COASTAL MUDSLIDE MORPHOLOGY AND PROCESSES ON EOCENE CLAYS IN DENMARK

D.B. PRIOR

Prior, D.B.: Coastal Mudslide Morphology and Processes on Eocene Clays in Denmark. Geografisk Tidsskrift 76: 14 - 33. København, juni 1, 1977.

The study deals with three localities: Røjle Klint, Røsnæs and Helgenæs concerning shallow mudslides. The mudslide morphology at the three slides is described together with detailed laboratory analysis of the characteristics of the eocene clays, i.e. to relate the field characteristics of the mudslides and their associated processes to the geotechnical and geochemical properties of the clays. The significans of postglacial changes in land-sea level relationship to land slide morphology consider the time scale of variations in coastal activity.

Dr. D.B. Prior, Department of Geography, The Queens University of Belfast. Belfast BT 7, 1 NN, Northern Ireland.

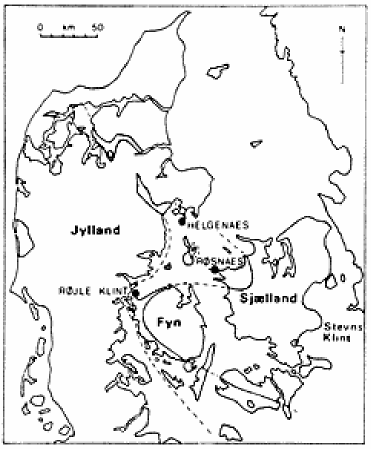

Fig. 1. Location map of mudslide sites in relation to the Eocene clay.

Introduction

Recent field investigations in Denmark have revealed the presence of a wide variety of mass movement phenomena. These include deep-seated rotational landslides, of different ages, and shallow mudslides, many of which are extremely active (Prior, 1973; Prior and Eve, 1975).

The landslides are almost entirely confined to very specific coastal areas where there is sufficient relief, steep slopes and most particularly, where there are outcrops of clayrich sediments of Eocene age. Elsewhere in Denmark, glacial sediments almost completely mask the underlying bedrock and while there are some examples of mass movement on glacial terrain (e.g., at Dollerup, in Jutland in 1957) these are very sporadic in occurrence and of only temporary local significance.

By comparison, certain coastal areas are dominated by mass movement topography and the coastal processes are considerably influenced by landslide activity. Stevns Klint, in eastern Sjælland, is one well-known site where active coastal retreat is linked to rockfall activity involving Danian and Senonian limestones.

This paper is concerned exclusively with mass movement landforms and processes associated with coastal outcrops of Eocene clay, principally at three sites, Røjle Klint in north-western Fyn, Røsnæs ind northwest Sjælland, and Helgenæs in Djursland. At all three localities the sub-aerial coastal slope morphology is affected by shallow sliding of weathered clay. This process involves the development of well defined landslides which move primarily as translational slides over basal shear planes inclined parallel to the surface slope topography. However, these mass movements are difficult to classify with precision since they may also move in a manner approximating to viscous flow. This occurs when the weathered clays are temporarily highly charged with water. The term »mudslide« is used here to indicate the predominant movement type. At both Røsnæs and Helgenæs the mudslides are developed within areas of larger scale, deep-seated rotational sliding of Eocene clay and overlying glacial sediments (Prior and Eve, 1975). At Røjle Klint the mudslide movements are the dominant sub-aerial processes.

The mudslide morphology at these three sites is described together with detailed laboratory analyses of the characteristics of the Eocene clays. Attempts are made to relate the field characteristics of the mudslides and their associated processes to the geotechnical and geochemical properties of the clays by applying conventional stability analysis procedures. The significance of post-glacial changes in land/sea level relationships to landslide morphology is also examined.

Fig. 2. General views of Røjle Klint coastline. Mudslide toe lobes have prograded on to the foreshore. Pleistocene deposits outcrop in the foreground.

Distribution and morphology of mudslides

The three principal mudslide locations are Røjle Klint, Røsnæs and Helgenæs (Figure 1) but other sites exist on the coast northeast of Fredericia and possibly on the island of Samsø, within the areas of the Eocene clay outcrop. There are quite distinct differences in coastal and mudslide morphology at each of the main areas and each will be considered separately.

Røjle Klint

Extremely widespread and very active slope instability can be identified in the areas known as Røjle Klint, east of the town of Strib, on the northwest corner of the island of Fyn. Here, the coastal siopes fringing the Lille Bælt rise steeply to elevations between 30-40 m. (Figures 2 and 3). To the east of Sølyst farm, the slopes have an average inclination of 20-30° and are underlain almost entirely by Eocene clays which can be observed outcropping on the foreshore below high water mark as part of a wave-cut platform and in the steep slopes above. Elsewhere, the slope deposits are composed of weathered clay, or clay that has been reworked by mudsliding. Glacial sediments form only a very thin veneer at the top of the coastal slopes. By contrast, the cliffs west of Sølyst are entirely composed of glacial sediments revealing the very important Pleistocene sequence of glacial and inter-glacial deposits dating from the Mindel period (Madsen and Nordmann, 1940).

Active mudslides occur in the area where Eocene clay is present in the coastal slopes, over a distance of 1-5 km to the east of Sølyst, extending inland a distance of approximately 300-400 m (Figure 3). Almost all of this densely wooded area shows some evidence of previous or incipient mudsliding and the entire coastal slope can be classified as »potentially unstable«. Some productive farmland, on the flatter areas above the coastal slopes, is being removed as the mudslides encroach inland. Some buildings are in vulnerable locations. There are no large, deep-seated rotational landslides at Røjle Klint and all the instability involves relatively shallow, very active mudslides. Two main categories can be recognised; shallow translational slides on steep slopes, and very elongate slides. Shallov translational slides occur as relatively short features on steep slopes (< 20°) and possess steeply inclined shear surfaces which may be rather irregular and undulatory in long profile. Slipped units of clay temporarily overlie the beach sands but are quickly eroded by the sea. Extremely fresh slides can be observed in spring time but by summer most of the deposited debris is removed. These features are therefore extremely ephemeral and often, a former slide can only be recognized by the absence of trees on the slopes.

The elongate slides are much larger with width/length ratios of less than 0,2 and appear »glacier-like« in form, deeply incised into the coastal slopes. Each mudslide has an abrupt, steeply sloping arcuate headwall op to 10 m in

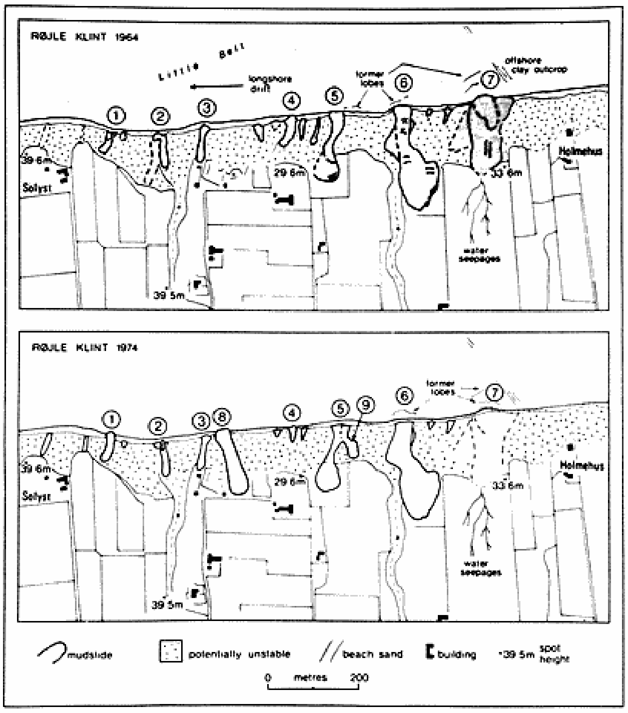

Fig. 3. Comparative maps of mudslide morphology at Røjle Klint, drawn from air photographs.

height with shallow rotational and translational processes extending the area of instability further inland. As the mudslides lengthen themselves they actively encroach upon agricultural land, damaging field boundaries. Below the headwalls the mudslides occupy deeply incised, elongate channels bounded by very pronounced marginal shear planes. These channels have an average slope of between 5 and 10° but the long profiles are irregular with short, steep sections contrasting with long segments which are only very gently inclined. At steep parts, tranverse cracks extend across the debris in the channels. Each channel may subdivide into smaller, very narrow slides and »flows« which meander downslope (Figure 4). In summer, these mudslides dry out and may be examined on foot, with some ease. However, in spring time (e.g., April, 1975) they were found to be extremely unstable and very dangerous. Fresh slicken-sided marginal shears marked the edge of treacherous »rivers« of mud with very high water contents and very low strength. Some low angle areas were virtually pools of liquid mud and were totally unapproachable. Experience elsewhere with very similar mudslides suggest that extreme caution must be exercised because of the danger of sinking and the possibility of abrupt, unpredictable rapid movements (Prior and Stephens, 1972; Hutchinson, Prior and Stephens, 1974).

Fig. 4. Small mudslide track (approximate width — 2 m) at Røjle Klint.

Mudslide debris is discharged from these channels on to the foreshore forming elongate rounded lobes. Each »toe« area may, in fact, be composed of several overlapping lobes often with trees buried within the debris. Sometimes trees move with the sliding material, remaining upright on the surface but inclined at a variety of angles. The distal parts of the lobes possess very regular convex profiles, except where they have been eroded by the sea. Marine erosion may remove an individual lobe almost completely. Mudslide debris is truncated, producing a flat, of very gently sloping inter-tidal wave cut platform in remoulded mud. The outline of the former lobe can be easily distinguished even though some beach sand accretion may take place over it. The fabric of the mudslide deposits is extremely well exhibited in such platforms and is composed of rounded aggregates of remoulded clay and blocks of partially weathered, fissured clay in a fine matrix. The presence of such platforms at the truncated ends of channels, even in spring, suggest that some of the mudslides are sporadic in activity and that sufficient time exists between successive mudslide emissions for planation to take place. This is in contrast to other adjacent sites where the lobes appear more permanent and where the rate and periodicity of debris supply temporarily exceeds that of marine removal.

The morphology of the mudslides at Røjle Klint is demonstrated in Figure 3 which compares the evidence of instability recorded by vertical air photography in April 1964 and April 1974. The photography scales (1:10,000-1964, 1:25.000-1974) have been matched approximately, with some loss in accuracy.

In 1964, there were seven major elongate mudslides (1-7 in Figure 3) of which 5, 6 and 7 were the largest. Other smaller slides can be identified, for example between 3 and 4, 6 and 7. These are mudslides on steep coastal slopes which were being eroded by the sea. Slide 1 was relatively inactive in 1964 with sand accretion over a truncated toe lobe. By comparison, slides 5, 6 and 7 had actively prograded over beach deposits. The two largest slides (6 and 7) occurred in association with surface and ground water supply; for 6 a small ephemeral stream and for 7 an area of sub-surface water seepage which could be clearly identified on the air photographs.

By 1974 considerable changes in mudslide distribution and activity had taken place. Overall, there was less evidence of recent slope movement but more marine erosion and deposition. Some of the smaller, steep slope mudslides had disappeared. However, slide 1 was obviously more active with a fresh lobe over the beach sands. A very large, totally new elongate slide (8) was present between 3 and 4 and had eroded 20-30 m of agricultural land. Slide 5 appeared to have declined in activity, although an additional tributary slide (9) had appeared. Slides 6 and 7 were relatively stable and the distal edges of the toe lobes had retreated considerably and was overlain by beach sand.

This photographic evidence indicates some interesting mudslide properties. For example, an individual elongate slide may substantially alter its level of activity. In this respect it should be noted that by April 1975 slide 6 was once again prograding vigorously. While this characteristic may reflect increases or decreases in instability for the slope as a whole there are enough exceptions to show that all the mudslides do not necessarily function in harmony. Also, it is evident that new, large elongate slides may become established relatively quickly with characteristic bilinear long profiles of steep headwalls and low angle accumulation slopes. In addition, the steeper slopes in clay are intermittently instable, producing a continuously changing pattern of translational sliding. For example, between April 1974 and April 1975 four new shallow translational slides were identified between slides 1 and 8. Røjle Klint therefore provides extremely interesting examples of two different mudslide types, both associated with the Eocene clay. There are clearly very complex spatial and temporal variations in the relationships between both types of mudslides and marine erosion processes.

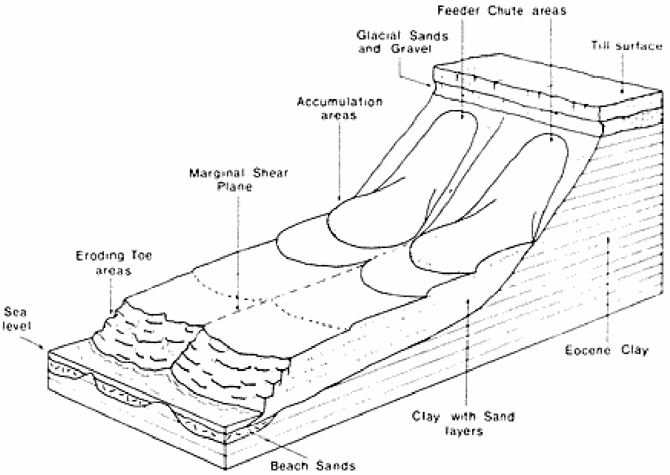

Fig. 5. Diagrammatic representation of a mudslide at Røsnæs.

2. Røsnæs

The Røsnæs peninsula comprises a narrow-ridged promontory about 15 km i length rising to a maximum elevation of 64 m. The south facing coastline, bordering Kalundborg Fjord is rather steep with relative relief of 40-50 m immediately adjacent to the coast. The slopes are composed of a variety of Tertiary and Pleistocene sediments. Eocene clay are overlain discontinuously by two till units separated by sand and gravels. Fluvioglacial deposits mantle the upper till and provide the surface kame moraine topography of the area. The Eocene clay outcrop below sea level and in the coastal slopes.

Several different types of landslide are present in this area, of various ages, including deep-seated rotational slides, retrogressive slides and mudslides (Prior and Eve, 1975). The most active mudslides occur in the vicinity of the Factory, approximately 6 km from Kalundborg, and are developed within a large rotational slide. The mudslides begin on the Eocene clay outcrop where it is exposed within the larger landslide and extend to the coastline between large, rotated blocks of till and glaciofluvium. The seaward edges of the mudslides and the rotated blocks are subject to continuing marine erosion.

Each mudslide has three distinct morphological components vizii, a steep head slope or »feeder« area, a low angle accumulation slope and a toe lobe (Prior and Eve, 1975 — Figure 5). Two basic types of feeder slope can be recognised. The majority are unstable slopes involving shallow slab slides on the outcrop of the Eocene clays and with inclinations varying from 30-40°. These show slicken-sided, planar shear surfaces together with exten-

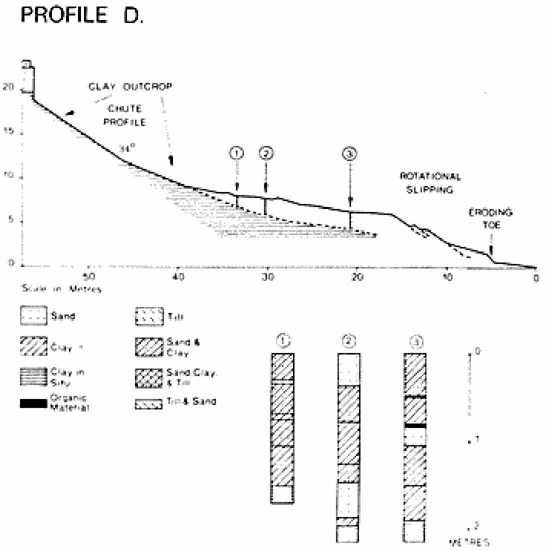

Fig. 6. Surveyed profile of a mudslide at Røsnæs.

Fig. 7. Mudslide toe lobe at Røsnæs which has been trimmed by marine processes.

sive cracking. By comparison, some of the feeder areas have very steep back slopes (34°) and distinct channels of elongate chutes are formed. Adjacent channels are separated by sharp crested ridges of clay which soften and »weather« by hydration and dehydration supplying material to the chute floor. During wet conditions rain water is absorbed by the clays, helped by the numerous fissures. Mud runs, flows, and miniature slides carry the weathered debris towards the thalweg of the chute.

Below the feeder slopes there are long segments of the mudslides at comparatively low angles 0-10° composed of overlapping lobes of clay. For example, Figure 6 shows a mudslide in which slope angles vary in detail from negative values (small reverse slopes) to 17° but the average slope of the accumulation area is 7°. This material is inherently more stable than that on the slopes above but is also subject to shallow translational sliding involving slabs 1-2 m in depth. Instability is bounded by well-developed parallel systems of marginal shear planes and each slab is markedly elongate. Width to length ratios vary between 0.5 and 0.1 with the width of each slab approximately twice the thickness. Preliminary observations of movement patterns show that displacement across the surface of each slab is uniform except for some reduction near the marginal shears and this suggests movement which approximates the »plug flow« type described by Hutchinson (1970).

The toe areas refer to those parts of the mudslide accumulation areas, which terminate at present sea-level and where the remoulded mudslide clay is eroded. The toe areas have much steeper overall profiles. For example, Figure 7 shows a toe with an average slope of 22°. Marine undercutting and trimming of these slopes produces small rotational slides and miniature slump blocks in clay. The mudslide debris can be examined in section where the erosion is most vigorous. Layers of remoulded clay are separated by sand layers which have been introduced to the mudslide debris by processes further upslope (Prior and Eve, 1975). The toe areas clearly show a continuous interplay between mudslide prograding and marine erosion and the outer limits of the toes change position depending upon whether mudslide or marine activity is dominant. But it must be emphasized, that marine erosion never attacks slopes in Eocene clay directly. Elsewhere marine processes are slowly modifying the front slopes of larger rotated blocks of glacial material, relics of former deep-seated landslide activity.

The detailed mophology of one of the Røsnæs mudslides is summarised in an angle/frequency diagram

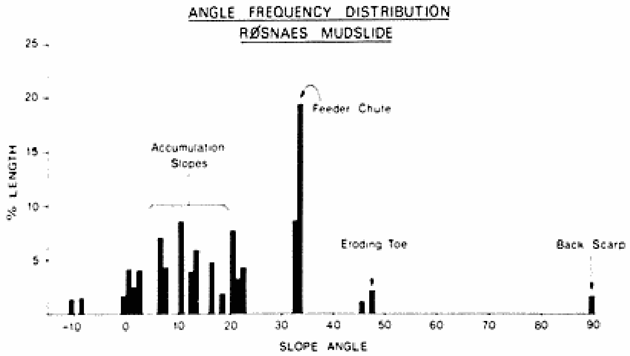

Fig. 8. Angle/frequency analysis of a mudslide at Røsnæs.

(Figure 8) based on profile surveying using a Watts quickset level. This diagram shows the relationship between slope angle and lengths of slope segments, the latter plotted as percentages of the total mudslide length. Four main groupings of angles/lengths are evident. The small, vertical back scarp is developed entirely in glacial deposits overlying the Eocene clay. Some steep slope angles (40-50°) are associated with the eroding toe areas. The steep slopes at 32-34° which comprise almost 30% of the total length of the mudslide are developed upon unstable and weathering Eocene clay. The majority of the slope segments clustered around 10° are indicative of the accumulation zone. A small proportion of the steeper angles together with the negative slope angles represent small rotational slides with steep front and gently inclined reverse slopes on the eroding toe area. It is apparent from this diagram that this mudslide is strongly concave and bilinear in form, with the accumulation zone accounting for approximately 65% of the total mudslide length. Examinations of other surveyed mudslide profiles for the Røsnæs area shows that this may reach 75% (Prior and Eve, 1975).

Helgenæs

The Helgenæs peninsula of Djursland represents an area of moraine accumulation related to southwards retreating ice lobes in the final Baltic stage of the last glaciation. Schou (1959) has discussed the coastal morphology of this area, particularly regarding the effectiveness of coastal erosion. The north/south Helgenæs coastline is described as being particularly exposed to marine erosion with the line of the coast at right angles to the resultant of wave work. Schou (1959) concludes that the cliff shoreline has retreated without altering its orientation although no actual measured rates of retreat are given.

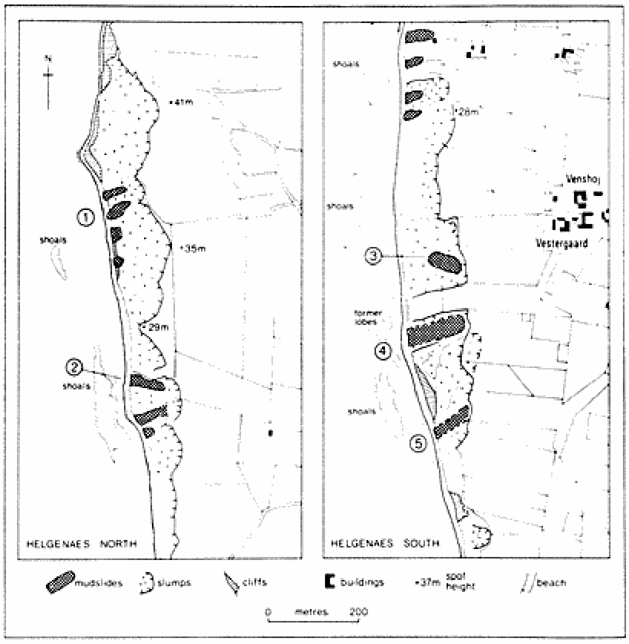

Fig. 9. Location map of landslides at Helgenæs.

The morainic topography, composed of tills, sands and gravels, rises 30-40 m above sea level immediately adjacent to the coast. Eocene clays outcrop intermittently beneath the glacial sediments which vary greatly in thickness. The cliff coastline for a distance of 2.2 km is dominated by landslide morphology of different types. These are mainly deep-seated rotational »slump« landslides involving Eocene clay at the base and large units of displaced glacial deposits. The largest individual rotational slide is at the northern end of the peninsula with a coastal length of 300 m and a bowl-shaped amphitheatre depression extending 150 m inland. Some of the front slopes of the rotated blocks (but not all) are currently subject to marine trimming and erosion but nowhere is in Eocene clay exposed to contemporary marine activity. Thus, erosion chiefly involves some steepening of slopes in till, sand and gravel. Distinct curvo-linear offshore shallows and shoals all along this coast may represent the remnants of the original outer margins of the rotational landslides and suggest an approximate coastal retreat of 100 m since the rotational instability took place.

Mudslides occur principally on the flanks of these larger slumped blocks or behind them. Figure 9 shows the locations of individual mudslides. Slides 1, 2, 4 and 5 are all associated with rotational slides and in particular slide 2 demonstrates the manner in which mudslides emerge to the coast on either side of the displaced blocks (Figure 10). Slides 4 and 5 show the same morphological association, but on a larger scale. Slide 3 is located within an area of rotational slides and is prevented from reaching the coastline by the reverse slope of the slump (Figure 11). All the mudslides are elongate in plan and are well vegetated. The presence of sub-parallel marginal shears suggest that displacement is continuing but by comparison to Røjle Klint and Røsnæs the general impression is of

Fig. 10. Mudslide adjacent to rotational slides at Helgenæs. Both types of landslide have been abandoned by sea level reduction due to isostatic uplift. Note the vegetated front slope of a rotated block.

relatively small movements. This is confirmed by comparison of field morphology with former air photograph coverage of the area. For example, there is little evidence of major discharges of mud on to the foreshore or the development of large actively prograding toe lobes (Figure 12). This is illustrated by surveyed profiles of selected mudslides (Figure 13). Mudslide 2, in particular, grades gently on to the beach with a front slope of 7°. Mudslides 1, 4 and 5 have only very small erosional notches just above the beach. Mudslide 3 does not reach the foreshore and has a low angle front lobe inclined at 5-9°. Indeed, the profiles of all the Helgenæs mudslides are remarkably low angle, with average inclinations of approximately 10°. This slope value includes short segments of each slide which are more steeply sloping, combined with some which are inclined upslope. These minor irregulations coincide with the positions of arcuate transverse cracks which extend across each slide and can be interpreted as very shallow successional slides which involve some rotation of small blocks of mudslide debris. In addition,

Fig. 11. Mudslide at Helgenæs within an area of rotational sliding (Profile 3).

Fig. 12. Low angle mudslide at Helgenæs.

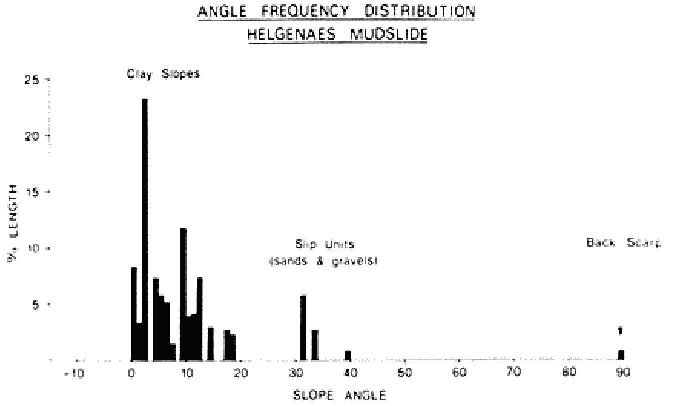

Fig. 14. Angle/frequency analysis of a mudslide at Helgenæs.

the average slope value includes very short segments at the upslope end of each slide which are more steeply inclined, composed of clay and/or glacial deposits.

The generally low slope angles of the mudslide are illustrated by angle/frequency analyses of mudslide 2 (Figure 14). This shows that, apart from the very small back escarpment and slip units in sand and gravel, the clay slopes are gently inclined at angles which vary from 0-19°. The longest segments vary between 0-10° and 34% of the slide slopes at less than 3°. An additional 20% of the slide slopes at 3-8°. A comparison of the angle/frequency diagram (Figure 14) with the surveyed profile (Figure 13) shows that the steeper angles in clay (16-19°) occur towards the upper parts of the mudslide.

Mudslides 1, 2 and 3 have many similarities, with long segments at low angles, essentially composed of overlapping lobes of mud with only infrequent minor irregularities. By comparison, slides 4 and 5 are much more irregular. Slide 5, in particular, has at least six identifiable shallow rotations with front slopes at 13-31° and reverse slopes inclined at 2-6° upslope. Successive slips in the central part of slide 4 give minor steps and undulations with steeper slopes at 17-36° and reverse slopes of 1-8°. It must be emphasized that the mudslides at Helgenæs are in marked contrast to both Røjle Klint and Røsnæs, both in overall level of activity, the generally subdued nature of the profiles and the presence of successive slipping.

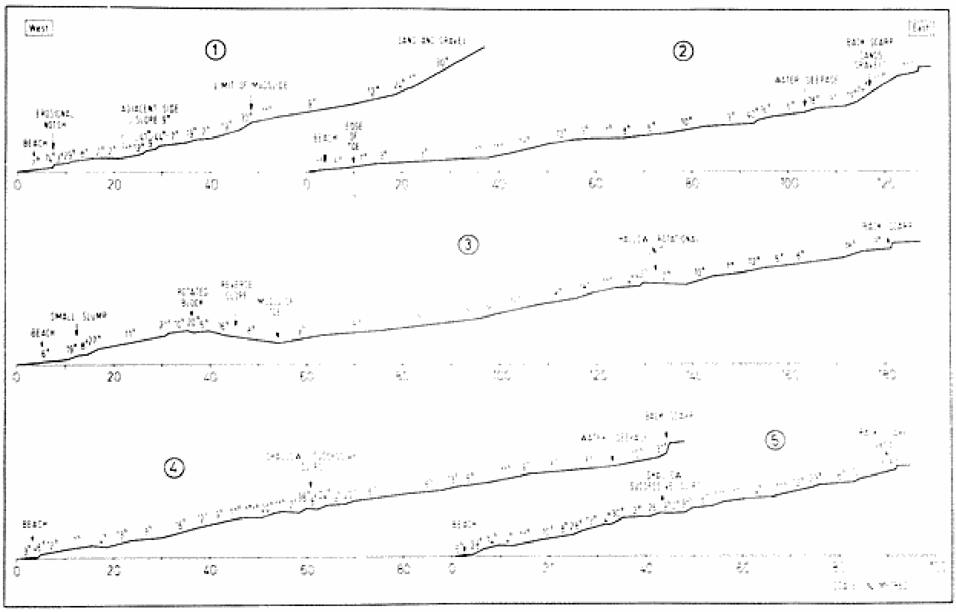

Fig. 13. Selected suveyed profiles of Helgenæs mudslides (compare Fig. 9).

The Properties of the Eocene Clay

Danish Eocene deposits consist of two very distinctive facies, namely the Mo clay which occurs mainly in northern Jutland around Limfjord and the so-called »Lille Bælt« clay. Nielsen (1974) has discussed the sedimentary characteristics of these deposits and notes that both the Mo clay and the Lille Bælt clay contain volcanic tuffs, especially near their bases. Also, the Mo clay is extremely diatomaceous whereas the Lille Bælt clay is largely unfossiliferous.

The Lille Bælt clay, of which the upper layers are referred to as »plastic clay« (Nielsen, 1974) outcrops on the coast at the three mudslide sites. It is also known from numerous boreholes in Jutland and Fyn, with thicknesses in excess of 100 m. Hvorslev (1937) has discussed the age of the Danish Eocene clay, particularly in comparisom to the London clay of southern England. It is concluded that the two are broadly contemporaneous. The lower Danish clay probably predates the oldest London clay, whereas the middle parts of the Danish succession are taken to be equivalent with London clay due to the presence of the crab Plagiolophus Wetherelli and both are ascribed a lower Eocene age. Deposition of the upper layers of Danish clay is believed to have continued until the Middle Eocene. Hvorslev (1937) notes that simultaneous deposition of »such uniform, peculiar clays may thus possibly be a common factor characteristic of the geographic or climatic conditions of that period«.

It will be demonstrated that there are many similarities in the properties of the London and Danish clays and the associated processes which produce mudslides. One immediately apparent similarity is that they are both heavily overconsolidated. The Danish clays, for example, were covered by ice sheets on several occasions during the Pleistocene period. Hansen and Mise (1964) estimate a probable thickness of ice during the last glaciation to have exceeded 100 m and infer a geological pre-load for that event alone of 500 t/m^2. In outcrop, the clays have a range of colours, from rusty/reddish brown to grey or grey/blue. They are often heavily folded and contorted. One of the most obvious characteristics is the extensive fissure systems produced by the release of consolidation load, both by deglaciation and by subsequent exposure by marine erosion.

A range of laboratory tests were conducted on samples from the three mudslide sites. The objectives were to examine the general characteristics of the material involved in mudslide activity and to establish the comparability of properties at the three localities.

1. Grain size analysis.

The sediments are very rich in clay-sized particles but the precise determination of the grain size distribution is problematical. Hansen and Mise (1964) report a clay fraction of 65-80%. Prior (1973), and Prior and Eve (1975) provide data from hydrometer analyses of samples from Røsnæs where the total clay fraction ($<5\mu$) can account for 65-76%. The sand and silt contents are variable but the latter is always dominant with an average of 18% for the 63-5μ range compared with an average of 9% for the $>63\mu$ range.

However, further work at all three sites has suggested that these results may not be precise since severe difficulties of reproducibility of data for a single sample have been encountered. This is regarded as being partly due to inadequacies in the hydrometer method and partly to the nature of the clays. The plastic clay is often very difficult to disperse, and has a very pronounced tendency to flocculate. Moreover, these characteristics seem to vary in an apparantly random manner.

There seems little doubt that the pre-treatment of the samples and particularly the dispersion methods can significantly affect the results. In order to investigate this and to establish the degree of similarity between the three sites, samples have been tested using a Coulter counter (model TA). The advantages and disadvantages of this method of size analysis have been evaluated by Walker and Hutka (1971) but in this case it can be used to provide a standard means of assessment of the clays.

The pre-treatment procedures were carefully controlled for each analysis. Samples were initially passed through a 63μ sieve and two dispersing agents employed, calgon $(NaPO_3)n\ Na_2O$ and sodium hexametaphosphate, Na_3PO_4. A high speed stirrer together with an ultra-sonic bath (125 watts, 50-60 Hz) were used to facilitate physical disaggregation. Different time periods were used for stirring and ultra-sonic treatment and the results evaluated.

The affects of variations in pre-treatment can be demonstrated using Figure 15 which presents Coulter counter traces for a sample of Helgenæs clay. The counter aperture used in these tests was 100μ producing an effective analysis of particle size in the range 2-40μ. LInes, 1, 3, 4 and 5 refer to different periods of stirring and ultra-sonic treatment with Na_3PO_4. LIne 2 refers to 15 minutes stirring and 15 minutes ultra-sonic treatment was $(NaPO_3)\mu Na_2O$. If the results of disaggregation using the two chemicals are compared (with the same disaggregation times) then it can be seen that line 2 represents a much less dispersed sample than line 4. Na_3PO_4 would thus appear to be more effective. The differences are considerable, varying with grain size category. For example, the calgon treatment yielded 51% less than 10μ while the sodium hexametaphosphate treated sample gave 67%. Considering that part of the sample $<5\mu$ the approximate values are 35% and 45% respectively.

For samples treated solely with Na_3PO_4 but with different ultra-sonic times a consistent pattern is obtained. As the length of time is increased the degree of disaggregation increases. For example, after 5 minutes the $<5\mu$ fraction accounted for 30% but increased to 45%

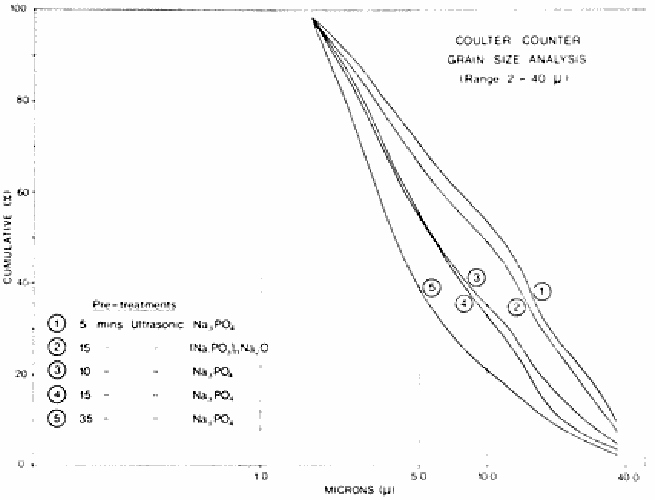

Fig. 15. Coulter Counter traces of samples from Helgenæs showing variations due to pre-treatment procedures.

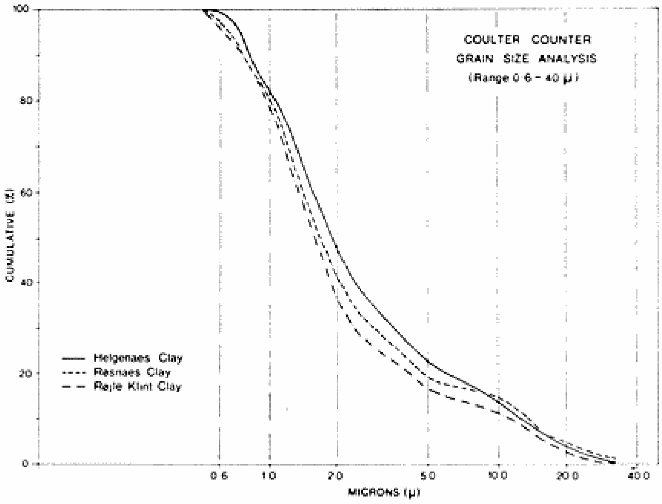

Fig. 16. Comparative Coulter Counter traces of samples from the three mudslide areas.

after 10 minutes and to 60% after 35 minutes. Such considerable variation in results makes the exact description of the clays very difficult. Moreover it points to the extremely doubtful quality of simple hydrometer analyses on such clays which have not been carefully pretreated.

Consistent results were, however, obtained following dispersal using an ultra-sonic probe (180 watts, at 70-80μ movement) for 10 minutes using Na_3PO_4, following methods described by Walker et al (1974). Figure 16 present data for all three sites using a »2-tube method« which overlaps 20 and 100μ apertures giving an effective analysis range of 0.6 — 40μ. The results show all three mudslide locations to have materials which are very similar in character with the maximum differences at the 2.5μ size of only 10%. The clay fraction (<5μ) accounts for between 77-83%. Of that fraction the <2μ clays account for 52% at Helgenæs, 59% at Røsnæs and 63% at Røjle Klint. These analyses refer specifically to samples of undistured Eocene clay and cannot be regarded as exactly representative of the mudslide debris at these sites. While the Eocene clay is the basic parent material from which the debris is derived the latter is composed of lumps and blocks of intact clay within a remoulded clay matrix. Hutchinson (1970) has noted this characteristic in association with mudslides in London clay and suggests, that this reflects the genesis of the slides through softening of the overconsolidated argillaceous sediments. Mudslide debris may thus possess its own characteristic grain size distribution including a wide spectrum of aggregate sizes. In practice this is extremely difficult to evaluate since these are unstable and cannot easily be separated from the matrix. Moreover, the block/matrix ratio varies considerably within an individual mudslide and with changes in overall water contents. The grain sizes which have been presented are therefore somewhat artificial in the context of actual mudslide processes but they do serve to characterize the material involved and show the similarities in the clays at the three sites where mudslides occur.

2. Clay Mineralogy

The mineralogy of the clay fraction from each site was examined using a Philips x-ray diffractometer yielding Cu K_α radiation. Each sample was subjected to x-rays in three different states, namely air dry, treated with ethylene glycol and after heating at 550 ° C for one hour. Røsnæs clay had already been examined using prepared homoionic samples as an aid to mineral identification (Prior, 1973).

Diffraction traces from 2-15° (2θ) are presented in Figure 17 and it is readily apparent that alle three areas gave similar peak patterns. The air dry preparations gave pronounced peaks at 12-13 Å and at 7-2Å with a »shoulder« on the edge of the 12Å peaks at approximately 10Å. Glycolation caused significant expansion of the 12-13Å peaks to between 16-17Å and revealed more clearly the peaks at 10Å. Heat treatment destroyed the 12-13Å peaks and 7Å peaks in the Røsnæs and Helgenæs samples byt the 7Å peak persisted for the Røjle Klint samples. Heat treatment enhanced the 10Å peak in all three cases. These results broadly conform to the previous tests on Røsnæs clay (Prior, 1973). Firstly, the 10Å peak firmly indicates the presence of illite. The 7-2Å spacing suggests either chlorite or kaolinite, or a combination, since the chlorite second order peak and the 001 kaolinite spacing coincide at this position. In this respect, the heat treatment is helpful because, chlorite, if present, should be relatively unaffected by dehydration, while it is well known that kaolin crystallinity can usually

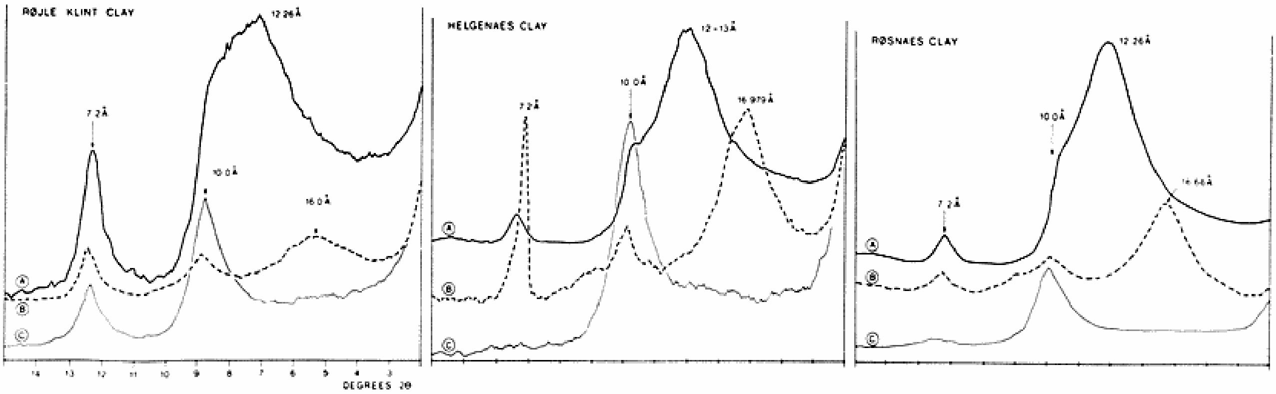

Fig. 17. X-ray diffractometer traces of samples from the three mudslide areas.

be destroyed by heating. The destruction of the peaks for Røsnæs and Helgenæs indicates the existence of kaolinite and while this may also be present at Røjle Klint there remains the possibility that the 7Å peak, or part of it, represents chlorite. The 12-13Å spacing, expanding to 16-17Å with glycol clearly shows the presence of a swelling clay mineral. This could be either vermiculite or montmorillonite. The distinction between the two is difficult to make solely on the basis of x-ray diffraction but further examination of the Røsnæs samples (Prior, 1973) convincingly indicated montmorillonite.

These interpretations agree with those of Nielsen (1974) of Eocene clay from Ølst in Jutland, 40 km to the north of Helgenæs. Peaks at 12-15Å, which on glycolation moved to about 17Å, were ascribed to montmorillonite. Illite was identified from 10Å peaks and kaolinite from 7-2Å peaks.

Differential thermal analysis is also widely used for clay mineral identification using the principle that changes occur in clay minerals when they are heated to high temperatures. Individual clays possess characteristic temperatures at which they loose water or undergo phase changes and these can be used for identification. Moreover in naturally occurring materials in which there is a mixture of minerals the dehydration patterns may be used to identify individual minerals. There is, however, the problem of overlapping endothermic and exothermic reactions and positive identifications are difficult. But, thermal analysis data can be valuable supplements to x-ray analysis.

The clays from Helgenæs, Røsnæs and Røjle Klint were air dried and subjected to heating using a Stanton-Redcroft D.T.A. apparatus (673-4) at heating rates of 16°C/min. The endothermic and exothermic temperature peaks are given in Table 1.

The dehydration curves from all three sites are remarkably similar and all are s-shaped with no distinct breaks between the changeover from inter-layer waste loss to OH lattice water loss. All three samples show pronounced endothermic reactions between 100-200°C, at around 550°C and between 850-900°C. Exotheronic reactions can be noted at 350°C and between 900-950°C. The 100-200° C reaction confirms the presence of montmorillonite because this mineral is characterized by considerable interlayer water loss at these temperatures. Also, the structure of many montmorillonites persists to temperatures between 800-900°C where an endothermic reaction represents the destruction of this lattice. This may, in part, account for the 850-900°C peaks, commom to all the samples. Similarly, the presence of illite and kaolinite is confirmed by the D.T.A. curves because endothermic reactions at about 550°C with exothermic peaks at 900-1000°C suggest illite. Kaolinite is indicated by endothermic reactions between 400-600°C and an exothermic peak at 550°C. It is clear, however, that the endothermic peaks at 550°C and exothermic peaks at 900-950°C could point to either illite or kaolinite or a combination of these minerals.

Table 1. Exothermic and endothermic peaks from differential thermal analysis of clays.

Helgenæs	114	557	869	350	930
Røsnæs	120	566	872	355	908
Røjle Klint	120	557	868	346	904

The D.T.A. results thus tend to validate the x-ray interpretations. The possibility of chlorite at Røjle Klint is not substantiated since characteristic endothermic reactions at 600-650°C and exothermic peaks at 840-900°C are absent. In addition, both types of analysis points to a predominance of montmorillonite over the other minerals. The quantitative evaluation of such data is difficult but for example if the D.T.A. curves are examined for peak area then the montmorillonite area is consistently twice that of the overlapping illite and kaolinite peak. The ratio of montmorillonite to illite plus kaolinite thus appears to be approximately 2 for the clays examined.

Indeed, there emerges a most striking similarity in the mineralogy of these sediments associated with mudslides at Helgenæs, Røsnæs and Røjle Klint.

3. Natural water content

The natural water content of the Danish Eocene clay has been determined by various workers. Mertz (1928) reported a value of 31% for Lille Bælt clay, while Hansen and Mise (1964) suggested a range of 28-48%. By comparison, Nielsen (1974) sampled the Eocene sequence at Ølst in Jutland over a vertical exposure of 10 m and showed the water content to vary greatly reaching a maximum of 70% at several horizons, and, in particular near the surface. These values refer exclusively to in situ Eocene sediments.

The natural water contents of the materials actually involved in mudslides at Røjle Klint, Røsnæs and Helgenæs, vary greatly within each site. Hutchinson (1970) has suggested that there may be difficulties in water content determinations on mudslides posed by the grain size variations and the presence of aggregates. It was shown that overall values have little meaning because there are substantial differences between matrix and aggregate values and that it is the former which best relates to mudslide processes. The remoulded matrix values at Røjle Klint, Røsnæs and Helgenæs vary greatly with depth, spatially through an individual slide, and more particularly all the values change markedly on a seasonal basis.

For example, samples collected during the months of July and August by hand augering to a depth of 3-5 m in a mudslide at Røsnæs showed a range of water content from 12% at and near the surface to a maximum of 43% at a depth of 2-5 m. By contrast, at the same site in the months of March and April surface water contents were as high as 60%. Similar seasonal variations were observed at Røjle Klint with surface values during summer months of 10-15% compared with 65-70% in spring time.

4. Geotechnical properties.

Tests were carried out to determine some of the basic geotechnical properties of the in situ clay at the three mudslides sites. In addition to the determination of various index properties two types of strength tests were employed, undrained fall-cone tests on remoulded samples, and drained direct shear tests on undisturbed blocks from Røsnæs.

a) Index properties: Table 2 provides data for soil density and Atterberg limits from samples from all three sites.

Table 2. Index properties of mudslide clays.

	Unit weight gm/cm^3	Plastic Limit	Liquid Limit	Plasticity Index
Helgenæs	1.71	36	61	25
Røsnæs	2.09	32	60	28
Røjle Klint	1.79	31	58	27

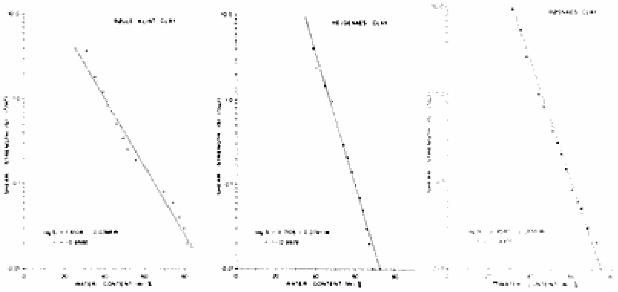

Fig. 18. Water content/undrained strength relationship from fall cone analysis.

There is a remarkable similarity in properties at each of the sites which is in general agreement with the homogeneity of grain size and mineralogy, already discussed. The liquid limits are rather low by comparison with other published analyses (Hansen and Mise, 1964, liquid limits 70-260; Prior, 1973, liquid limits 70-273). Indeed, a feature of these sediments is the occasional sample which yields very high values but as yet this characteristic is unexplained.

b) Undrained fall-cone tests: These were carried out using a Geonor fall-cone on remoulded samples at different water contents, to examine its effects on undrained strength. Figure 18 compares the results from each of the three mudslide localities. While there are certain potential sources of error, in both strength and water content determination, there is a significant statistical relationship in each case between strength and water content. From these tests the broad similarities between the clays at the different sites is maintained, especially Helgenæs and Røsnæs. Røjle Klint clay exhibits a similar range of strength properties but over a sligthly wider range of water contents.

c) Drained direct shear tests: Intact blocks were obtained by excavation from outcrops of Eocene clay at Røsnæs. These contained very distinct systems of parallel and sub-parallel fissures. Shearing tests were carried out with displacement parallel to the dominant fissure planes, incorporating a natural fissure as the potential shear surface. Tests were made using Wykeham Farrance direct shear boxes (6 cm^2) adapted for reversals. Undisturbed blocks were trimmed and consolidated for two days at a varity of normal loads in the range 0.5-3.25 kg/cm^2. These low values were considered appropriate because the thickness of mudslide slabs rarely exceeds 2 m and this range of normal stresses can be expected to approximate the field conditions. The tests were carried at a strain rate of 0.00127 mm/minute to determine »peak« strength and thus shearing rate is considered slow enough to yield

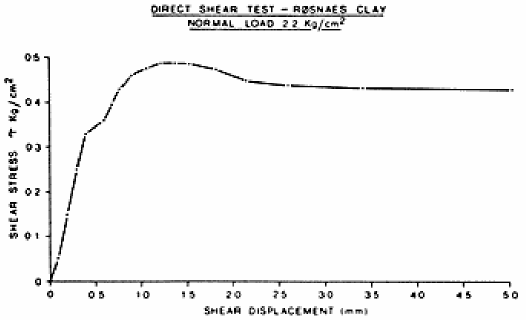

Fig. 19. Stress/strain curve for one direct shear test of Røsnæs clay.

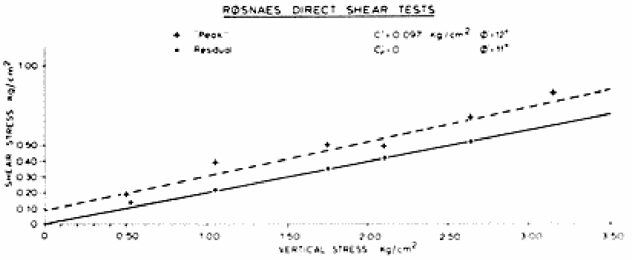

Fig. 20. Strenght envelopes for Rosnæs clay from direct shear tests.

drained strength parameters. Residual values were obtained by numerous reversals.

Typical stress/strain curves for the Røsnæs clay show very small differences between »peak« and »residual« values (Figure 19) and this is undoubtedly related to the presence of a fissure on the plane of shear. Also, the curves show small increased displacements just before the maximum stress is achieved. This phenomenon seems also to have been observed by Hvorslev (1937) in tests on Lille Bælt clay.

»Peak« and »residual« strength envelopes for a range of vertical stresses are provided in Figure 20 and yield the following data

$$C' = 0.097\ \text{kg/cm}^2 \quad , \quad \varnothing' = 12^\circ$$
$$C'_r = 0 \quad , \quad \varnothing'_r = 11^\circ$$

These are very similar, suggesting that the shear strength along parallel systems of natural fissures is almost at a residual value, and confirms the views of Skempton (1946) who suggests that fissures act as stress concentrators and that fissure strengths are unlikely to be much higher than residual.

The Røsnæs $\varnothing'_r$ value of 11° closely agrees with results from the Lille Bælt clays obtained by Hvorslev (1937) and reported by Skempton (1964) as 11-12°. In view of this and the overall similarity of the sediments at Røjle Klint and Helgenæs the Røsnæs results are applied to a preliminary consideration of mudslide processes at all three sites.

Stability analyses

The Danish mudslides can be divided into three main groups; the very active slides at Røjle Klint, the apparently relatively stable slides at Helgenæs, and those at Røsnæs which appear to be intermediate between the other sites in terms of levels of activity. It is proposed to examine the possible mechanisms which relate slope geometry and strength properties.

The fundamental type of instability common to all three sites, but particularly Røjle Klint and Røsnæs is shallow translational sliding with shear planes developed at depth parallel to the surface slope. At Røjle Klint this type of slab sliding occurs on a range of slopes, and at Røsnæs this type of sliding occurs on the upper steep feeder slopes (up to 34°) by those mudslides which have developed characteristic bilinear concave profiles.

Translational sliding of this type can be examined using the method of infinite slope analysis (Skempton and DeLory, 1957). Some of the slides might be considered »first-time« slides involving in situ clay and peak strength parameters, especially those on freshly eroded and steepened slopes. However, caution is needed in this respect because the exposed clay is heavily overconsolidated and is subject to rapid weathering and fissure development. Also, hydration and dehydration along the fissures, helped by the ability of montmorillonite clays to absorb water can rapidly reduce the strength properties towards residual values. Since the translational sliding occurs on slopes where fissuring is present and given the similarity between peak and residual strength envelopes, already discussed, it is more appropriate to consider the materials as possessing the characteristic C'_r =), $\varnothing'_r$ = 11°. The stability of slopes subject to translational sliding can therefore be evaluated using the equation

$$F = \frac{C'_r + (\gamma z \cos^2\beta - \mu)\ \tan \varnothing'_r}{\gamma z \sin \beta \cos \beta}$$

where F = factor of safety, x is the unit weight of slide material, z is the vertical thickness of the slide material, β is the slope of the surface (and slide plane), μ is the pore water pressure at the slide plane, C'_r is residual cohesion and $\varnothing'_r$ is the residual angle of shearing resistance on the slide surface. Assuming F = 1 (failure condition) it is possible to calculate the dimensionless pore water pressure ratio r_μ which will be necessary for failure.

$$r_u = \frac{u}{\gamma z} = \cos^2\beta\ (1 - \frac{\tan \beta}{\tan \varnothing'_r})$$

Considering the slopes at Røjle Klint (>20°) or the steep feeder slopes of bilinear slides (34°) it is evident that these angles are considerably steeper than the limiting slope with zero pore water pressure on the slip surface. Indeed, to maintain stability r_μ must be negative.

Another approach which can be used to demonstrate the susceptibility of these steep slopes to sliding is an extension of equation 1. This defines stability in terms of the ultimate slope angle against sliding or maximum stable slope angle (BC).

$$\tan B_C = \frac{\gamma - m. \quad \gamma_w}{\gamma} \tan \text{Ø}'_r$$

where m is the ratio of pore water pressure to depth and γ_w is the density of water. This gives an ultimate slope for these clays of approximately 6° for m = 1, when water level is at the surface and seepage is parallel to the slope. For m=o or zero pore water pressure the corresponding slope angle is 11°. At both Røjle Klint and Røsnæs the steep slopes considerably exceed the ultimate slope values and are therefore unstable even at very low pore water pressures. Therefore, it is not at all surprising that these slopes are subject to translational slides during winter and spring when seasonal rises of pressure occur as a result of precipitation, snow melt and consequent soil and ground water recharge. Stability can only be expected during periods of very dry weather or in summer when evapotranspiration exceeds precipitation and the weathered clay slopes become dry. Of course, where small ephemeral streams, field drains or sub-surface flow lead water towards these steep slopes instability is likely to be particularly severe and may be continued even during periods of dry weather. These conclusions are in agreement with field observations of the mudslide activity at Røjle Klint and Røsnæs and are consistent with the known seasonal rhythm of other mudslides on clay rich sediments, especially London clay, (Hutchinson, 1970) and Liassic clay (Prior et al., 1968) and show that the occurrence of mudslides can be explained by a relatively simple stability model comprising pore water pressure, slope angle and residual strength parameters.

But, the low angle segments of the bilinear mudslides at Røjle Klint and Røsnæs are also unstable and movement takes place in remoulded clay as elongate shallow translational »plug flow« slides 1-2 m in depth. Also, the Helgenæs mudslides which generally lack a well developed steep »feeder« slope and have very low angle profiles are still subject to instability by a combination of translational and successional sliding. These low angle slopes can also be evaluated using the two dimensional model (equations 1 and 3). The ultimate slope angle for stability with pore water pressure at the surface and lateral seepage is once again approximately 6°.

Two distinctly different situations must be accounted for. On the one hand, where this angle is exceeded on the accumulation slopes the instability can be expected in relation to pore water pressure fluctuations. Clearly the magnitude of pore water pressure needed for failure decreases as slope angles increase. Since, in winter and spring the ground water surface is likely to rise to or near the surface on slopes with moderate angles, the slopes above 6° can be expected to become seasonally active much in the same way as steeper feeder slopes — but with lower movement potential.

However, at Røsnæs for example, and at Helgenæs, substantial segments of the mudslides are inclined at less than 6°. For example, both angle/frequency calculations for Røsnæs and Helgenæs mudslides (Figure 8 and 14) show angles lower than 6°. Stability analyses using equation 1 readily indicates that for z = 1m, γ = 2.09 gm/cm^3 and Ø'$_r$ = 11 failure will only occur on slopes less than 6° if artesian pore water pressure can be generated. For example, using this method of analysis a mudslide slope of 3° will need a piezometric surface located well above (c.55 cm) the upper surface of the mudslide before instability could be expected to occur. The generation of artesian pore-water pressures in landslides has been discussed by Hutchinson for a variety of localities (Hutchinson, 1970; Hutchinson and Bhandari, 1971; Hutchinson, Prior and Stephens, 1974; Hutchinson and Kojan, 1975). Artesian pressures can occur in association with steep feeder slopes above low angle accumulation slopes and is related to the mechanism of »undrained loading« (Hutchinson and Bhandari, 1971) where material discharged from the feeder slopes produces loading at the rear of the accumulation slopes. These authors have actually recorded pore-water pressures considerably in excess of hydrostatic ($\gamma_w \cdot z$) and indeed approaching geostatic ($\gamma \cdot z$) in a loaded area of a mudslide in London caly, very similar in geometry to the bilinear slides at Røjle Klint and Røsnæs. Also, it appears that this slope geometry is associated with a variety of mass movement phenomena, at a variety of scales. For example, it can produce dangerously fast movements on mudslides in Liassic clay (Hutchinson, Prior and Stephens, 1974). Also, Hutchinson and Kojan (1975) infer that this mechanism was involved in an extraordinarily large debris slide in Peru with volumes of 10^9m^3 which moved at rates in excess of 100 km/hour.

So far, no reliable pore water pressure measurements have been made on the Danish mudslides. Attempts were made in April 1975 at Røjle Klint but had to be abandoned due to the extremely treacherous nature of the mud on the accumulation slopes. However, the mere existence of very active mudslides with substantial lengths of slopes below the ultimate angle of instability does support the concept of undrained loading and its importance to landsliding. Active mudslides on London clay are now rather limited and the Danish mudslides appear to offer considerable potential for further detailed documentation of this important phenomenon.

There are, however, additional factors which must be considered in relation to the instability of the low angle accumulation slopes. Firstly, the outer and lower edges of the mudslides, especially at Røjle Klint and Røsnæs are subject to some coastal erosion. This undercutting and unloading of the toe areas enhances the tendency for movement over residual shear planes within the accumulation areas as well as shallow rotational sliding on the outer edges of the toes. Secondly, the accumulation areas often possess layers of glacio-fluvial sand between successive layers of remoulded mudslide clay. These sand horizons represent weathering and periodic free fall of material from the slopes in glacio-fluvial deposits which overlie the Eocene clay. These sand horisons are extremely well developed at Røsnæs (Prior and Eve, 1975) and can account for lateral water seepage within the accumulation areas. Where they encourage free drainage of the mudslides they may reduce the potential for instability but equally they may increase it by channelling and concentrating sub-surface water. Thirdly, the very pronounced reduction in remoulded undrained shear strength with increasing water content, a function of the high clay content and the ability of montmorillonite to absorb water, may produce very low strength mud slurries which may move in a manner approximating to viscous flow. Indeed, where there are local concentrations of ground water small mud runs with levees may develop with very low angle depositional lobes of very wet debris.

Discussion

The stability analyses and consideration of the instability mechanisms of the Danish mudslides clearly reflect the fundamental influences of the properties of the overconsolidated Eocene clay. Marine erosion and removal of overlying glacial deposits has exposed the clays at three main coastal locations and has provided the initial high coastal relief and steep slopes which favour mass movement. The exposure of the clays in this way has meant the removal and reductions of confining overburden land and extensive fissure systems have been produced as unloading progressed. These fissures, in turn, control the general strength properties of the clay since they represent planes of weakness across which shear strengths have been reduced to the residual level. In addition, weathering and softening of the clays is also promoted by the fissures as excess water penetrates along them. This process is encouraged by the mineralogy and geochemistry of the clays. The high clay content, dominated by montmorillonite swelling minerals favour the absorption of water, either provided by precipitation or by ground water circulation. As water is absorbed remoulded plastic and viscous mud is produced with very low strength values. Instability therefore results as these processes operate on a wide range of slope angles, at varying rates of marine erosion and in response to changing environmental and climatic conditions. Conventional stability analysis procedures, particularly the infinite slope method are applicable to these mudslides using residual strength parameters and show the importance of pore water pressure fluctuations in promoting instability. Very moderate pressures are sufficient to cause failures in steeply sloping clays while undrained loading and artesian pressures, together with marine erosion are needed to maintain instability on mudslide slopes near or below the ultimate angle of 6°. There are, thus, many general similarities between the Danish mudslides on Eocene clay and the mudslide mechanisms which have been identified on London clay slopes in south-east England (Hutchinson, 1967, 1970, 1973). One minor difference is that the ultimate angle for London clay is slightly higher (c. 8°).

Hutchinson (1973) has discussed the morphological variations of coastal slope instability on London clays in response to varying rates of toe erosion by marine processes. Three contrasting situations are envisaged. Firstly, where erosion is in balance with weathering the slopes undergo parallel retreat under the influence of translational sliding (Type 1). Adjacent mudslides develop in mutual competition. Secondly, where the rate of coastal erosion is more rapid than weathering and slope activity (Type 2), the amount of debris removed by the sea exceeds that discharged by mudsliding on the slopes. This leads to erosion of the in situ clay and gradual steepening of the slopes. This, in turn, results in deep-seated rotational sliding involving base failure. The coastal slope morphology then evolves through a series of stages as marine erosion trims the rotated block and mudslides develop on the exposed clay in the back of the larger landslide. Mudslides will progressively decline in activity as they degrade to too low an angle to continue movement. Eventually, the sea, having completely eroded the former rotational slide will steepen the in situ clay again and another rotational slide will occur. Cliff retreat is achieved in this manner by distinct cyclical activity.

Thirdly, where the coastal slopes are abandoned by the sea (Type 3) zero erosion results in a process of free degradation in which the slopes gradually pass through successive stages, involving gradual reduction of the general slope angles. This involves the initial development of bilinear profiles by mudslide activity. Then, as the angle of the feeder slope decreases by mudsliding the accumulation slope lengthens and the bilinear profile is replaced by a single gradual slope at, or near, the ultimate angle.

It will be apparent, from the descriptions of the mudslide and landslide morphology at Helgenæs, Røsnæs and Røjle Klint, and the stability analyses, that these concepts have many applications to the development of the Danish coastal morphology. But, there are also some interesting variations.

At present, no reliable data exists concerning contemporary (or recent) rates of coastal erosion at these three sites. However, on the basis of exposure and fetch, particularly to westerly winds (Schou, 1959) it is reasonable to infer that Helgenæs is the most vulnerable to storm generated marine erosion. On the other hand, Røjle Klint, on the edge of the Lille Bælt is the most protected from high wave energy conditions. The three sites might therefore be expected to show variations in coastal landslide morphology and processes which reflect the differences in intensity of marine erosion, and to some extent this is the case.

However, it is also very important to consider temporal variations in the effectiveness of erosion, because land/sea level relationship have altered considerably in the late- and post-glacial periods in Denmark. This is due to isostatic uplift and eustatic sea level changes, combined with the details of the deglaciation (Hansen, 1965). The entire sequence of events is complex but the principal factor of relevance to the slope morphology at Helgenæs, Røsnæs and Røjle Klint is the post-glacial transgression which began approximately 6000 B.C. following a period when sea level may have been as much as 30 m below present. The timing of the maximum stage of the post-glacial transgression (Litorina) is not known exactly but may have been approximately 2000 B.C. (Hansen, 1965). Since that time, isostatic uplift has gradually elevated northern Denmark, bringing the Helgenæs coast to an altitude of +8 m above sea level, and the Røsnæs coast to + 4,5 m. But, there has been no uplift at all in the Røjle Klint area, since the zero isobase passes exactly through that site.

In terms of the coastal slope processes, these land/sea level variations represent time-based reductions of marine erosive activity at the base of the slopes, which began earlier at Helgenæs than at Røsnæs. The absolute time difference is not the same as that indicated by the simple differences in elevation because it is known that the rate of isostatic uplift has declined. Also, by strict comparison, it can be implied that the Røjle Klint coast, where there has been no uplift, has been subject to relatively unchanged overall erosive conditions for approximately 4000 years.

Considering these factors in relation to the slope models proposed by Hutchinson (1973) it is possible to suggest some explanations for the variations in landslide morphology and processes at the three sites.

1. Helgenæs

Significant marine erosion of the slopes has occurred, promoting oversteepening and rotational failure of large units of glacial sediments and Eocene clay (Type 2 conditions). Some of these rotational slides appear to be very deep-seated and have failure planes which appear to extend substantially below present sea level. This is suggested partly by the presence of offshore remnants of eroded blocks. More particularly, present sea level is largely in contact with rotated glacial deposits which comprise the upper parts of each individual landslide (Figure 9). If these deep-seated slides were originally base failures, then the implication is that they may have been initiated before the Litorina transgression achieved a level equivalent to that of present marine activity. Also, the gradual lowering of sea level relative to the land since the Litorina maximum has reduced the rate of erosion of the rotated blocks of till and gravel and some now have entirely stable, vegetated front slopes (Figure 10). The cycle suggested by Hutchinson (1973) for the Type 2 condition is only likely to be repeated on a small scale, where block erosion is continuing, notably at the extreme northern end of the coastline. Even here, the tendency for further reactivation of rotational sliding has been reduced by groyne constructions.

Mudslides have developed on the Eocene clay outcrop behind the larger rotational slides. The mudslide morphology represents a progressive decline in activity as each slide profile reduces its inclination towards (and sometimes below) the ultimate angle of 6°. There is, however, some variation in the achievement of the ultimate angle in each case. More active slides, at slightly steeper angels, are still capable of small scale displacement by successional slipping. The process of profile reduction, which has involved the removal of the steeper feeder slope, has also been aided by the gradual lowering of sea level leading to zero erosion at each mudslide toe. The mudslides thus represent a combination of Hutchinsons (1973) models, having been initiated as a result of Type 2 conditions and then progressing to Type 3 conditions by increasing abandonment as sea level withdrew. For those mudslides which were eroded by the Litorina transgression it is logical to imply that Type 1 conditions probably existed temporarily during the change from Type 2 - 3. The Helgenæs coastal morphology demonstrates a combination of landslide processes, initially produced by active coastal erosion of overconsolidated clays, but substantially modified by changes of sea level, particularly the regression which commenced approximately 4000 years B.P..

2. Røsnæs

The Røsnæs coastal landslide morphology shows the development of mudslides in association with deep-seated rotational landslides. The latter include simple, rotational, compound and multiple retrogressive types (Prior and Eve, 1975). The failure surfaces appear, in some cases, to extend well below present sea level. But, the presence of notches and small abandoned terraces on some of the landslide blocks at approximately +4 to 5 m is also evidence of a formerly higher sea level since these landslides were formed. These larger slides can be interpreted in similar way to those at Helgenæs, as representing Type 2 conditions, when the rate of marine erosion exceeded sub-aerial slope activity and steepening of the slopes resulted in rotational failure. To some extent, this erosion is continuing and the front edges of some of the landslide blocks continue to be trimmed and truncated by coastal processes, producing steep erosional slopes in glacial sediments. There is therefore some potential for the cycle to be continued even though present sea level represents a decline in the height of marine attack on these slopes, which reached a maximum during the Litorina transgression.

Mudslides at Røsnæs are generally more active than at Helgenæs and thus is due to a combination of continuing marine erosion of the mudslide toes and the generally steeper average slopes (Table 3). While sea levels have declined in elevation since Litorina times, marine erosion at present sea level is still in contact with the actively prograding mudslide lobes. They cannot therefore be described as having been abandoned by the sea, to the same degree as at Helgenæs. Also, the steep feeder slope is still a significant component of each mudslide geometry and the bilinear profiles have not progressed so far towards achieving the ultimate angle of stability. One measure of the differences between Røsnæs and Helgenæs mudslides is the ratio of accumulation slope length to feeder slope lengths (Table 3). At Helgenæs, the greater degree of abandonment of the mudslides by the sea level reduction is reflected in high ratios (up to 50:1) whereas the Røsnæs slides show ratios of between 3:5 and 2:1. The accumulation slopes at Røsnæs have moved towards and below the ultimate angle, but they in turn cannot achieve inherent stability because of the combined effects of undrained loading from the feeder slopes and marine erosion stimulus to the system. The mudslides at Røsnæs can be interpreted as having been originally associated with deep-seated landsliding in response to Type 2 conditions. But the continuing interplay between toe erosion and feeder slope activity may represent an approach to Type 1 conditions, with a balance between slope and marine processes. Alternatively, in some cases, the reduction in sea level may have been just sufficient to allow slope reduction by mudsliding to occur faster than toe erosion by the sea (Type 3 conditions). Some of the mudslides show lengthening of the accumulation slope component as the length and angle of feeder slope is reduced. In these cases, local site factors which affect feeder slope activity, such as ground water supply, exert a major influence on the manner and stage of development of the mudslide morphology. The Røsnæs coastline thus demonstrates a very complex range of landslide types reflecting a time based interplay between local slope processes and post glacial sea level changes.

3. Røjle Klint

By comparison to Helgenæs and Røsnæs, the Røjle Klint coastline possesses very active mudslides. Both shallow translational slides and larger competing bilinear mudslides are present, the latter developing where there is a surface and ground water supply which encourages enlargement and rapid extension inland. The rate at which enlargement can occur (< 10 years for one new bilinear slide to develop) is remarkable. Marine erosion is responsible for the rapid removal of the mudslide debris and there are complex short term relationship between rates of removal and rates of mudslide deposition. Only in some very isolated localities is the base of the slopes occasionally exposed directly to marine erosion, probably during maximum storm conditions. This is not sufficient to produce deep-seated rotational slides. Rather, the slopes weather rapidly along fissures and reduce their angles by fall and shallow sliding processes. The general conditions at Røjle Klint appear to be very similar to those described by Hutchinson (1973) as Type 1 conditions with slope activity broadly in balance with marine erosion. The relatively sheltered location of Røjle Klint, on the edge of the Lille Bælt, encourages this balance. Also, the presence of a gently inclined offshore wave-cut platform in Eocene clay suggests that cliff retreat by these processes has been continuing for some time and this is consistent with the geomorphic history of the site. Because Røjle Klint is located on the zero isobase of the Litorina transgression there has not been any major change in sea/land level relationship over the past 4000 years. There has not been a progressive post-glacial abandonment of these cliffs by the sea such as exemplified at Helgenæs and to a lesser extent at Røsnæs. Cliff retreat by the interplay between marine and slope processes can therefore be expected increase in the width of the offshore platform and its effect in slowly reducing the wave energy conditions at the base of the slopes.

The continuing removal of mudslide debris precludes the development of longitudinal mudslide profiles which can progress towards the achievement of the ultimate angle of stability. This is demonstrated by the accumulation slope/feeder ratios which remain very low (Table 3). As mudslide debris is removed from the foreshore, the Eocene clay outcrop exposed by mudsliding will continue to advance inland. Unloading, fissuring, weathering and softening will facilitate new mudslides, and competition between adjacent slides will continue, with more aggressive slides replacing those whose activity shows any tendency to decline.

Table 3. Generalised mudslide morphopoly.

	Isostatic Uplift	Average Mudslide Slope	Accumulation Slope	Feeder Slope	Ratio of Accumulation To Feeder Slope Length
Røjle Klint	0	20-25° 18-22°	10° 10°	20-25° 30-34°	1:10 (*) 1:1 or 1.5:1
Røsnæs	4-5m	15- 5° 19°	12° 7.5°	30° 34°	3.5:1 2:1
Helgenæs	c8m	10° 10°	7° 8°	33° 31°	7:1 50:1

Røjle Klint, in fact, represents an ideal site for the study of these processes on overconsolidated clays, including the mechanisms of mudslide initiation, rates of movement and undrained loading. Moreover, agricultural land and settlements will continue to be destroyed by these processes. Any remedial action must primarily reduce the effectiveness of marine removal processes along the entire base of the slope. But, even with a condition of zero erosion the reduction of these slopes towards their ultimate angle of 6° will require a considerable additional amount of cliff top retreat. For example, the reduction from an average angle of 20° to 6° for a slope with a relative relief of 30 m will require cliff top retreat of 203 m. In addition, this slope reduction by natural mudsliding is likely to take a very long time. The Helgenæs site provides an analogy. Even though erosion effects have been gradually reduced since 4000 B.P. by isostatic uplift to +8 m the slopes there have not yet achieved total stability.

Conclusion

The study of coastal landslides in Denmark illustrates some of the basic mechanisms which give use to slope instability on oversonsolidated clays. The mudslides exhibit many similarities both in form and process with those associated with London clay in south-east England. Present slope instability is the result of the geotechnical and geochemical properties of the clays together with climatically induced pore water pressures on slopes which are subject to variations in the rates of coastal erosion. To some degree, the mudslides can be grouped in terms of coastal erosion rates following Hutchinson's (1973) classification of London clay coastal landslides.

But, there are additional time scales which must also be considered in order to explain the differences in present morphology and degree of mudslide process activity. Each of the three sites has its own time scale of variations in coastal activity, related to isostatic and eustatic changes in sea/land level relationships in the post-glacial period. The present mudslides must therefore be considered from the point of view that Helgenæs and Røsnæs have each been subject to former lower and higher sea levels. During the final regression sea level was reduced faster and to a lower level at Helgenæs than at Røsnæs. The mudslides at Helgenæs have therefore had a longer period of progressive abandonment than those at Røsnæs. The mudslides at Helgenæs thus show a greater reduction in overall slope (and activity) towards the ultimate angle than those at Røsnæs. By comparison, the Røjle Klint site has been largely unaffected by isostatic uplift. The present level of the sea has remained essentially unaltered since Litorina times and present mudslide processes are very much more active than at Helgenæs or Røsnæs.

This time based variation in sea levels and its effects on mudslide process and form cannot, as yet, be precisely quantified. This is partly because of inherent differences between the sites in terms of exposure to marine energy. Indeed, it is probable that, of the three sites, the Helgenæs coastline is the most vulnerable to wave attack yet in spite of this the greater lowering of sea level has allowed mudslide processes to proceed towards greater stability. Also, the rate of isostatic uplift has decreased and thus, the exact time scales of diminishing marine erosion in relation to landsliding at Helgenæs and Røsnæs are quite different. Also, there is undoubtedly some variation in landslide morphology within each site attributable to purely local factors.

Nevertheless, even with such imprecision it is possible to broadly explain the present differences in mudslide form and processes at the three sites, on the same geological material, by reference to varying time scales. The Danish coastal mudslides provide an example of the necessity for any short term process measurements and process analyses to be rigorously placed within their appropriate time dimensions.

The author wishes to gratefully acknowledge the assistance of Mr. Richard Eve particularly in the field surveying of the sites. Miss Julia Clingham gave valuable assistance with laboratory analysis. Mr. Bill Renwick, Clark University, Worcester, Massachusetts reviewed the manuscript and provided much needed constructive discussion. The project was supported by financial assistance from the Queens University of Belfast, Northern Ireland.

RESUME

Undersøgelsen er sammen med tidligere arbejder (1973-75) et studium af skræntprocesser på specifikke kystlokaliteter: Røsnæs, Røjle Klint og Helgenæs, hvor den nære prækvartære overflade underlejres af eocene lerforekomster. De foreliggende studier fokuserer på mudslides af mere overfladisk art samt på mere dybtliggende rotational landslides. Førstnævnte som dominerende proces i Røjle Klint, medens de samme processer på Røsnæs-Helgenæs foregår inden for større landslides af rotational karakter. Morfologien beskrives på de tre lokaliteter, jvfr. figurerne 2,5 og 9. Endvidere er der foretaget detaillerede laboratorieanalyser af de geofysiske og geokemiske egenskaber af den eocene Lillebælt-ler. Endelig er tidsfaktoren behandlet i relation til den postglaciale udvikling.

1. Røjle Klint. Øst for gården Sølyst har skrænten en hældning på 20°-30° og udgøres af et tyndt morænedække over eocen Lillebælts-ler. Vest for gården dominerer moræneaflejringer (dislocerct klint). Aktive mudslides kan konstateres over en 1-5

km lang strækning øst for Sølyst og ca. 3-400 m ind i land (fig. 2). De aflange slides har et bredde-længde-forhold 1-5 og er gletscherlignende af form, dybt indskåret i kystskrænten. Hver mudslide har en abrupt, stejlt hældende, hesteskoformet øvre skrænt, op til 10 m høj med mindre rotational og translaterale processer, der indicerer en ustabil zone længere inde i land. De aktuelle mudslides udgøres af dybt nedskårne, aflange kanaler, afgrænset af skarpt markerede glideplaner (shear planes), fig. 4. Hældningen i disse strømme er 5°-10° med irregulære »fald«-sektioner (stejle partier). Der er stor forskel på overfladepræget om sommeren, hvor de er udtørrede, opsprækkede, og om foråret, hvor de er våde, ustabile og farlige at færdes omkring. Der er da tale om floder af »mud« med et meget højt vandindhold og lav styrke. Ved foden dannes aflange, afrundede lober, ofte med konvekse profiler undtagen hvor de er blevet eroderet af havet. Morfologien fremgår iøvrigt af fig. 2, udtegnet efter flyfotos 1964 og 1974. I 1964 var der 7 steder aflange mudslides, af hvilke no. 5, 6 og 7 var de største.

I 1974 havde den marine erosion overtaget, kun lobe 1 var tydeligt aktiv foruden de nydannede skred 8 og 9. I 1975 var no. 6 atter aktiv.

2. Røsnæs. Langs sydkysten mod Kalundborg Fjord er eocent ler diskontinuert overlejret af to morænedække adskilt af sand- og grusaflejringer. Fluviatile aflejringer danner den øvre topografi med kames. De eocene leraflejringer træder frem på havbunden samt lokalt i kystklinterne. Flere typer landslides fremtræder her (Prior og Eve, 1975). Hver mudslide består af tre distinkte morfologiske komponenter: en stejl øvre skrænt (feeder area), en svagt hældende akkumulationsskrænt og en frontal lobe (eroding toe area, fig. 5). Back slopes har ofte hældninger på 30°-34°. Fig. 8 viser et længde-hældningsdiagram, der demonstrerer fire morfologiske hovedgrupper: 1) Den lille stejle back scarp udformet i glaciale aflejringer, 2) Stejle klintpartier i den eroderede toe-slope, 3) De stejle skrænter (feeder chute) 32°-34°, der optager ca. 30% af den totale længde, samt 4) Hovedmassen (65%) af skræntsegmenter omkring 10°'s hældning i akkumulationszonen.

3. Helgenæs. Istidstopografien bestående af moræner, sand- og grusaflejringer når langs kysten højder af 30-40 meter. Eocent ler ses under disse dække af varierende tykkelse. På en strækning af ca. 2,2 km er kystklinten domineret af land slide morfologi, fig. 9-10. Det drejer sig hovedsagelig om dybtgående rotational slump-slides. Det største enkeltskred findes ved den nordlige ende af halvøen med en kystlængde på 300 m og en bowl-formet, amfiteatralsk lavning, der strækker sig 150 m ind i land. Mud slides forekommer på siderne af disse større skred, fig. 9 angiver placeringen af enkelte mud slides 1-5. Karakteristisk for dem alle er den svage hældning 5°-9°. Fig. 14 viser et længde-hældningsdiagram for mudslide 2. Bortset fra den meget lille back scarp (90°) og slip units i sand og grus (30°-40°) er lerskrænterne af ringe hældning 0-19°. De længste segmenter har en hældning på 0-10° og 34% af samtlige skrænter er under 3°. Det må bemærkes, at skrænterne ved Helgenæs står i udpræget kontrast til Røjle Klint og Røsnæs, både hvad angår aktivitetsniveau, den generelt dæmpede topografi og tilstedeværelsen af successive glideflader.

De geofysiske og geokemiske egenskaber gengives ved undersøgelser af kornstørrelsesfordelingen via Coulter counter, fig. 15-16 (leraflejringer mindre end 5 u = 77-83%, mindre end 2 u = 52% for Helgenæs, 59% for Røsnæs og 63% for Røjle Klint), lermineralogi via røntgenanalyser, fig. 17, og differential-termiske analyser, der angiver mængden af montmorillonit til illit + kaolinit til ca. 2. De geofysiske egenskaber fremgår af tabel 2 ved beskrivelsen af volumenvægt og Atterberg grænser. Stabilitetsanalyserne inddeler de undersøgte mud slides i tre typer: de meget aktive slides ved Røjle Klint, de tilsyneladende stabile slides ved Helgenæs og de intermediære typer ved Røsnæs. For en nærmere diskussion af disse forhold savnes troværdige målinger af porevandstrykket.

Marin erosion og fjernelse af de overliggende glaciale aflejringer har blotlagt den eocene ler i de tre vigtige kystlokaliteter, der alle fremviser initialt højt relativt relief med stejle skrænter, der favoriserer skræntbevægelser. Blotlæggelsen af leret har betydet fjernelse og reduktion af det omhandlede overliggende land og udstrakte fissur-systemer er blevet resultatet, efterhånden som skredene fandt sted. Hutchinson (1973) har undersøgt den morfologiske variation af instabiliteten af kystklinter i London clays i respons til varierende hastighed af marin erosion. Tre forskellige situationer opstilles: 1) hvor erosionen er i balance med de skræntdannende processer, 2) hvor den marine erosion har overtaget, 3) hvor den marine erosion er standset. Helgenæs er dannet under type 2 betingelser, men før litorinatransgressionen. Dette har initieret de dybtgående skred. Røsnæs henføres til samme type med bemærkning, at forholdene også i dag forefindes i den aktive form. Røjle Klint henføres derimod til type 1.

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