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Coastal Landslides of Southern England

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Прибрежные оползни южной части Великобритании

Ревизийей некоторых больших оползней на побережии южной части Великобритании было установлено: — Утёсы представляют непрочные осадки мезозойских и третичных пород. — Отмечается целый ряд процессов как оползни пород, грязевые потоки, глубинные ротационные и трансляционные оползни. Эти процессы отмечаются эрозионной поверхностью, гидрогеологическими и геотехническими особенностями пород и специфическими стратиграфическими ассоциациами.

Coastal Landslides of Southern England

Some major landslides along the coast of Southern England are reviewed. The cliffs consist of weak sedimentary rocks of Mesozoic and Tertiary age. A variety of processes can be identified including rock falls, mudslides, deep rotational and translational slides. These processes are determined by wave erosion, the hydrological and geotechnical properties of the rocks, and by particular stratigraphic associations.

This is a review of the mechanisms of major landslides at selected sites along the coast of Southern England, from the River Thames of north Kent to the River Exe in Devon (Fig. 1). The rocks exposed consist of weak sedimentary lithologies of Mesozoic and Tertiary age.

Oversteepening by marine wave erosion at the base of the coastal slope is obviously the general, long-term cause of all such landslides. However, the variety of cliff profiles, rates of erosion, types of landslide and frequency of their movement can be explained by the geotechnical and hydrological properties of the rocks involved, and by different stratigraphic associations. The geology of the landslides described is conveniently divided into three categories: (a) where there is only one rock type, (b) where a minor aquifer overlies mudrocks, and (c) where a major aquifer of stronger rock overlies weaker rocks.

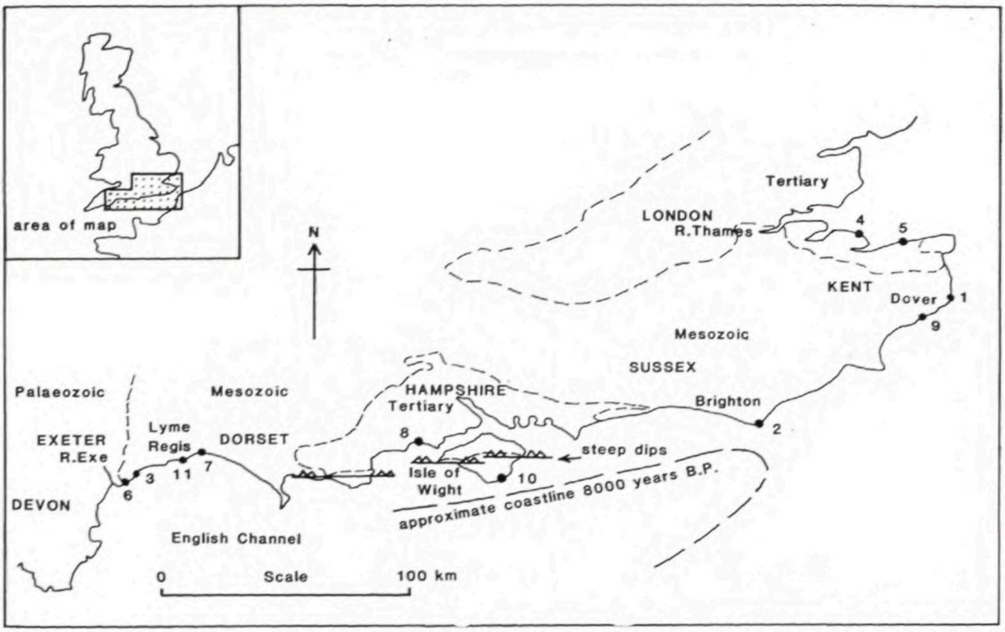

Fig. 1. Geological map showing location of landslides described in text (localities 1 — 11)

Geological setting

The lithologies exposed on the coast of Southern England consist of porous limestones, including chalk, weakly cemented sandstones and sands, moderately strong mudstones, weak shales and stiff overconsolidated clays. Their age ranges from Permo-Triassic at the western end of the section, in Devon, to Lower Tertiary around the Hampshire and London Basins (Figs. 1 and 2). Most of the limestones are of Upper Jurassic and Upper Cretaceous age. There is a general increase of strength with age of the mudrocks and sandstones.

In most places the structure is very simple, with gently dipping or horizontal strata related to major open folds of Tertiary age. Only minor extensional faulting has occurred. The exception to this general rule is an east-west zone of steep to vertically dipping strata along a monoclinal flexure, through the Isle of Wight and east Dorset (Fig. 1). This fold strongly affects the style of coastal morphology in these areas but will not be considered further in this paper.

Although the local direction of gentle dip may exercise some control on the landslide acitivity, the style of landsliding within one cliff profile is dominantly dependent on lithology and on contrasting strengths and permeabilities.

The ages of the present landslides are related to the postglacial rise in sea level, since the Pleistocene. It has been estimated that sea level was still 35 m below its present position about 8000 years ago (Fig. 3), with a coastline very different from that of today (Fig. 1). Most of the large landslides studied began their current activity when sea level was close to its present value, within the last 5000 years. Indeed, because of the rate of

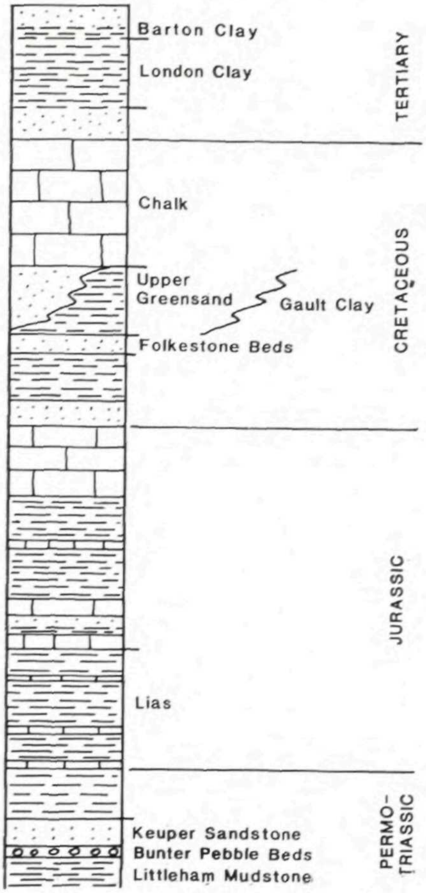

Fig. 2. Relevant parts of the Stratigraphy of Southern England

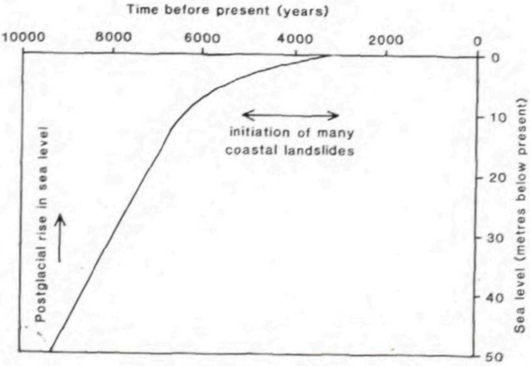

Fig. 3. Relationship between rise of sea level and initiation of landsliding

erosion, most of the landslide features seen today are less than a few hundred years old.

Landslides involving one rock type

Chalk

The Upper Cretaceous Chalk of England is a porous, very fine-grained bioclastic limestone. Its mineralogical purity gives it a strikingly white appearance. The Chalk is a moderately weak rock, generally exhibiting a closely spaced orthogonal joint pattern, parallel and perpendicular to the bedding. Consequently this formation has a high porosity and hydraulic conductivity, making it an important groundwater aquifer.

The two significant coastal outcrops of gently dipping Chalk, forming the complete height of the cliff, are around Dover (Fig. 1, locality 1) and Brighton (locality 2). At these localities there are vertical cliffs of Chalk up to 160 m high, which suffer occasional rock falls where undercut by wave erosion. The geometry of the rock falls is determined by the directions of near-vertical joints in the rock mass (Fig. 4).

Sandstone

There are no thick formations of sandstone forming cliffs comparable in magnitude to the Chalk. However there are lower cliffs composed solely of sandstone at a few localities, for example in the Keuper Sandstone (Triassic) of east Devon (Fig. 1, locality 3). This is a red, moderately porous, moderately strong sandstone with few joints and bedding planes. Cliffs up to 20 m in height show vertical or overhanging profiles with a wave-cut notch at the base. Cliff failure occurs by vertical slabbing parallel to the face, in the absence of suitable natural joints.

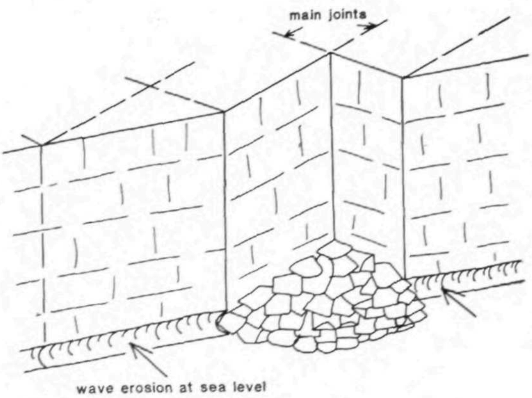

Fig. 4. Rockfall of Chalk cliff

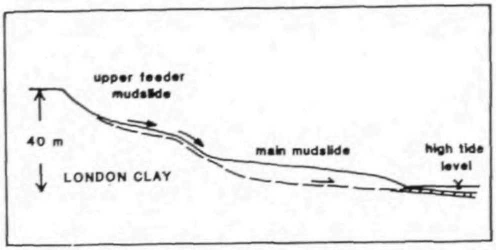

Fig. 5. Cliff profile in London Clay where mudslides dominate

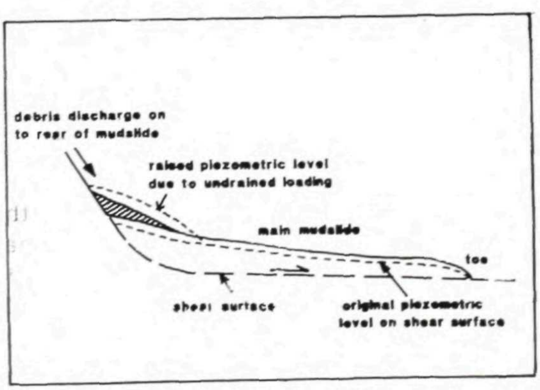

Fig. 6. Destabilisation by undrained loading

Overconsolidated clay

Mudrocks constitute a major proportion of the cliffs of southern England. They range from very stiff, overconsolidated silty clays to moderately strong, calcareous mudstones. The London Clay (Tertiary) is the most notable example of the former, and has been extensively studied along its coastal outcrop in north Kent (Fig. 1, localities 4 and 5) (Hutchinson, 1965a, 1970, 1983; Hutchinson and Bhandari, 1971; Bromhead, 1978, 1979; Bromhead and Dixon, 1984). It is a clay of high plasticity (liquid limit 90 %; plastic limit 27 %) and low residual shear strength ($\emptyset = 11-14°$).

The cliff profiles in London Clay are up to 40 m high with average slope angles of 10—20°. Two main processes of failure occur, shallow translational mudsliding and deep rotational landsliding. Mudsliding occurs where sufficient water is supplied to the exposed clay to soften and degrade it. The movement occurs by basal and side shear of the weakened debris which soon reaches its residual shear strength. Often an upper feeder mudslide provides occasional rapid undrained loading on to the top of a larger lower mudslide, which temporarily destabilises it by increasing the pore pressure (Figs. 5 and 6). If the overall rate of mudslide movement keeps pace with wave erosion at the toe of the slope, then the cliff is protected from oversteepening. If the movement does not keep pace with wave erosion, perhaps because the rate of erosion is temporarily accelerated in a tidal surge or storm, oversteepening can result in deep rotational sliding. The shear surface of this rotational sliding is approximately circular in cross section where the London Clay extends far enough below sea level (Fig. 7). A backtilted subsided portion of the cliff top is commonly observed. In areas where the base of the London Clay is reached by the shear surface, a non-circular movement occurs causing internal disruption of the slipped mass and a graben often develops at the backscarp

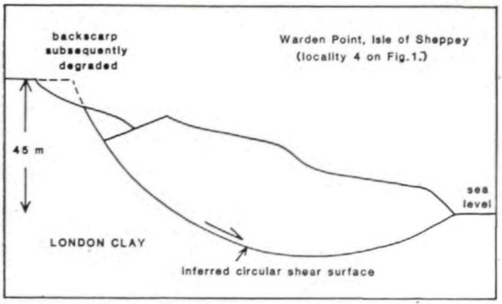

Fig. 7. Cliff profile in London Clay after circular rotational sliding

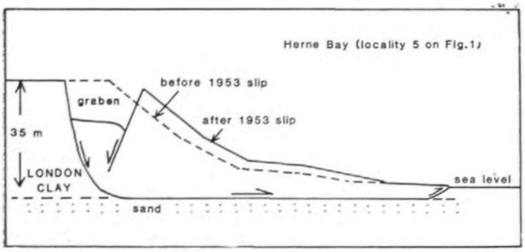

Fig. 8. Cliff profile in London Clay after non-circular sliding

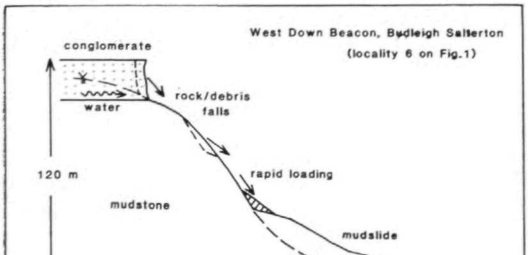

Fig. 9. Cliff profile in Permo-Triassic mudstone overlain by conglomerate aquifer

(Fig. 8). In plan view, the mudsliding coast has many semicircular depressions, each with its own mudslide system, whereas the deeper rotational slides have a large width compared to their length and are often flanked by subsidiary mudslides.

Much stabilisation of the north Kent coast has been performed in the last 20 years. Surface drainage to stabilise the mudslides has to be accompanied by protection of the toe from wave erosion, or rotational failure could be induced. Regrading to a stable angle with toe weighting, wave protection and surface drainage is necessary to stabilise deep rotational slides.

Landslides involving a minor aquifer overlying mudrocks

Where mudrock cliffs are capped by an aquifer, this can provide a greater supply of water onto the upper slope and hence increase the amount and rate of mudrock weathering and softening to a weaker clay. Two stratigraphically different examples from southwest England illustrate this situation. The first landslide is at Budleigh Salterton in Devon (Fig. 1, locality 6). Here 20 m of weakly cemented, porous conglomerate or pebble beds (Bunter) overlie 100 m of slightly calcareous, silty mudstone (Littleham Formation) of Permo-Triassic age (Kalaugher and Grainger, 1981) (Fig. 9). Groundwater emerges from the base of the conglomerate causing minor debris falls of both conglomerate and mudstone. The mudstone debris degrades to a silty clay matrix of low plasticity enclosing fragments of unweathered mudrock and pebbles from the conglomerate. A large, thick mudslide has developed in front of an embayment in the lower cliff. This mudslide moves only once or twice a year, reaching velocities of 1—2 m/hr for a few hours, on a basal shear surface inclined at about 15° to the horizontal. The triggering mechanism for movement is usually a fall of debris onto its upper end from higher up the cliff. This is a larger and more dynamic example of the undrained loading experienced on the London Clay coast.

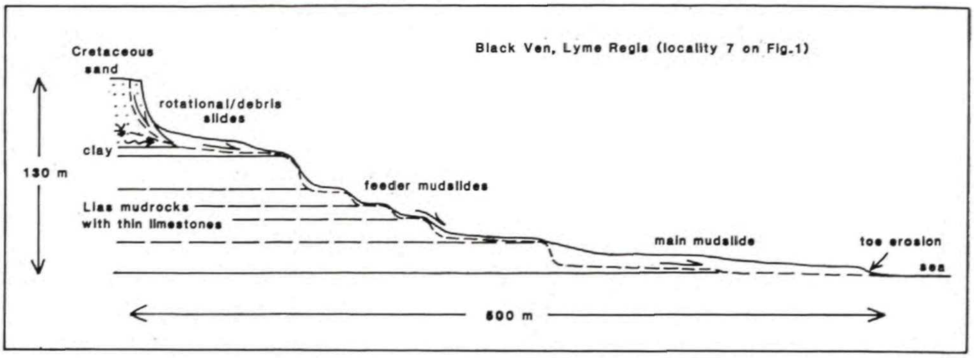

Fig. 10. Cliff profile in Lias mudrocks overlain by Cretaceous sand aquifer

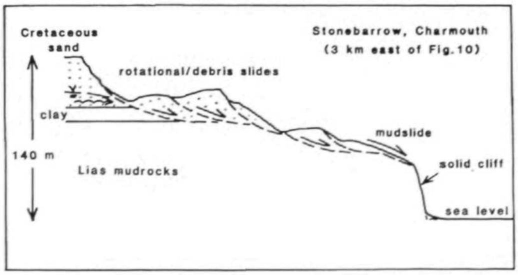

Fig. 11. Cliff profile in Lias mudrocks overlain by aquifer, with eroding mudrock lower cliff

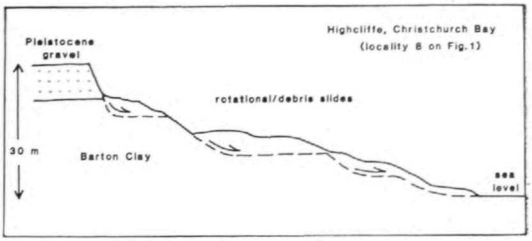

Fig. 12. Cliff profile in Barton Clay overlain by gravel aquifer

The second example of this stratigraphic arrangement of lithologies occurs at Black Ven, Lyme Regis in West Dorset (Denness, 1972; Conway, 1974; Hutchinson, 1983) (Fig. 1, locality 7). In this case the aquifer consists of 45 m of Upper Greensand (Cretaceous) sands and weak sandstones, with a thin Gault Clay at its base, resting unconformably on Lias (Jurassic) weak mudstones, shales and stiff clays. Small rotational failures are induced in the sands and the clay at its base by emerging groundwater. The water-softened debris accumulates on a ledge on top of the mudrocks. When saturated it flows and slides over a series of steps in the mudrock cliff profile, eroding and incorporating more clay material (Fig. 10). Therefore a rapid succession of undrained loadings of each mudslide occurs in one event, leading to very large displacements of the lowest mudslide on a very low-angle slope, across the foreshore. The steps in this cliff profile are produced by slightly stronger calcareous beds within the mudrock succession. A similar geological profile occurs at the neighbouring site of Stonebarrow (Brunsden, 1974; Brunsden and Jones, 1976), but here wave erosion is rapid enough to maintain a solid mudrock cliff at the toe (Fig. 11).

There have been no attempts to stabilise any of these examples but drainage of the upper aquifer is the most important aspect to consider in situations of this kind. Smaller cliffs (30 — 37 m high) with the same hydrological contrast occur at Christchurch Bay im Hampshire (Fig. 1, locality 8), where Pleistocene gravel overlies Barton Clay (Tertiary) (Barton, 1973; Barton et al., 1983; Barton and Coles, 1984). This clay is more variable than the London Clay and a stepped profile has resulted, with small rotational slides and debris slides developed (Fig. 12).

Landslides involving a major aquifer of stronger rock overlying weaker rocks

The Chalk is underlain by weaker rocks, usually weak sandstone, sand or stiff clay. Where Chalk outcrops in the upper part of a cliff section, and its base is above sea level, the association of a thick, relatively strong aquifer over weaker, less permeable rocks results in landslides of different forms. They often occur as large and spectacular events separated by long periods of quiescence.

Two contrasting stratigraphic situations are considered, first in the east where Gault Clay underlies the Chalk, and secondly in the west where weak sandstone and fine sand (Upper Greensand) is found beneath the Chalk. At Folkestone Warren, near Dover in Kent (Fig. 1, locality 9), 130 m of Chalk overlie 45 m of Gault Clay which in turn rests on sandstone (Folkestone Beds) below sea level (Fig. 13) (Hutchinson, 1969; Hutchinson et al., 1980). A railway traverses the zone of accumulated landslide debris and has been dislocated by movements several times, the largest event being in 1915 after four months of very high rainfall. Several factors contribute to the mechanism of movement here. Non-circular multiple rotational sliding takes place on surfaces which extend through the Gault Clay and along its base (Fig. 13). The low residual shear strength of the clay (down to $\varnothing = 7^\circ$), and the pore pressure in the underlying sandstone partly control reactivation along these surfaces. Groundwater from the Chalk aquifer discharges into the landslide mass of chalk debris which also raises the pore pressure on parts of the shear surfaces. In the 1915 movement, high pore pressure resulted in a reactivated rotational slide which in turn destabilised the Chalk backscarp. A large rock fall from the backscarp pro-

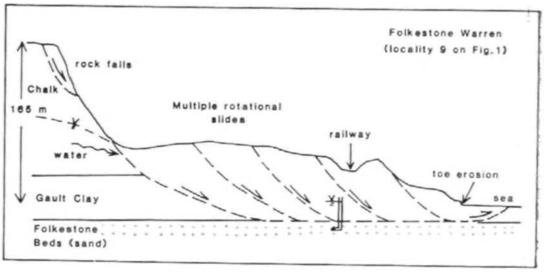

Fig. 13. Cliff profile in Chalk overlying Gault Clay

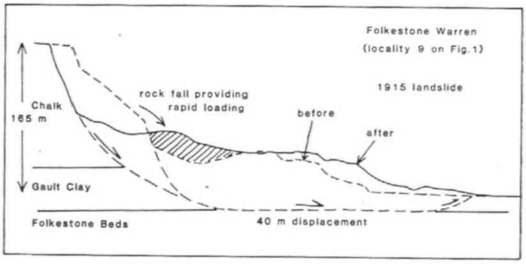

Fig. 14. Cliff profile in Chalk overlying Gault Clay where undrained loading occurred

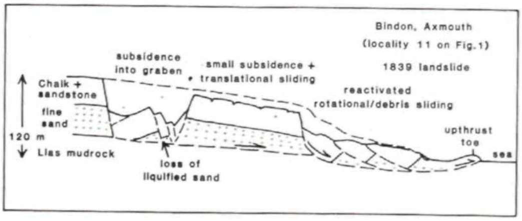

Fig. 15. Cliff profile in Chalk and Upper Greensand overlying Lias mudrocks

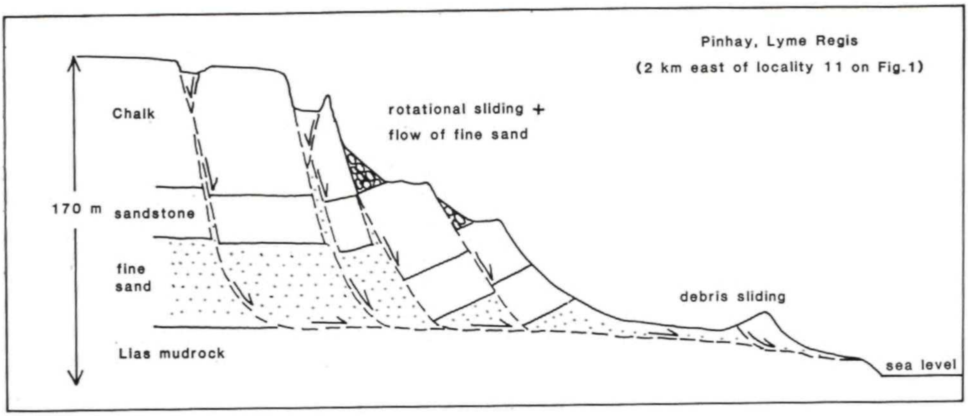

Fig. 16. Second cliff profile in Chalk, Upper Greensand and Lias mudrocks

vided rapid undrained loading which aided the 40 m displacement of the slide (Fig. 14). The shape of the basal shear surface means that weight on the toe at beach level is another important stability factor. Toe erosion and loss of beach gravel have been compensated by the installation of massive concrete toe weighting. Drainage adits have also been provided to reduce pore pressures in the slipped mass. A similar geological situation has formed a landslide zone of the same type on the southern coast of the Isle of Wight (Fig. 1, locality 10) (Hutchinson, 1965b).

The other example of a landslide in this category is near Axmouth in East Devon (Fig. 1, locality 11) where 40 m of Chalk and sandstone overlie 40 m of fine sand (Upper Greensand) and a thin Gault Clay resting on Triassic-Jurassic mudrocks. Several kilometres of coastline are subject to frequent landslides (Arber, 1973; Pitts, 1979, 1981, 1983) but the most notable event occurred in 1839 at Bindon, again after a very wet year had made the water table in the aquifer very high (Pitts, 1974). The cliff at this point was about 100 m high with the ground surface and the strata dipping gently seawards. The cliff profile after the event displayed an enormous graben structure inland from a large block of ground which had only suffered minor displacement (Fig. 15). The fine sand in this succession is subject to liquefaction when disturbed at high pore pressure. The reactivation of a rotational failure in landslide debris at the sea cliff is thought to have allowed forward sliding of the Chalk and Greensand on its weak mudrock base. This was accompanied by liquefaction of the fine sand which permitted subsidence of the massive Chalk and sandstone into the graben. This landslide has remained stable for the 150 years since it formed. In other places nearby, rotational sliding has accompanied the subsidence of large blocks into the fine sand (Fig. 16) (Grainger et al., 1985)

Conclusion

Although marine erosion of the base of cliffs in weak rocks maintains an oversteepened and hence destabilised profile, the groundwater hydrology and geotechnical properties of the lithologies present determines the size, frequency and shape of landslide movements. Rock falls and rotational sliding characterise the activity at the top of these cliffs, forming vertical or steep backscarps. Many weak rocks disintegrate with movement and the addition of groundwater. Therefore the lower parts of the cliff profiles are generally formed of debris slides or mudslides, moving on low-angle shear surfaces and at their residual shear strength. If wave erosion at the toe is faster than the rate of debris movement downslope, a sea cliff is maintained in undisturbed strata. If the movement of debris is faster than toe erosion, the rock is protected from wave action. Stabilisation of coastal cliffs to protect cliff-top property from landsliding involves a combination of wave protection, toe weighting, regrading to a long-term stable angle, plus surface and subsurface drainage to control pore pressures and to reduce the softening of mudrocks.

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