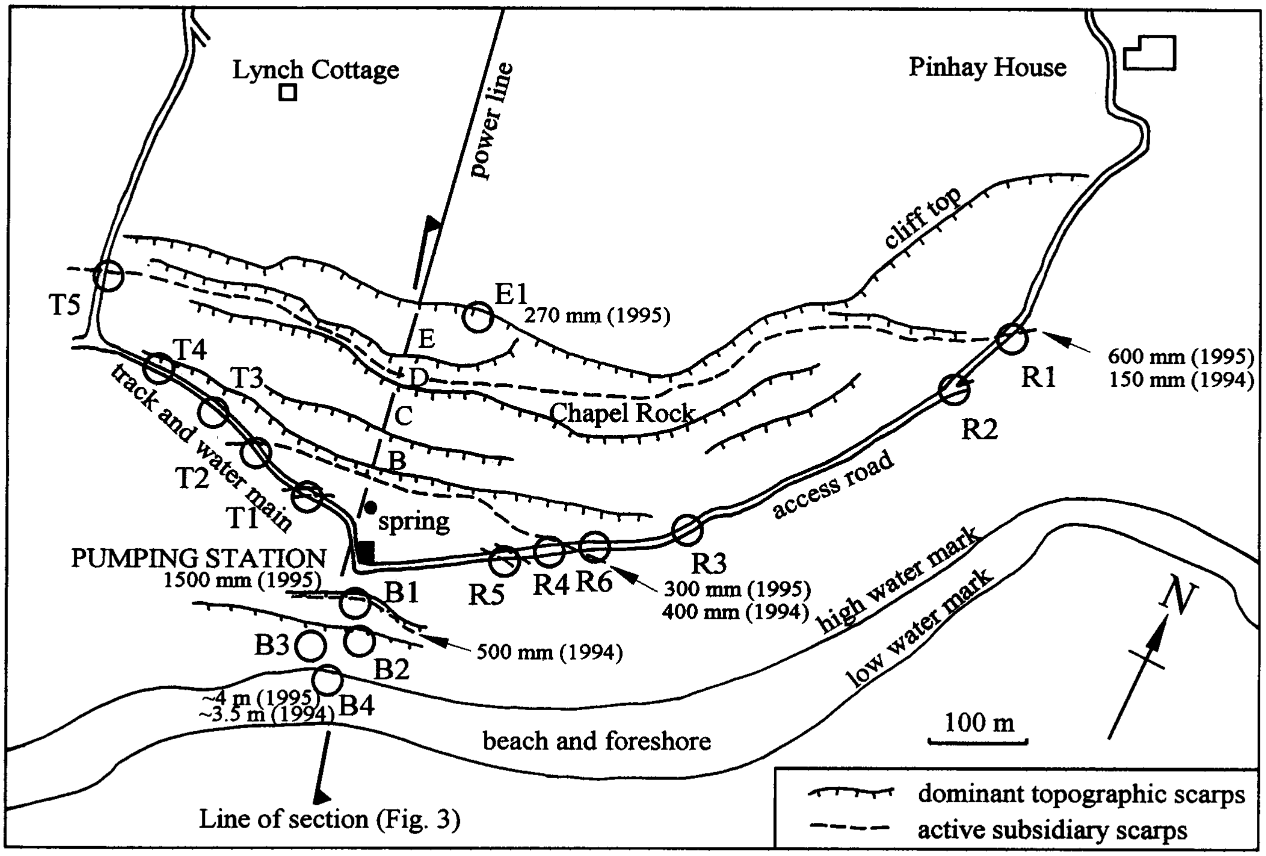

Figure 2: Map showing the main scarps of the landslide and the locations (circles) of the survey pegs in relation to the road, track and pumping station. The displacements are those known to have occurred in February of the year indicated.

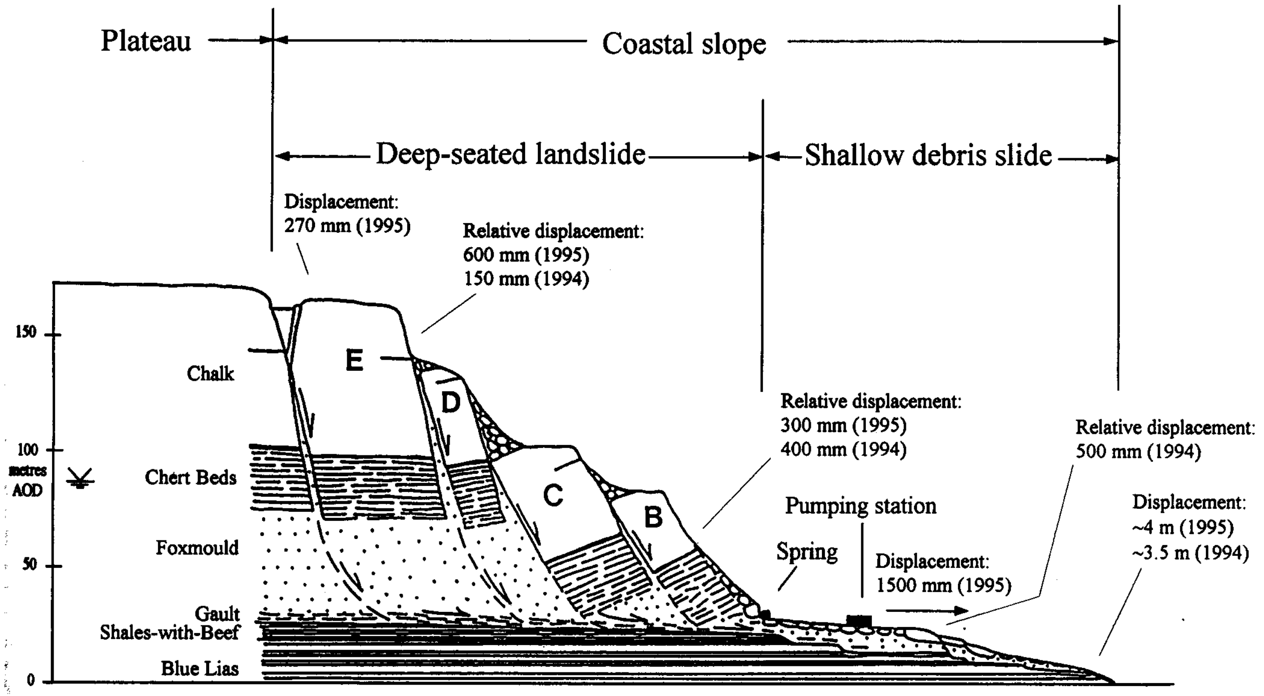

Figure 3: A cross-section through the landslide showing the "deep-seated landslide" and the "shallow debris slide" in relation to the geology and the plateau and coastal slope. The displacements are those known to have occurred in February of the year indicated.

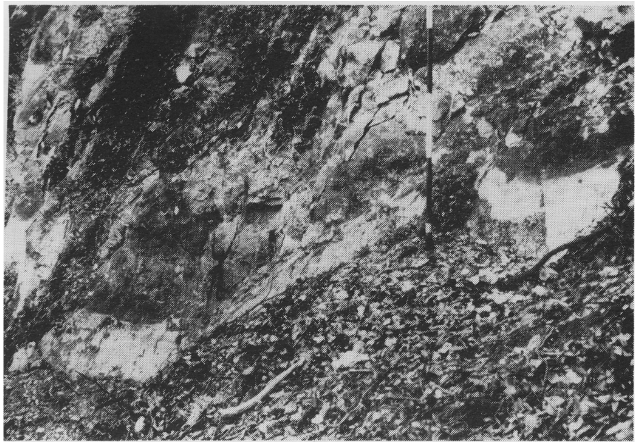

Figure 4: Newly exposed chalk on scarp at the base of block B near the spring, following the movements of the landslide in February 1994 (photograph taken on 7 March 1994).

Figure 5: Disruption of the access road in February 1994 where crossed by the scarp at the base of block B (photograph taken on 7 March 1994).

As the shallow debris moves towards the foreshore there is an increase in internal deformation which means that by the time it reaches the back of the beach it has degenerated to a debris flow.

The Blue Lias consists of alternating beds of weak dark grey shale and strong grey muddy limestone, exposed in the foreshore and, except where masked by landslide debris, in the minor sea cliffs which extend from beach level either side of the toe of the shallow debris slide. The stratigraphic top of the Blue Lias is at approximately 18 to 20 m AOD, but the actual top is thought to have been eroded to about 11 m AOD beneath the shallow debris slide under the pumping station, as shown on the cross-section (Figure 3) (Grainger *et al.,* 1985). The cross-section also demonstrates the interpreted mechanisms of landsliding at the site. The uneven ground profile in the deep-seated landslide has resulted from subsidence into the liquefied Foxmould sand of extensive slipped masses of Chalk and Chert Beds. The slipped masses became detached along steeply inclined joints and have been subjected to rotation associated with reactivation and retrogression.

Extrapolation from the foreshore exposure indicates that the Blue Lias is overlain beneath the deep-seated landslide by up to 5 m of Shales-with-Beef, with its upper surface forming the major unconformity between the Lower Jurassic and the Cretaceous, dipping seawards at 1°. The black shales forming the Shales-withBeef have a very low shear strength in directions parallel to the bedding (Grainger *et al.,* 1985). It is inferred that basal sliding occurs at the level of the unconformity, between the Gault and Shales-with-Beef, which also acts as a hydrogeological barrier to downward movement of groundwater. It is at this level that the spring water emerges at the toe of block B. The water table level inland is known to be at a considerably higher level, within the Chert Beds (Figure 3).

The unconformity is overlain by the Gault, which is approximately 8 m thick at Pinhay and consists of a weak clayey silt, grading upwards into the silty fine sand of the Foxmould which extends up to 75 m AOD. The Foxmould sand is only weakly cemented and its grain size distribution makes it prone to liquefaction when pore pressures increase and the effective stresses are reduced. The overlying moderately strong sandstones and chert of the Chert Beds, together with the Chalk, form an aquifer 90 m thick which is more fractured and transmissive than the Foxmould.

DISPLACEMENTS IN 1994 AND 1995

As reported earlier (Grainger and Kalaugher, 1995) there was reactivation in February 1994 of displacements on the scarps which separate the slipped masses in the deep-seated landslide. Two of the scarp-slip displacements, in front of block E (Figure 4) (150 mm) and in front of block B (400 mm) were traced laterally to the track and road (Figure 5) and found to be consistent over distances of 1000 m and 400 m respectively. The spring supply became contaminated with sediment and its flow was much reduced for several days. Scarps up to 300 mm high intersected the road and prevented vehicular access.

The shallow debris slide moved seawards at the same time and the relative movements on the scarps within it showed evidence of further internal deformation. The toe of the shallow debris slide moved approximately 3.5 m, as a debris flow, towards the foreshore between 21 and 28 February 1994 but the area around the pumping station, being near the head of the debris slide, was displaced by a lesser amount. The estimated displacement of about 1 metre was compatible with the displacement of the deep-seated landslide.

As a consequence of the reactivation monitored early in 1994, more extensive photographic monitoring (Kalaugher, 1984; 1985) was combined with limited surveying at key locations from August 1994. Survey pegs were installed in pairs across the main scarps and tension cracks in the access road (locations R1 - R6), in the track to the west of the pumping station (locations T1 - T5) and in the shallow debris slide (locations B1 - B4) (Figure 2). Between the two pegs in each pair the initial slope distances were established by tape measurements and the initial differences in elevation by levelling.

One additional pair of pegs was installed so that changes in the slope distance between the Chalk plateau (cliff top) and the rear of the slipped mass (block E, Figures 2 and 3) could be determined. From a point near the pumping station measurements by EDM were made to the beach and to a fixed EDM reflector on the top of the rearmost slipped mass (block E) to determine overall movements.

Colour transparencies for photographic monitoring were taken from two locations on the rock platform, accessible only at low tide, and from survey pegs and other specially marked points. It was concluded in August 1994, after monitoring with photographs taken earlier in the year, that no appreciable changes or displacements had occurred since April 1994.

Between September 1994 and January 1995 monitoring visits were made every fortnight: the deep-seated landslide was apparently inactive with only minor changes being recorded along the road and the track. The debris flow at the toe of the shallow debris slide had been eroded by wave action, particularly after the level of the beach had been lowered by scouring of gravel and cobbles in the early autumn of 1994.

In the following months the toe of the shallow debris slide continued to move, as shown by the increase in separation of the pair of pegs at B4 (Figure 6a) and in January 1995 there were also signs of minor displacements affecting the scarps in the shallow debris slide seaward of the pumping station (for example at B2, Figure 6a). By 3 February 1995 displacements of up to 150 mm had occurred at R1 (Figure 6b) where the main scarp at the base of block E intersects the access road below Pinhay House (R1, Figure 2) but elsewhere along the road and track no significant changes were observed (for example at T3, Figure 6b).

Surveying at R1 showed that by 20 February 1995 the difference in elevation between the two pegs had increased by 276 mm since November 1994. At R4 the scarp at the base of block B showed more than 40 mm of displacement in the same period. Surveying by EDM from near the pumping station showed 70 mm of seaward movement relative to the top of the rearmost slipped mass (block E, Figure 3). The shallow debris slide showed major extensional movements by 20 February (Figure 6a).

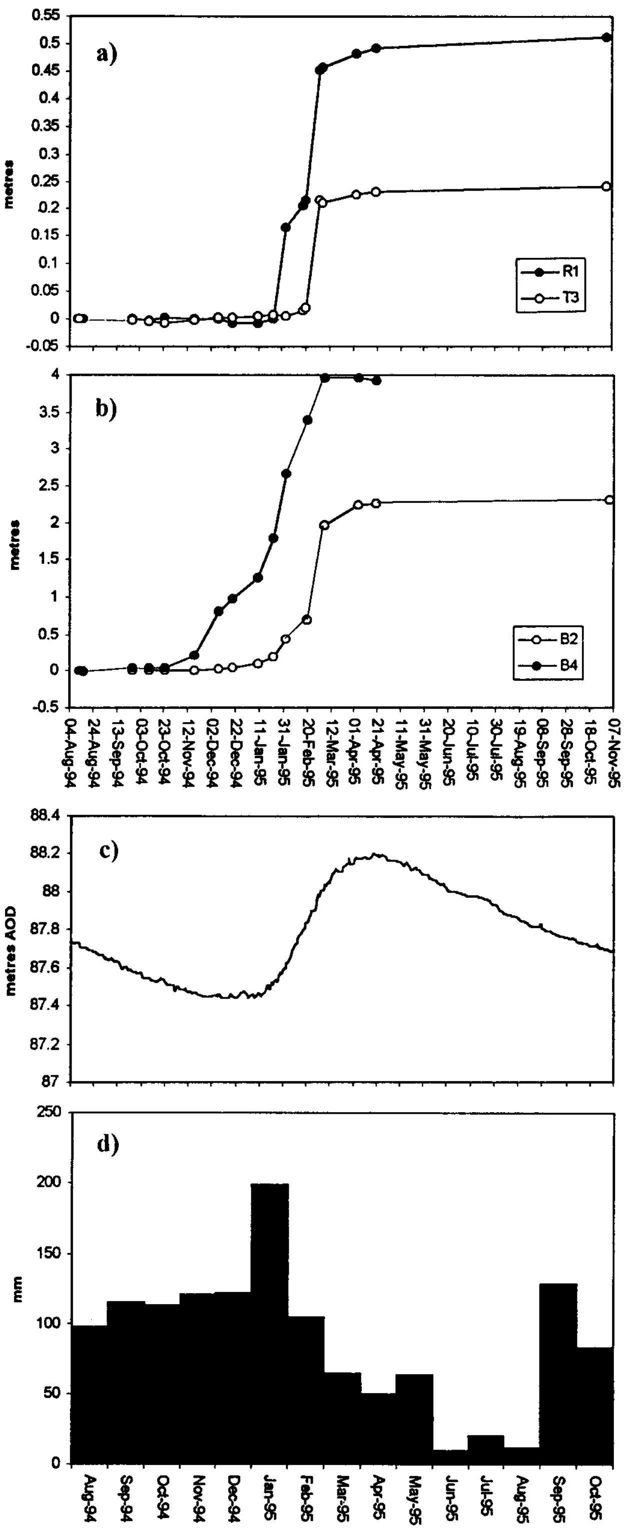

Figure 6. Survey results of displacements across scarps (a) in the deep-seated landslide (b) in the shallow debris slide plotted for comparison with (c) groundwater at a monitoring borehole at Whitlands and (d) rainfall data for Pinhay House (August 1994 - October 1995).

On 25 February 1995 it was reported that the power line from the cliff top to the pumping station, the pumping main (beside the track) and the access road had been disrupted by landsliding. Levelling of the stations along the road and track on 3 and 6 March 1995 revealed that since 20 February 1995 there had been relative vertical movements of up to 320 mm between pairs of pegs. There had also been a relative movement of 270 mm on the rear backscarp above block E, and an additional 300 mm of chalk was freshly exposed on the scarp at the foot of block B. Surveying by EDM showed that the pumping station had moved approximately 1.5 m seawards since 20 February, which is consistent with the observations across the scarps in the deep-seated landslide. In the shallow debris slide there was evidence of increased seepage of groundwater and extensive movements (the slope distance between the pegs at B2 had increased by more than 1 m since 20 February, Figure 6b).

From 6 March to 20 April 1995 the displacements across the scarps in the road showed only 10 - 40 mm of additional movement at each, again consistent with the surveying by EDM which indicated that the head of the shallow debris slide (and the pumping station) had moved a further 100 mm seawards since 3 March 1995.

Between 20 April and 3 November 1995 (which included the very dry months of June, July and August) no appreciable further movement occurred in the deep-seated landslide or in the shallow debris slide (Figure 6a, b).

In summary, the pattern and scale of displacements of the slipped masses in the deep-seated landslide in 1995 were similar to those observed in 1994, resulting in similar damage to the road, track, pumping main, and power line. The head of the shallow debris slide, and the pumping station, were affected by a similar scale of displacements. The scarp between the Chalk plateau and the rear of the most inland of the slipped masses (block E) was only reactivated in 1995, there being no observational evidence in 1994 of recent movement on the scarp. In the shallow debris slide, the scarp immediately seaward of the pumping station degraded more in 1995 than in 1994 but overall displacements of the shallow debris slide were similar in each year.

THE RELATION BETWEEN LANDSLIDE ACTIVITY AND RAINFALL AND GROUNDWATER LEVELS

After the very wet autumn of 1960 (the rainfall for 1960 was 150% of the annual average of 913 mm, with most of the excess falling in the autumn) Humble Point (Figure 1) was affected by major landsliding early in 1961. The main from the pumping station was damaged (Wallace, 1976) and the reported movements in the upper cliff involved the slipped masses of the deep-seated landslide. A similar relation between rainfall and landsliding was shown by the detailed study of the shallow debris slide in 1982-84 which revealed that substantial displacements near its toe followed each 2 - 3 month period of above average rainfall (Grainger *et al.,* 1985).

The activity throughout the undercliff and the movements of the scarps of the deep-seated landslide in February 1994 were reported by Grainger and Kalaugher (1995) as having followed the high rainfall (20 mm) which fell during the night of 22/23 February, following a very wet winter period.

The major displacements of the deep-seated landslide in February 1994 and February 1995 were each in winters with six-month values of rainfall (October - March) which were about 50% above average. Values almost as high have been recorded for other recent winters (40% in 1987-88, 33% in 1989-90) but these winters occurred after drier than average years (1987 and 1989 each had 95% of the long-term average annual rainfall) and there were no significant displacements of the deep-seated landslide or the shallow debris slide.

Monthly rainfall figures show that the dates of each major displacement (23 February 1994 and 25 February 1995) do not correspond with the wettest months of their respective winters, but follow several months of above average rainfall (e.g. Figure 6d). Since displacements of the slipped masses in the deep-seated landslide seem to occur only after prolonged wet periods, it is appropriate to investigate the possibility of correlation with groundwater levels. The nearest groundwater level monitoring borehole is inland at Whitlands [SY 3050 9142], 0.75 km from the undercliff (Figure 1), where the water table is within the Upper Greensand aquifer. Records from the borehole show that the landslide activity in February 1994 and February 1995 occurred at times when groundwater levels, already high, were rising rapidly in response to extended periods of high rainfall (e.g. Figure 6c). The highest groundwater level at the borehole, in years when no significant landslide activity was reported, was 87.8 m AOD, which occurred in 1988. The landslide in February 1994 occurred at exactly the same groundwater level and the landslide in February 1995 at a level of 87.9 m AOD. The peak groundwater levels in 1994 and 1995 reached 88.0 m AOD and 88.2 m AOD respectively.

DISCUSSION

The disruptive movements at Pinhay involving the deep-seated landslide seem to be related to unusually high levels of prolonged rainfall over a period of months but do not necessarily occur when groundwater levels recorded beneath the plateau are at their peak values. Indeed, because of the time taken for the water to seep down to the water table, landslide activity has occurred, and ceased, while recorded groundwater levels continued to rise (Figure 6c). The pattern of rainfall immediately preceding a displacement suggests that the rate at which groundwater levels continue to rise above an already high level may be significant.

Whatever disturbance is caused to the groundwater pattern in the Chalk and Upper Greensand aquifer by landslide movements, the water table will everywhere continue to be drawn down towards the Pinhay source and the other springs in the undercliff. When heavy rainfall is prolonged the seepage from the landslide, although increased, will be unable to keep pace with the extra drainage requirement brought about by the rapid rise in groundwater level inland. The top flow line (phreatic surface) will be raised and higher pore pressures will exist in the undercliff until the longer-term flow conditions are re-established. The higher pore pressures will reduce shearing resistances, particularly within the Foxmould sand, and lead to widespread reactivation of landsliding. If, later on, there is a reduction in the intensity of rainfall there could be a reduced requirement for drainage with consequent lowering of pore pressures in the landslide while the groundwater level in the borehole continues to rise, but at a slower rate. In this way the landslide could be restabilised while the water level in the borehole continues to rise.

In contrast to the deep-seated landslide, the middle part of the shallow debris slide and the debris flow at its toe are reactivated in response to high rainfall over a period of only a few weeks. The scarp immediately seaward of the pumping station is also reactivated when the head area of the shallow debris slide is involved in movements of the deep-seated landslide. The position of the scarp is controlled by a step in the bedrock beneath the debris slide (Figure 3) and so appears to retrogress as the debris moves seaward over the step.

CONCLUSIONS

The displacements of the slipped masses of the deep-seated landslides of February 1994 and February 1995 followed several months of heavy rainfall in wetter than average years. The rainfall resulted in exceptionally high groundwater levels in a nearby inland monitoring borehole, with rapid increases in level corresponding with the onset of the landslide displacements. During each of the two major displacements the deep-seated landslide has moved seaward by between one and two metres taking the head of the shallow debris slide and the pumping station with it.

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