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RENEWED LANDSLIDE ACTIVITY AT PINHAY, LYME REGIS

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During the first four months of 1994, periods of excessively wet weather led to increased landslide activity along the coast of east Devon and west Dorset, including the undercliff of the Axmouth-Lyme Regis National Nature Reserve. Close monitoring of the landslide movements in an area around the Pinhay water source and pumping station was started in February 1994. The distribution of the movements is described and explained by comparison with a previous interpretation of the site. The large rotated blocks of Chalk and Upper Greensand forming the slope above the pumping station underwent relative displacements of up to 400 mm, which were remarkably consistent over scarp lengths of up to 1 km. Seaward of the pumping station, the landslide of Chalk and Greensand debris over Lias bedrock also increased its activity, with movements of several metres at its toe and renewed displacement on its backscarp. In response to increased awareness of the risk to the continuity of the water supply, regular photographic monitoring and surveying of the area was instigated, to provide a warning of any failure.

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INTRODUCTION

The Pinhay water source and pumping station are located on the Dorset coast, approximately 3 km west of Lyme Regis, within the Axmouth-Lyme Regis National Nature Reserve in an area of landslides known as the undercliff (Figure 1). The spring source is located at a height of about 30 m above OD and approximately 160 m inland from the beach. The pumping station is situated 50 m seaward of the spring. An access road leads down south-westwards from Pinhay House through the landslide zone to the pumping station, a distance of just over 1 km. Water is pumped from the station via a main to the west along the coastal path and then north-west to a holding reservoir outside the landslide zone. Overhead power and communication lines are connected to the pumping station from the cliff top.

The topography in the undercliff is dominated by the effects of landsliding. The landslides occur as large infrequent events and smaller more frequent movements. The reader should refer to the earlier paper by Grainger *et al.* (1985) describing a detailed study of the stability of the area around the pumping station, undertaken between 1982 and 1984. The study identified four ways in which landslide activity threatened the water supply:

1) Movement of the ground from which the spring issues could impede the flow of water and also endanger the pumping station.
2) Movement of the landslide debris on the seaward side of the pumping station could eventually lead to retrogression of the backscarp and hence to undercutting of the building's foundation.
3) Movement of the ground to the west could fracture the pumping main.
4) Movement of the ground to the east could block the access route.

The only movements recorded in 1982-84 were in the landslide debris between the pumping station and the beach. These movements showed a correlation with periods of high rainfall. The rate of activity in this part of the landslide suggested that a few tens of years would elapse before the pumping station was affected by undercutting, and consequently detailed monitoring was halted.

A new assessment of the stability of the area, in 1993, revealed changes to the landslide area close to the beach, but no significant displacement on the rear backscarp of this landslide, seaward of the pumping station, since 1984. However the scale of the changes observed nearer to the beach prompted a decision to monitor annually using a photographic comparison technique, developed specifically for inspection on site (Kalaugher and Grainger, 1990; Grainger and Kalaugher, 1991), to start in February 1994. The technique allows simultaneous viewing on site of a 35 mm colour transparency taken earlier and the current scene it represents. The transparency is viewed with one eye and the current view is observed directly with the other eye from the same location as the original photography. The two images are fused stereoscopically by the observer, and any difference between the two images, such as movement of part of the scene, is immediately obvious and the amounts of displacement may be determined on site. The system utilises a standard 35 mm single-lens reflex camera mounted on a survey tripod for the photography and a similarly mounted viewing device for the later comparison.

The main objective of the first visit, on 21 February 1994, was to obtain a photographic record of the lower slope. Following a very wet autumn and winter, and then high rainfall (20 mm) on the night of 22/23 February, a partial loss of the water supply and disruption of the power lines was reported on 23 February. Hence further visits were made on 24 February, 28 February, 7 March and 16 March 1994 to monitor landslide movements and to determine the extent of the problem. This paper describes the findings of these site visits, and the regular monitoring set up as a consequence to warn of future risks.

GEOLOGY

All of the strata in this area, where undisturbed by landsliding, are very gently dipping or virtually horizontal. The succession and significant geotechnical features of the formations, from sea level to the top of the cliff, are shown in Figure 2, which represents an interpretation of published geological information, taken from Grainger *et al.* (1985).

The Blue Lias consists of alternating beds of dark grey mudrock (shale and mudstone) and grey argillaceous limestone, exposed in the foreshore and seaward edge of the cliffs just above beach level except where masked by landslide debris, and are seen to be dipping east at up to 4° at this location. The stratigraphic top of the Blue Lias is at approximately 18 - 20 m above OD, but is thought to have been eroded by landsliding to about 11 m above OD under the pumping

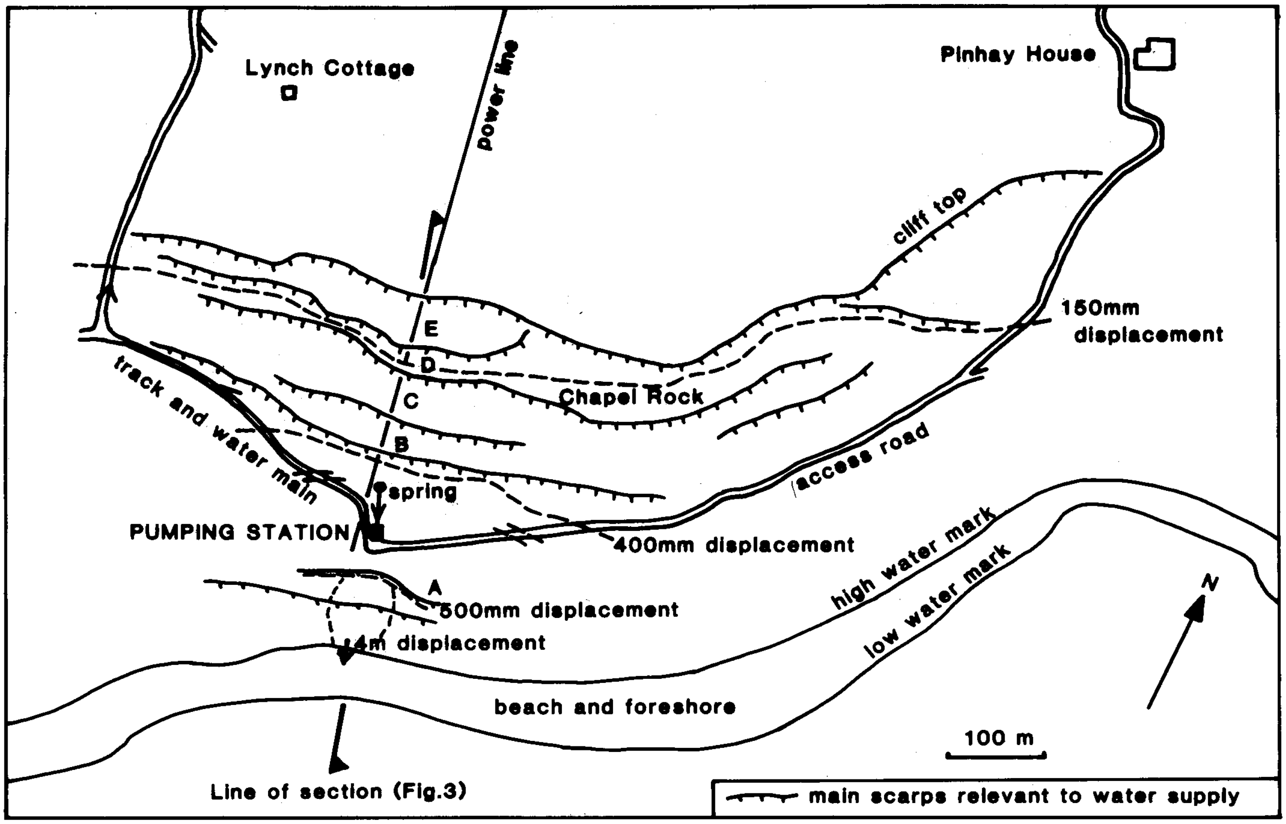


Figure 1. Location map.

station and to descend in a series of steps down towards the beach, as shown on the cross section (Figure 3).

The bottom 5 m thickness of the Shales-with-Beef Formation is thought to overlie the Blue Lias under the main cliffs, landward of the pumping station, with its upper surface, formed by the major unconformity between the Lower Jurassic and the Cretaceous, dipping seawards at approximately 1°. These black shales have a very low shear strength parallel to bedding-plane discontinuities (Pitts, 1981).

By extrapolation from exposures nearby (Conway, 1974; Pitts, 1981), the Gault is interpreted to be approximately 8 m thick here and is composed of clayey silt. It grades up into the silty fine sand of the Foxmould (Upper Greensand) which extends up to 75 m above OD. These sands are only weakly cemented and, being of low permeability, are particularly prone to liquefaction at high pore pressures, which can occur during landsliding.

The Foxmould, in turn, is overlain by the moderately strong sandstones and chert of the Chert Beds (also Upper Greensand), up to 25 m thick, which form an aquifer together with the Chalk which makes up the rest of the 170 m height of the main cliffs, landward of the pumping station.

INTERPRETATION OF LANDSLIDE MECHANISMS

The geological cross section through the pumping station (Figure 3) demonstrates the interpreted mechanisms of landsliding at the site (Grainger *et al.,* 1985). Large blocks of Chalk and Chert Beds became detached along steeply inclined joints, subsided into the partially and temporarily liquefied Foxmould sand and rotated to form the stepped ground surface profile seen today. The orientation of the scarps between the blocks is consistently east-west, suggesting a structural control on the jointing which the scarps follow. It is inferred that basal sliding occurs at the level of the unconformity between the Gault and Shales-with-Beef. The unconformity also acts as a hydrological barrier to downward movement of groundwater (Pitts, 1983).

These large landslide blocks have existed for at least several hundred years but are subject to occasional further displacements, probably in response to exceptionally high groundwater levels. Before 1994, the latest significant displacement in this part of the slope occurred in 1961 (Macfadyen, 1970). The Pinhay water supply emanates from a spring at the toe of block B (Figure 3), landward of the pumping station. The water table inland is known to be at a considerably higher level, usually within the Chert Beds (Figure 3), and thus is drawn down towards the unconformity creating a hydraulic gradient which causes flow of groundwater seawards through the landslide blocks.

The Lias bedrock beneath the area from the pumping station down to the beach is overlain by landslide debris from the Chalk, Chert Beds, Foxmould and Gault (Figure 3). The debris gets thinner towards the sea where its rate of movement over the eroded Lias surface increases. The detailed study of this area in 1982-84 showed a strong correlation of the rate of movement with high rainfall (Grainger *et al.,* 1985). The backscarp of the active part of this debris slide is approximately 33 m seawards of the pumping station. At the toe of the slope, the debris descends to beach level where it is removed by wave erosion.

OBSERVATIONS IN FEBRUARY AND MARCH 1994

On 21 February a site visit was made to establish the system of photographic monitoring, with the intention of returning at least annually thereafter to record and assess the significance of changes. The area seaward of the pumping station was the main priority. A full photographic monitoring survey was made of this area from locations on the foreshore and within the landslide which were then marked. The slope landward of the pumping station was photographed as was a prominent crack in the tarmac road below Pinhay House, at the site of previous repairs.

Following a period of high rainfall (20 mm) on 22/23 February, which came after six months of higher than average rainfall (totalling 856 mm compared to a long-term average for those six months of the year of 533 mm), there was a significant movement of the landslide, involving some of the ground upslope from the pumping station. Within a few hours the pumping main was fractured, the spring supply became contaminated with sediment and its flow much reduced. The power lines were disrupted and the electricity supply failed. The access road was severely affected by several scarps and tension cracks which cut across it.

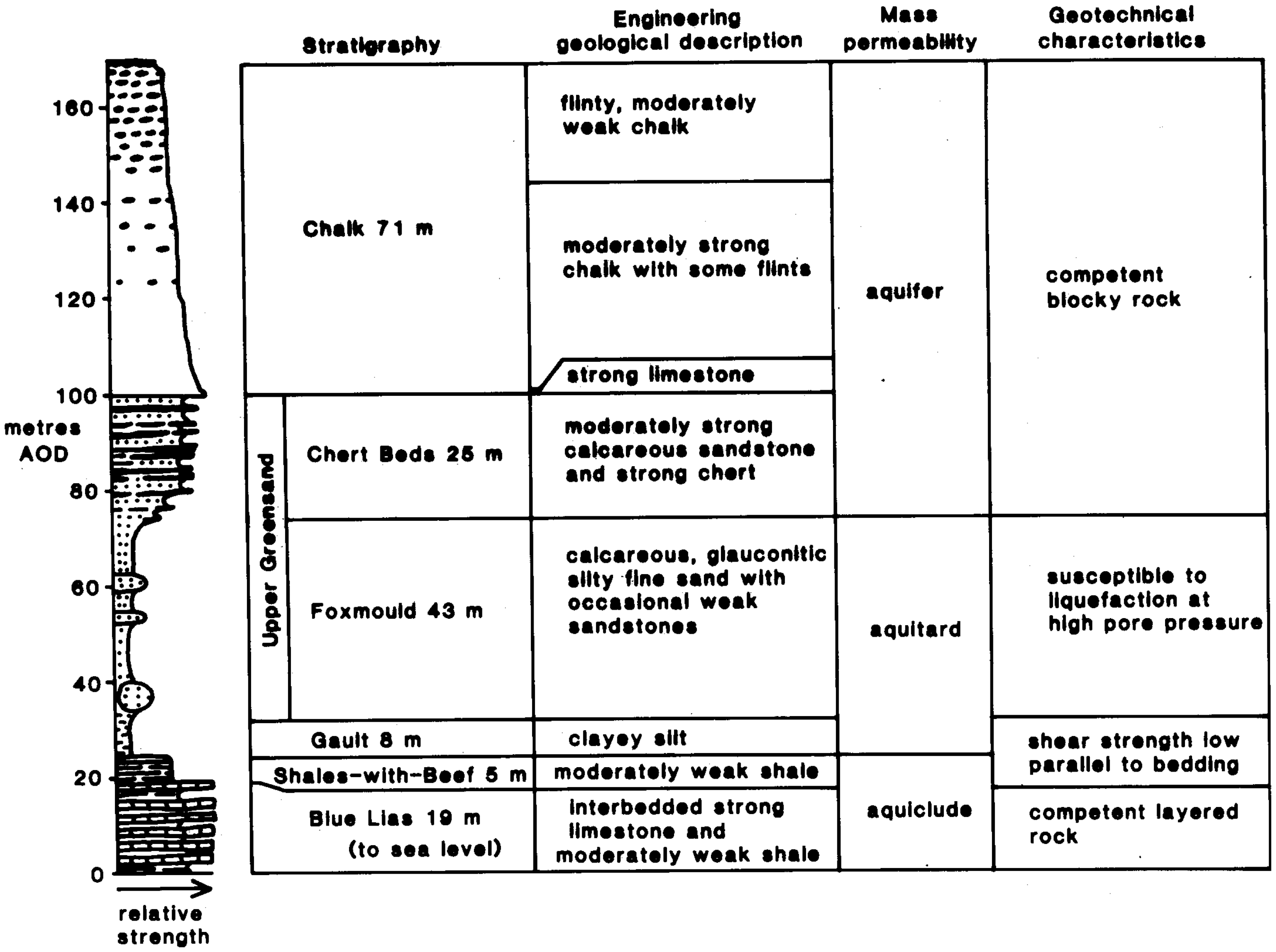
Consequently on 24 February an emergency site visit was made, although the monitoring transparencies taken on 21 February were not yet available for the comparison technique to be used on site as intended. New photography from the toe of the lower slope showed that several metres of forward movement had occurred there since 21 February, when the new and previous transparencies were compared in the office. Also, up to 300 mm of new downward movement was found below the backscarp seaward of the pumping station. On the access road, a new scarp about 240 m from the pumping station (at the location of previous repairs) was photographed and its vertical displacement estimated to be 150 - 300 mm. Several other new tension cracks were observed in the road, and at the uppermost site, photographed on 21 February, the crack had developed as a scarp with approximately 150 mm of vertical displacement.

The next visit was on 28 February, to monitor changes since 21 and 24 February. From the foreshore monitoring location, not accessible on 24 February, the toe of the landslide seaward of the pumping station had evidently moved forward and slumped onto the beach. The low cliffs and slopes either side of this area also displayed small falls of landslide debris onto the beach and forward movements of several metres with trees displaced or fallen.

The photographic monitoring showed 3.5 m of forward movement of the toe between 21 February and 28 February, almost all of which had occurred by 24 February. The backscarp seaward of the pumping station showed no further movement since 24 February. A detailed comparison of transparencies revealed small but perceptible displacements of the ground in front of blocks E and B (Figure 3). Such movements explain the failure of the power line, temporary partial loss and turbidity of the water supply, and minor cracks reported in the pumping station building itself.

By the time of the next visit, on 7 March, there had been very little further displacement. To investigate the apparent displacement of the ground in front of block B, a reactivated scarp was followed westwards from the break in the road, 240 m east of the pumping station, above the spring and the pumping station, to the footpath and water main 180 m west of the pumping station. In places, where the front of block B is a steep (60°) Chalk face, the recent subsidence of the ground in front had exposed clean Chalk at its base, consistently measuring about 400 mm. Other tension cracks across both the path and road, nearer the pumping station, equate with the level of the spring itself and with a decrease in slope angle. These cracks are thought to relate to the forward (rather than downward) movement of the area, including the pumping station, seaward of their location.

By 16 March an additional 0.5 m of movement of the toe was recorded, and a slight further movement at the backscarp seaward of the pumping station. On this occasion, an upper scarp, related to the movements in February, was traced for 1 km from the road to the



Stratigraphy	Engineering geological description	Mass permeability	Geotechnical characteristics
Chalk 71 m	flinty, moderately weak chalk	aquifer	competent blocky rock
	moderately strong chalk with some flints		
	strong limestone		
Chert Beds 25 m	moderately strong calcareous sandstone and strong chert		
Foxmould 43 m	calcareous, glauconitic silty fine sand with occasional weak sandstones	aquitard	susceptible to liquefaction at high pore pressure
Gault 8 m	clayey silt		shear strength low parallel to bedding
Shales-with-Beef 5 m	moderately weak shale	aquiclude	
Blue Lias 19 m (to sea level)	interbedded strong limestone and moderately weak shale		competent layered rock

Figure 2. Stratigraphic column, with important properties (after Grainger et al., 1985).

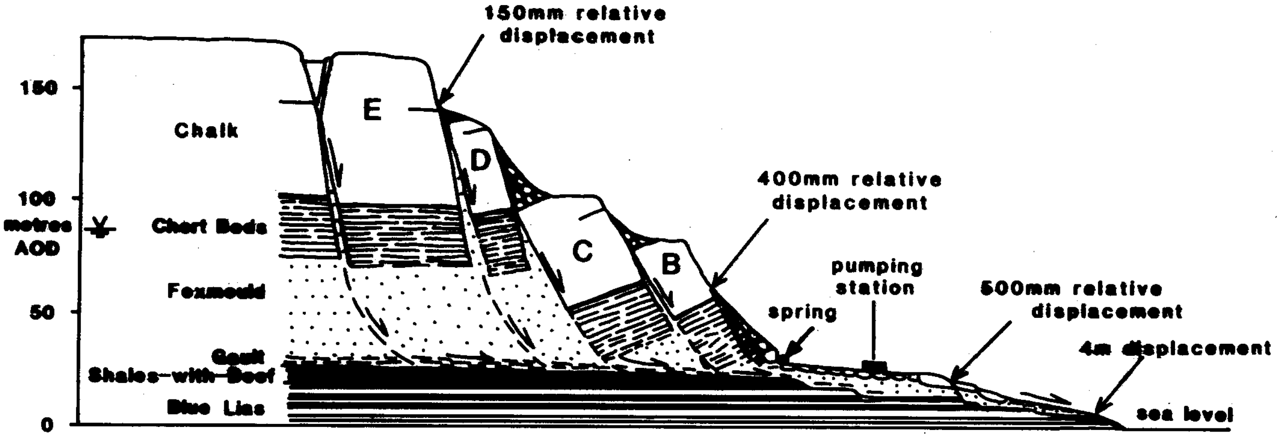


Figure 3. Cross section through the pumping station (after Grainger et al., 1985) showing positions of displacements recorded in February-March, 1994.

footpath (Figure 1). The relative displacement on this scarp was downward by approximately 150 mm and had resulted in falls of substantial Chalk blocks in places. Its trace passed landward of Chapel Rock (Figure 1) and crossed under the power lines at the foot of the main Chalk face, on the seaward face of block E (Figure 3) as suspected from the photographic interpretation. To the west it emerged as a crack on the track 300 m below the junction to Lynch Cottage, in an area of previous movement.

This series of site visits had thus revealed there had been relative movements between the large blocks upslope from the pumping station. Two of these downward displacements, in front of block E (150 mm) and block B (400 mm) were traced laterally to the track and road, distances of 1000 m and 400 m respectively. These movements, consistent over considerable distances, demonstrate the deep-seated nature and vast scale of the major landslide blocks. The movements also explain the coincidental damage to the power lines, water main, spring source and access road first seen on 23 February 1994. The possibility of minor undetected movements seaward of blocks D and C and landward of block E also exists. All of the above movements appeared to achieve at least temporary stability by the beginning of March.

The flatter area around the pumping station must have moved seawards at the same time, to accommodate the displacements behind. This led to minor structural damage and the increased stress on the cables.

The rear part of the shallow landslide seaward of the pumping station underwent a movement of about 500 mm on its backscarp. Between the backscarp and the toe there appears to have been stretching and the toe had moved seawards relative to the foreshore by approximately 4 m. The major part of these movements took place between 21 February and 24 February.

RESULTS OF MONITORING FROM AUGUST TO DECEMBER 1994

Once it had been realised at the end of March 1994 that the movements of the pumping station and slope above it, which caused the disruption to the water supply, had ceased, and the spring flow returned to normal, repairs were effected and the supply restored. However, to give some warning of future supply failures and to provide an assessment of the risks to personnel on site, a system of frequent photographic monitoring and survey checks was put in place in August 1994.

Pairs of survey pegs were established either side of the main scarps and tension cracks in the access road and the track, at the cliff top (the rear of block E) and down the footpath to the beach (16 pairs in total) and their relative heights and separations measured by levelling and taping. Surveys from the pumping station to the top of block E and to the foreshore by electronic distance measurement were also established and checked for repeatability. An extensive set of monitoring colour transparencies was taken from known positions, to complement the survey measurements. Through the autumn of 1994, the site was visited twice monthly. During each visit the measurements between pegs were checked and the slides used to assess changes. Most landslide activity was noted at the toe of the slope where marine erosion had been particularly severe during that period. A few minor changes elsewhere were recorded and their significance in terms of risk to the water supply reported.

This system of monitoring was due to continue at least until the summer of 1995, and would then be reviewed.

CONCLUSIONS

All of the landslide movements monitored in 1994 are likely to have been triggered by the high rainfall (20 mm) of the night of 22/23 February, which followed a very wet autumn and winter period (the rainfall in the previous six months was 160% of the long-term average for that part of the year). High pore pressures on the basal sliding surface and within the Foxmould sand reduced shear resistances to the point of failure.

The temporary partial loss of the spring water was caused by movement of the landslide debris seaward of block B, disrupting the flow path to the spring. As the flow returned to its normal volume after a few days, the potential ponding of groundwater in the slope to raise pore pressures to even more dangerous levels, did not occur.

The displacements of the large blocks of Chalk and Upper Greensand landward of the pumping station are reactivations of previous landslides and are thought to be the first movements of any significance since 1961. The consistency of the displacements over lengths up to 1 km is remarkable and confirms the deep-seated nature of the landslide. The east-west orientation of the main scarps is thought to be structurally controlled, as it is not parallel to the coast. Further movements of a similar scale could occur at any time when the groundwater conditions are right, and will become increasingly likely if the debris which forms the active slide, seaward of the pumping station, continues to move forward and is eroded by wave action.

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