Coastal landslide morphology at Røsnæs, Denmark

By D. B. Prior and R. M. Eve

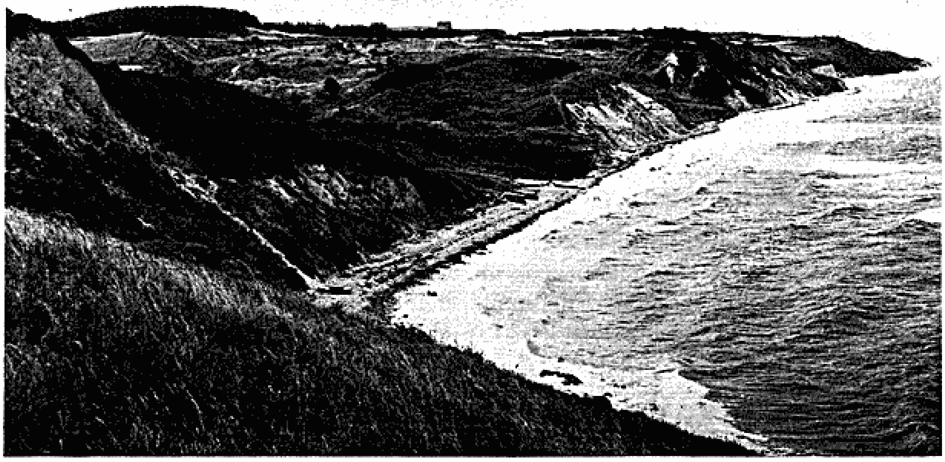

Fig. 1. The coastline of Røsnæs, bordering Kalundborg fjord, illustrating a variety of landslide types.

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Based on the field studies the coastal landslide morphology and the moss movement types in the Røsnæs area are described and classified, followed by a general discussion of the factors which promote slope instability.

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Introduction

The coastline of the Røsnæs peninsula of north-west Sjælland possesses a number of different types of mass movement phenomena of classic proportions. These have been briefly described by Schou (1949) and mentioned by Guilcher (1958). In a recent paper, Eocene clays from this area were analysed and a predominantly montmorillonite clay mineralogy identified (Prior, 1973).

Hitherto there has been no systematic mapping and classification of the mass movement types in the area and this present paper provides an inventory of the coastal landslide morphology together with some general discussion of the factors which promote slope instability.

Topography and geology

The Røsnæs peninsula comprises a narrow, ridge-like promontory about 15 km in length and rising to a maximum elevation of 64 m. The morphology of the gently sloping northern coast contrasts markedly with that bordering Kalundborg Fjord. This south facing coastline is rather steep and falls abruptly along most of its length, with relative relief of 40–50 m immediately adjacent to the coast, (Figs. 1 and 2). The slopes are composed of a variety of Tertiary and Pleistocene sediments which are well exposed in the coastal cliffs and in various quarry pits in the area. The generalised succession includes Eocene clays overlain by a lower till unit separated from an upper till by sands and gravels. Fluvio-glacial deposits also mantle the upper till and provide the surface kame moraine topography of the area.

THE EOCENE CLAYS

Eocene clays outcrop below sea level, on the foreshore, and in the coastal cliffs. They can also be traced inland since the surface of these deposits rises gradually towards the centre of the Røsnæs ridge. These "plastic clays" occur elsewhere in Denmark, notably in and around the Little Belt and on parts of the coast of Djursland. Analysis of samples from the Little Belt has enabled various

Table 1. Some properties of the Danish Eocene clay

	Clay (%)	Water content (%)	Plastic limit	Liquid limit	Plasticity index
Hansen & Mise (1964)	65-80	28-48	25-55	70-260	45-210
Prior (1973)	65-71	-	31	70-273	39-242
Prior & Evé (1975)	67-79	33-43	30-36	63-75	33-39

Table 2. Some properties of the tills at Røsnæs

	%	%	%	%		Na	Mg	Ca	K
	Clay	Silt	Sand	Stones	pH	(me/100 gm)			
Upper till	24.1	33.7	36.3	5.8	8.6	5.69	3.63	14.55	0.16
Lower till	14.9	36.7	43.7	4.7	8.3	3.57	2.33	15.00	0.24

Table 3. Percentage lithology of the stone fragments in the tills

	Chalk	Limestone	Flint	Shale	Quartz	Igneous	Red Granite	Metamorphic
Upper till	19.6	17.7	14.0	9.3	6.0	19.1	13.5	0.5
Lower till	27.6	16.8	8.8	15.2	6.4	25.2	-	-

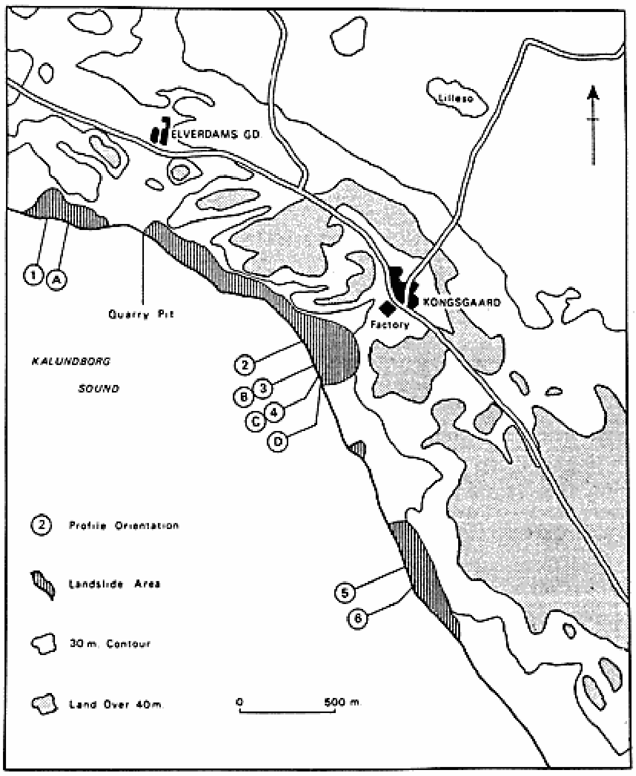

Fig. 2. Location map showing major landslide areas and surveyed profile lines.

authors to describe the physical properties of the clays (Mertz, 1928; Hvorslev, 1937; Hansen and Mise, 1964). Table 1 compares the main index properties from the Little Belt with those from Røsnæs, including data from Prior (1973) and the results of more recent sampling.

The Røsnæs clays vary considerably in colour. They are bright green where exposed below sea level but are predominantly grey or greyish blue in the cliff exposures, with rusty brown oxidation patches. One of the most obvious characteristics of the in situ clays is the extensive fissuring. The fissures are often slickensided and polished. Their orientation is variable but commonly there is a single dominant direction with a strong degree of parallelism. Where undisturbed the fissures are mainly horizontally arranged, or only slightly inclined, but in places they show quite considerable distortion and folding (Fig. 3).

These clays possess montmorillonite, illite and kaolinite clay minerals with some quartz (Prior, 1973). The cation exchange capacity averages 41 me/100gm and the main exchangeable cations are sodium, calcium, magnesium and potassium in decreasing order of abundance. The sodium values are extremely high, averaging 65 me/100 gm. The difference between the exchange capacity and the sodium levels is probably due to the presence of free salts which may be removed together with the exchangeable cations in sample preparation.

The high liquid limits and plasticity index values are primarily a function of the clay content, the clay mineralogy and the high sodium cations values. It is remarkable, however, that only some samples show the extremely high liquid limits of over 200. As yet there has been insufficient analysis to explain this.

The Røsnæs clays are heavily over-consolidated, since during the Pleistocene period they were covered by ice sheets on several occasions. Hansen and Mise (1964) cite a probable thickness of ice to have exeeded 1000 m and estimate the geological pre-load to have been as high as 500 t/m^2.

THE TILL UNITS

In places, the Tertiary clays are covered by two distinct till units, often separated by sands and gravels. These two tills are essentially very similar and tables 2 and 3 give their main properties.

The lower till contains less clay-sized particles and more silt and sand than the upper till, which by contrast contains a significantly higher proportion of igneous rocks (32.70 %) and includes pieces of red granitic porphyry (13.54 %) which are noticeably absent from the lower till. The general chemical properties, including pH and exchangeable cations are basically similar in both tills. One further distinctive feature of the lower till is that it often contains irregular blocks of Eocene clay picked up

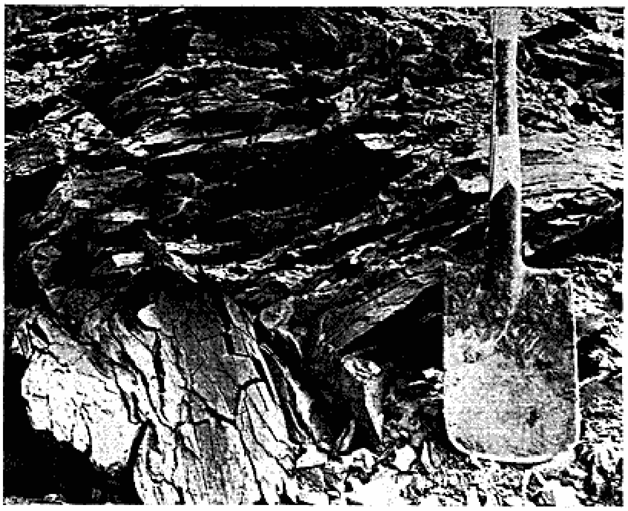

Fig. 3. Extensive fissuring in Eocene clays.

by the eroding ice and incorporated within the glacial sediments.

These glacial deposits, together with the extensive and varying thicknesses of fluvioglacial materials, give a distinctive morainic topography, comprising kames, kettles and morainic ridges. There is also some dissection by meltwater channel systems, large steep-sided dry valleys running towards the coast.

Schou (1949) and Hansen and Nielsen (1960) have interpreted the Røsnæs peninsula as representing a retreat stage of the Norwegian ice, from the north and north- east. The upper till stone content is consistent with this interpretation, while the lower unit may be ascribed to previously more extensive Baltic ice from the south-east.

The distribution of landslide types

The different types of landslide in the Røsnæs area are best developed in the area around the Insulation Factory, near Kongsgaard farm, approximately 6 km from Kalundborg and 3 km from the village of Ulstrup (Fig. 2). Here, the main road passes through hummocky morainic topography and the nearby coastal slopes rise steeply to over 40 m. The entire coastal morphology is dominated by landslides which occupy intermittently about 2.5 km of the coastline. The two basic types of landslide which can be recognised are slumped blocks and mudslides.

THE SLUMPED BLOCKS

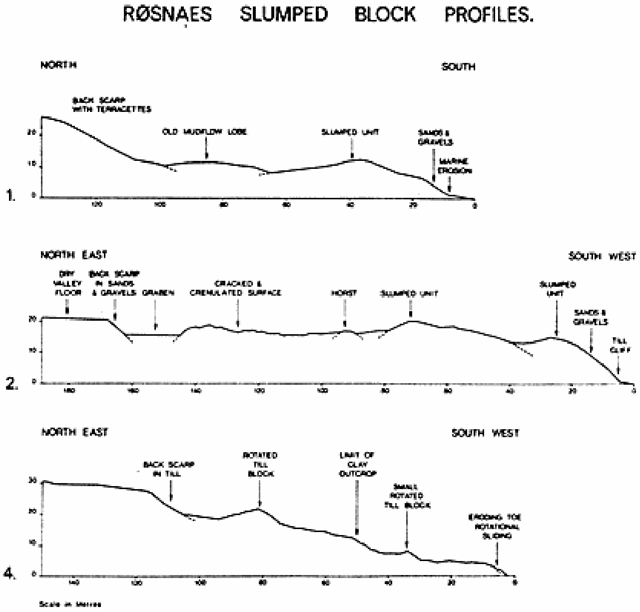

Fig. 4. Profiles illustrating slump block landslides.

The general term "slumped block" is applied to landslides where there is both downward displacement and some rotation of intact blocks of soil and rock. These characteristics are present on the Røsnæs coast, but further more precise definition of this type of landslide can also be applied here, following Skempton and Hutchinson (1969). Classifying landslides on clay slopes they distinguish between rotational slides, compound slides and multiple retrogressive slides. Rotational slides are identified where the surface of failure is curved and concave upwards, and where a back tilt is imparted to the slipping mass which sinks at the rear and heaves at the toe. Conpound slides indicate the presence of some heterogeneity within the slope materials, such as the Eocene clays underlying the glacial deposits. Compound slides typically have failure surfaces which combine curved and planar elements. Movements can be both rotational and translational (implying distinct lateral displacement as well as a vertical component. Multiple retrogressive slides are more complex landslides which may develop from both rotational and compound slides by later failures and additional movements. Commonly, these landslides have several failure surfaces which combine to form a single basal slip surface. Movement may be either predominantly rotational and/or translational.

All three types can be identified in the Røsnæs area. If the slope angle, from the top of the rear scarp to the bottom of the toe of each landslide is considered (Hutchinson, 1967) then it is apparent that the purely rotational slides have slopes in the range 14–15$^1/_2$°. The $^1/_2$° rotation looks rather strange? The movement of the compound and multiple retrogressive slides would appear to have been both rotational and translational and are associated with slopes af 8–10$^1/_2$°.

A number of profiles are provided in Figures 4 and 5 to illustrate the landslide topography. They were accurately surveyed using a Watts Quickset level and staff. The location of each profile is given in Figure 2.

The simple, rotational slump blocks are shown by profiles 1, 5 and 6 and each possesses a steep back scarp (27–35°) in glacial deposits. The angle of backtilt of the rotated blocks varies considerably from 7–27°. However, surface wash and creep processes on these unconsolidated materials has undoubtedly modified the slope angles since failure and colluvial infill has occurred in the depression behind each block. Profile 1 (Fig. 4) shows infill by deposits associated with a small inactive mudflow lobe (seen in cross section) from adjacent slopes. The front slopes of the rotated blocks have also been modified by marine erosion and the glacial deposits have been cliffed and terraced. Profiles 5 and 6 show notching to a maximum height of 5.02 and 3.95 m respectively above mean sea level. It is possible that these notches represent the effects of the Litorina marine transgression of the Neolitic period since Schou (1949) locates the Røsnæs peninsula between the 4 and 6 m isobases for this sea level. This infers that some of the rotational slumping (at profiles 5 and 6) pre-dates this transgression and further, that some of the blocks have remained in place since Neolithic times, undisturbed by later slope instability.

The compound landslides are best developed in the area south-west of Kongsgaard (Profiles 2 and 3). These profiles cross the same basic landslide unit but provide contrasts in the detailed morphology of the seaward edge of the landslide. The back scarp is developed in sands and gravels, is partly vegetated and inclined at angles between 31 and 41°. At the base of the scarp there is a flat-floored depression which from its position appears to be a small graben form bounded by adjacent, steeply inclined shear plane surfaces. Seawards of the graben the topography rises across a series of cracks and stepped units to a central high point which resembles a miniature horst. The surface on both sides of the horst is heavily cracked and minor ridges and linear crenulations run across the landslide parallel to the horst and graben. This topography has a very fresh and sharp appearance suggesting that the landslide is currently, or has been very recently, active. There is not the same evidence of modification of the topography by colluvial processes as seen in the rotational slide areas.

Profile 2 shows the presence of large, intact units of till and glaciofluvium at the seaward edge of the landslide. These are actively being attacked by marine processes giving an erosional slope. No Eocene clay can be seen along profile 2, although it outcrops just offshore below sea level. By contrast, the clays outcrop at the surface on parts of profile 3 where there are several active mudslides. These will be discussed in detail later, but it must be noted that a characteristic of the compound slides is that mudslides may considerably modify their seawards edges.

A fine example of the properties of multiple retrogressive slides can be seen at a quarry pit on the coast immediately south of Elverdams Gd. (Fig. 2). The stratigraphy and cross-sectional details of the landslide are well displayed in the east face of the pit. Figure 6 provides an interpretation of the section. Eocene clay outcrops at the base of the section and is overlain by lower till. This in

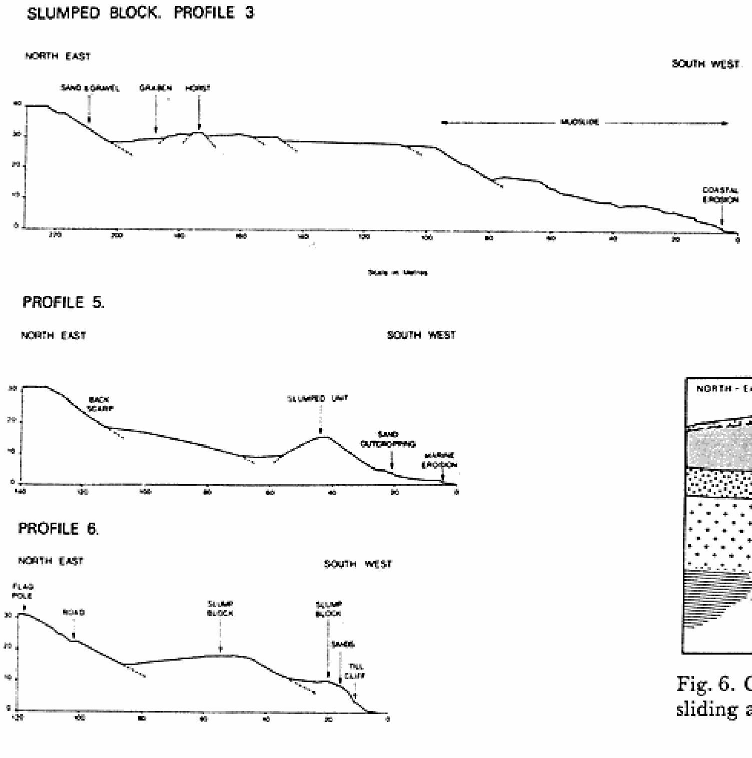

Fig. 5. Profiles illustrating slump block landslides.

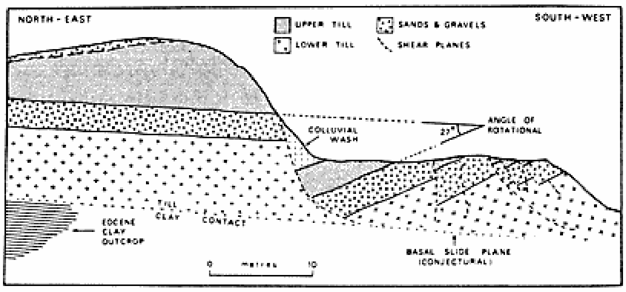

Fig. 6. Cross section through an area of multiple retrogressive sliding at the quarry pit.

Fig. 7. General view of the main shear plane at the quarry pit.

Fig. 8. Close-up of the breccia comprising the shear plane at the quarry pit. Shattered flints show distinctively.

turn is covered by sands and gravels followed by the upper till. There are some very thin surface gravels. A distinct, curved shear surface bounds a displaced block which is itself fragmented by other minor fractures and shear planes. The main block has been displaced vertically 8 m and rotated by 27°. The back slope of the landslide has been modified by erosion at the head and colluvial infill at the base. Figures 7 and 8 show the characteristics of the main shear plane. Near the surface it can be seen as a simple discontinuity through the sediments, but this is replaced at greater depths by a wedge-shaped breccia zone which thickens with depth. Within the breccia, which reaches maximum thicknesses of 25–30 cm there are angular fragments of various rock types including shattered flints in a predominantly sandy matrix. Where displaced sands and gravels contact the breccia, the sands show iron enrichment and oxidation. As the shear surface cuts across intact lower till the latter is fractured, with intersecting crack systems running obliquely away from the shear plane. The cracks are distinctively lined by iron oxidation products. Figure 7 shows the general nature of the shear while Figure 8 provides a close-up of the breccia.

The main, concave-upwards shear appears to be tangential to the outcrop of the Eocene clay which probably functioned as the basal slide surface for the retrogressive slide complex. The main shear is joined by subsidiary, curved shears which seem to have developed subsequent to the main displacement. This is somewhat conjectural due to incomplete exposure but can be inferred from the general disposition of the outcrops.

As can be seen from the quarry pit section there is a tendency for the slump landslide topography to be complex, and both rotational slides and compound slides may develop multiple slide units, apparently to a common basal slide surface. This is also evident from profile 4 where part of a compound slide has developed several discrete minor rotated blocks of till and Eocene clay. Each small block has a steep front slope and reverse slope. As in profile 3 the morphology of the multiple retrogressive segment is further complicated by active mudslides and marine erosion.

THE MUDSLIDES

Active mudslides occur at several localities on the Røsnæs peninsula but are particularly well developed near the Insulation factory. The term "mudslide" is used here in preference to "mudflow". Hutchinson (1970) has discussed the problem of terminology with respect to similar phenomena developed on London clays in south-east England. The mudslides at Røsnæs appear to move mainly over discrete basal slide surfaces and between sharply defined marginal shears. However, it is probable that from time to time when the water content is very high the movement may approximate to that of a viscous fluid. Prior and Stephens (1971) have also noted the complex variability in behaviour of similar materials in north-east Ireland where both basal sliding and viscous flow have been observed within the same mudslide.

Mudslide movement at Røsnæs has not, as yet, been monitored in detail. Observations in April, 1972 and periodically from July, 1973 until the spring of 1974 suggest a definite seasonal rhythm. The mudslides are most active during winter months but are entirely stationary in summer and autumn. This seasonal cycle is very similar to that recorded on mudslides and mudflows elsewhere (Prior et al., 1968; Hutchinson, 1970).

The Røsnæs mudslides have three distinct morphological components which also represent different mechanisms of slope instability.

(a) the feeder areas

Each mudslide usually has a steeper slope at its upslope end with angles varying from 30–34°. These slopes supply material to the lower, seaward parts of the mudslides. Two basic types of "feeder" area can be recognised. Some are composed of small, shallow slab and rotational slides on the outcrop of slumped Eocene clays. These areas show slickensided basal shear surfaces together with extensive cracking. Each slide has a back scarp with additional curved crack systems further upslope indicating the positions of incipient failures. By contrast, some of the feeder areas have very steep back slopes and distinct channels or elongate chutes are formed (Fig. 9). The chutes are inclined at angles of $> 30°$ and their sides slope steeply towards the chute axes. The upslope end of each channel is a near-vertical outcrop of in situ Eocene clay overlain by glacial deposits. Adjacent chutes are separated by sharp crested ridges of undisturbed clay. The supply of clay to the channels is controlled by weathering predominantly by hydration and dehydration. When wet, the clay sludges into the channel from the headwall and from the sides of the chutes. During dry periods shrinkage occurs giving extensive cracking and this results in free-falling of clay fragments from the headwall and rolling of particles to the channel floors from the side slopes. The material remains temporarily within the chute and is mainly discharged during wet periods by both shallow sliding and viscous flow. The glacial deposits, especially sands and gravels, become incorporated within the chute materials by periodic free-fall from the steep headwall. Thin layers of sand are intermittently introduced into the chute floors, to be, in turn covered by newly weathered clay. While the subsequent movement down the chute causes some mixing, thicker sand layers persist and occur as discrete horizons within the lower parts of the mudslides.

(b) the accumulation areas

Immediately downslope from the feeders the mudslides possess comparatively low slope angles. These areas are composed of overlapping lobes of clay and debris derived from the feeders. Material accumulates temporarily on these slopes before moving seawards. The surface micro-relief is typically quite subdued with small convex irregularities together with some transverse cracking. Each mudslide is bounded by marginal shear planes, which are steeply inclined, although sometimes adjacent accumulation areas may override and overlap. Movement within the accumulation areas seems to occur by shallow translational sliding of intact units or slabs. Shallow auger holes within the accumulation areas reveal striking variations in the texture of the materials.

(c) the toe areas

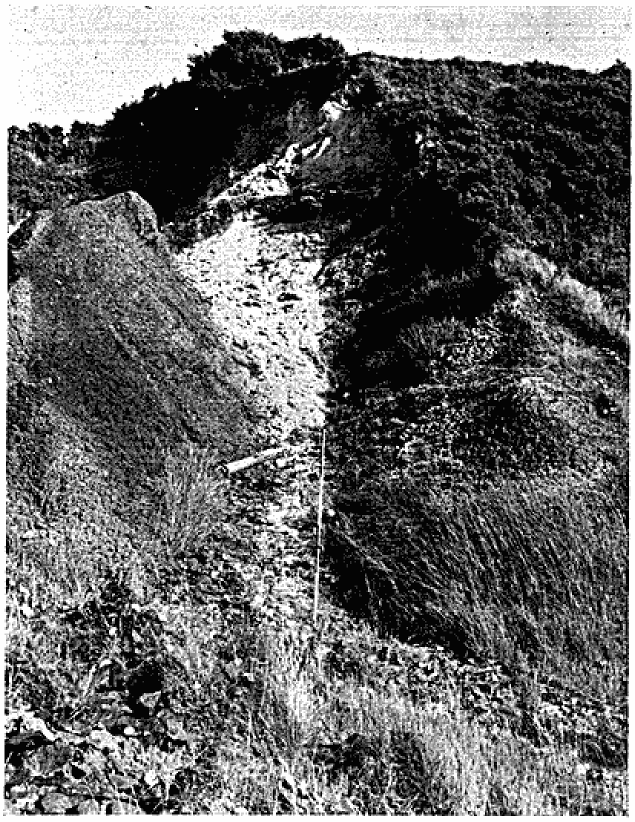

Fig. 9. A typical mudslide chute feeder area.

All the active mudslides terminate at present sea level and are being eroded, (Fig. 10). The toe areas have steeper slopes than the accumulation areas and show evidence of shallow rotational sliding giving miniature slump blocks. Polished and scratched shear planes can easily be identified bounding individual blocks. Sub-parallel, curvo-linear cracks occur at the junction between the toe and accumulation areas. The mudslide materials are exposed in section, where coastal erosion is most vigorous (Fig. 12). Reworked Eocene clay, without natural fissures, is sandwiched between layers of sand, or alternatively there is intermixing of glacial materials within a matrix of clay. The in situ clay can frequently be observed on the foreshore. It is intermittently buried by the advancing toes and exposed again by marine removal. These areas clearly demonstrate a continuous interplay between mudslide supply and coastal erosion. In fact, the mudslide toe areas change position quite dramatically, advancing and retreating depending upon whether mudslide or marine activity is dominant.

Four mudslide profiles are provided (Fig. 11 and 13) to illustrate the basic morphological components. Profile A refers to a small slide within a larger area of slumping south-west of Elverdams Gd. This particular slide is relatively inactive. The feeder slope is well-vegetated and is not at present contributing to the lower slopes. Some

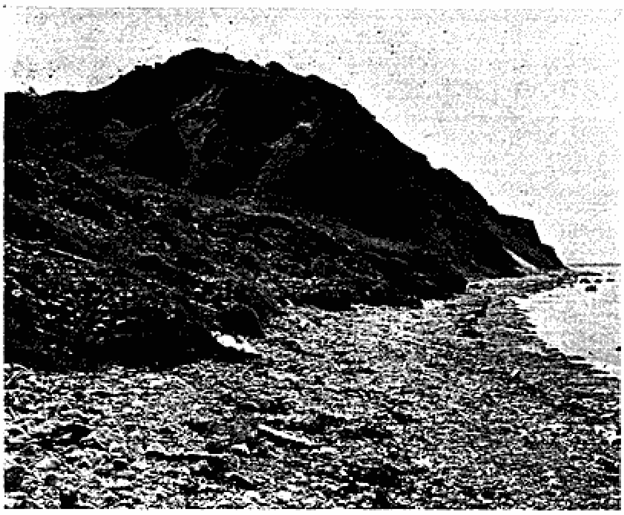

Fig. 10. The toe area of a mudslide which has been trimmed by recent marine erosion.

shallow translational sliding takes place on a slope of 6° but the main movements appear to the shallow rotations associated with marine trimming. These toe movements, of course, encourage shallow sliding further upslope.

By comparison, profiles B, C and D depict very active mudslides within the slumped area near the factory at Kongsgaard. Profile B demonstrates a feeder slope inclined at 30°, and shallow slumped units of clay and till are found beneath it. A general area of shallow translational sliding is inclined at 11° and its seaward edge shows rotational movement associated with marine erosion. Profile C is very similar except that the area subject to translational sliding is only gently inclined (3° average slope) and also has some reverse slopes. All three profiles essentially relate to mudslide activity on the seaward margins of slumped block topography and involve movements of Eocene clay already disturbed by this larger scale instability.

Profile D is somewhat different and demonstrates the chute-type feeder area. Mudslide activity begins on a steep slope (34°) on the outcrop of in situ Eocene clay. Weathering processes provide material on this slope which eventually accumulates below it, giving a surface slope of 7½°. Shallow augering shows the Eocene outcrop providing a basal surface at 9°. There is a distinct concave break of slope at approximately 5 m above mean sea level, beneath the accumulation debris. Once again, the toe area is subject to shallow rotational slipping with slide planes inclined at 34°.

Shallow hand augering was carried out, (using a 9.6 cm drill) but difficulties were encountered by boreholes closing at depths between 2 and 3 m. Figure 13 shows the results. All the boreholes show the layering of materials in the accumulation areas. Undisturbed, fissured clay was

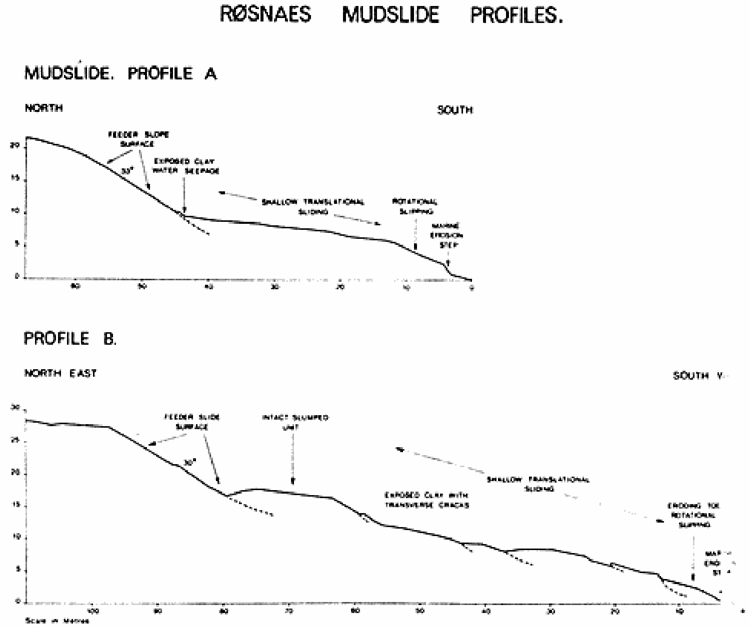

Fig. 11. Mudslide profiles.

only detected in boreholes 1, 2 and 3 on profile D. Thin organic rich horizons are notable within the mudslides (holes 3, 5, 6 and 7). Considerable variations in natural water content are found in the different textural horizons.

Discussion

The landslides on the Røsnæs coast are undoubtedly the product of a complex inter-action of factors. Steep slopes, the Eocene clay, marine activity and climatic factors combine to produce conditions ideally suited to different kinds of slope instability, both at present and in the past. In fact, there are many similarities between the Røsnæs coast and the mass-movement landforms associated with coastal slopes on London clay in southern England. These have been described in detail by Hutchinson (1967) and by Skepton and Hutchinson (1969). Both areas possess rotational landslides and mudslides while multiple retrogressive slides have been identified on Gault clay in the Folkestone area. Hutchinson concludes that where there is rapid coastal erosion, rotational or compound sliding predominates, whereas shallow translational slides and mudflows are associated with less severe rates of marine removal. In the Røsnæs area this subdivision cannot be wholly accepted. Firstly, the different mass-movement types occur together and secondly, the rates of erosion have varied not only spatially but temporally. It has already been suggested that the Røsnæs landslides are not all of the same age. While there is abundant evidence of contemporary instability some landslides apparently predate the Flandrian high sea level, while others were probably affected by it. Skempton and Hutchinson (1969) also cite multiple retrogressive slides as "occurring most frequently on actively eroding slopes of fairly high relief on which a thick stratum of overconsolidated, fissured clay is overlain by a layer of more competent rock". This describes almost exactly the combination of circumstances at Røsnæs.

The steep coastal slopes at Røsnæs are partly the result of marine trimming of the glacial deposits forming a major moraine. Oversteepening of the primary moraine slopes began at least as early as Neolithic times and morphological evidence shows this marine process to be still continuing. The Eocene sediments exposed by this erosion exert a fundamental influence on the resulting landslide activity. These deposits, like the London and Gault clays, are fissured, heavily over-consolidated and clay rich. The Røsnæs clays are dominated by swelling montmorillonite minerals and have medium to high plasticity. Landslides are very commonly associated with such materials since they undergo pronounced changes in physical properties when hydrated and dehydrated. The marine erosion of these sediments at Røsnæs also gives lateral and vertical unloading. This produces expansion and softening of the over-consolidated clays leading to weakening of the slopes due to the opening of crack and fissure systems (cp. Hutchinson, 1971). Where there is abundant water supply these sediments have the capacity for high water absorption and large pore water pressures can be generated within the sediments.

Pore water pressure distribution within slope materials is fundamental to a consideration of their stability. This is certainly the case at Folkestone where Hutchinson (1969) has suggested that movement of the multiple retrogressive slides takes place mainly at times of maximum pore water pressures. Also, stability analysis of mudslides and mudflows inevitably involves a consideration of field pore water pressures in relation to measured soil strength properties such as cohesion and friction. Recent work elsewhere on this category of mass-movement has suggested that instability, especially in feeder areas, is seasonal and reflects the climatic control of pore water pressures (Hutchinson 1970; Prior and Stephens, 1971).

There is little data available, as yet, concerning measured pore water values in the Røsnæs area. However, the mudslide movement rates vary seasonally and the following observations are considered worthy of note. Firstly, this locality is one of the driest parts of Denmark, receiving only 40–50 cm of rainfall annually. However, seasonal fluctuations in pore water availability can be easily observed. In winter and spring the mudslide areas become very wet, with areas of standing water and water seepage from the toe areas. By contrast, during summer the sites become dry and a hard surface crust becomes established. Attempts to measure pore water pressures during July, 1973 using electrical diaphragm piezometers yielded negligible values between the surface and depths of 2.5 m. High water availability in winter is the result of rainfall and the reduction of evapo-transpiration loss by low air temperatures (mean January temperature is approximately 0°C). It is likely that the period of maximum pore water pressures coincides with the spring thaw. Low pore water values in summer result from the effectiveness of evapo-transpiration due to relatively high air temperature (mean July temperature is approximately 17°C).

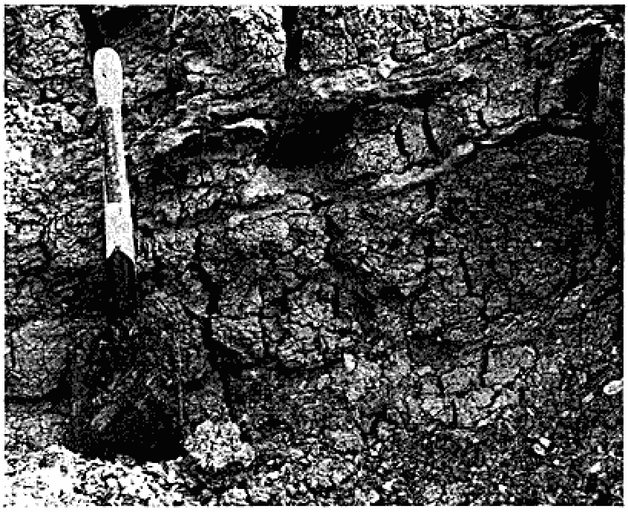

Fig. 12. Section through mudslide materials showing sand horizons.

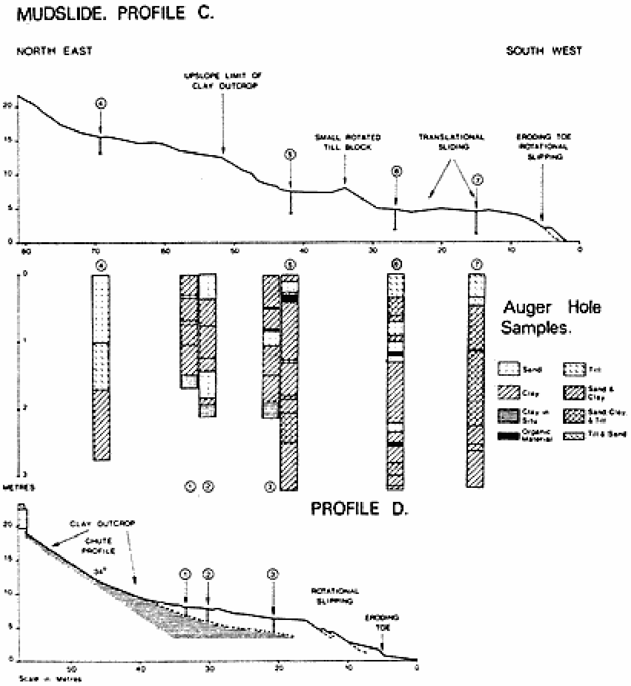

Fig. 13. Mudslide profiles.

The overburden of highly permeable glacial sands and gravels facilitates the supply of water to the underlying Eocene clays. In this respect, attention must be drawn to the presence of former meltwater channels which will tend to concentrate the sub-surface water flow. It is hardly coincidental that the most active landslide areas truncate several of these channels. Also, the natural incorporation of layers of sand within the mudslides undoubtedly aids the mobility and concentration of water at distinct horizons within the accumulation areas and encourages their instability.

Local climatic conditions, through their effect on weathering processes also influence the stability of the Eocene clays. These are subject to seasonal and even daily rhythms of hydration and dehydration. Severe volumetric changes are also associated with freezing and thawing and these processes are particularly efficient in weathering swelling clays with natural fissures. Weathering is one of the most important processes determining the rates of clay supply to some of the mudslide systems.

In summary, marine erosion stimulates unloading and weakening of the Eocene clays. Climatic conditions provide seasonal pore water surpluses which contribute to the reduction of the capacity of the Eocene clay to resist stress. Different types of slope failure reflect variations in these fundamental processes and the effects of other local factors, such as topography, detailed stratigraphy and variations in these conditions since late-glacial times. Further work is continuing to evaluate the detailed geotechnical and geochemical properties of samples of the Eocene clay and aims at a more precise evaluation of the variables involved in landsliding, by conventional stability analyses.

RESUMÉ

Røsnæs-halvøen er et ideelt studieobjekt for en række massebevægelser af klassiske proportioner. Der er på den 15 km lange halvø, hvis største højde når kote + 64 m DNN, en udpræget kontrast mellem den jævnt skrånende flade mod nord og de stejlt udskårne klinter mod Kalundborg Fjord. Klinterne er ofte 40–50 m høje og dannet af tertiære og pleistocene sedimenter. Eocene plastiske lerlag er bl.a. til stede, overlejret af 2 morænedækker, eventuelt af fluvio-glaciale aflejringer, der således danner de for områdets topografi karakteristiske kamesbakker.

Det eocene plastiske ler kendes i øvrigt fra Lillebælt og Djursland. Det er in situ, karakteristisk ved en udpræget opspaltning med rene, polerede flader. Orienteringen er forskellig, men der er normalt en enkelt dominerende retning med udpræget parallelisme. Hvor de er uforstyrrede, er sprækkerne hovedsageligt horisontalt arrangeret, men visse steder udviser de betydelige forstyrrelser og foldninger (fig. 3). Der er tale om høje værdier af Atterberg-tal (liquid limit og plasticitetsindeks), en funktion af lerindhold, lermineralogi og høje natrium kation-værdier.

Den øvre moræne modsvarer norsk is, den nedre er baltisk moræne.

De 2 vigtigste typer »landslides« er »slumped blocks« og »mudslides«. Slumped blocks omfatter 3 typer:

1. »rotational slides« af intakte blokke af soil og undergrund, hældning $14–15^{1}/_{2}$°.
2. »compound slides«, der typisk har glideflader, som kombinerer kurvede og planare elementer.
3. »multiple retrogressive slides« er komplekse landslides, der kan videreudvikles fra såvel 1. som 2. ved yderligere glidning og ekstra bevægelser. Hældning $8–10^{1}/_{2}$°.

Alle disse 3 typer findes på Røsnæs. Rotational slides ses på profilerne 1, 5 og 6. Compound slides ses på profilerne 2 og 3, og multiple retrogressive slides på fig. 2.

Aktive mudslides findes på adskillige lokaliteter på Røsnæs. De viser udpræget sæsonrytme. Røsnæs mudslides har 3 distinkte morfologiske komponenter, der også repræsenterer forskellige mekanismer af skræntinstabilitet:

- a. fødeområderne, hældning 30–40°. Der findes 2 typer, jfr. bl.a. fig. 9.
- b. akkumulationsområderne og
- c. terminalområder, jfr. fig. 10.

4. Mudslides-profiler gengives på fig. 11 og 13 til illustration af de basale, morfologiske komponenter.

Landslides på Røsnæs er et produkt af et komplekst samspil af faktorer: stejle skrænter, plastisk ler, marin aktivitet og klimatiske faktorer. Det giver i kombination betingelser, der er ideelt egnede til at frembringe forskellig slags skrænt-instabilitet såvel i dag som i fortiden.

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REFERENCES

Guilcher, A. (1958) Methuen, London.

Hansen, J. B. and Mise, T. (1964) Geoteknisk Institut Bull. 17 Copenhagen.

Hansen, and Nielsen, (1960).

Hutchinson, J. N. (1967) Proc. Geotech. Conf. Oslo.

Hutchinson, J. N. (1969) Geotechnique, London.

Hutchinson, J. N. (1970) Geotechnique, London.

Hutchinson, J. N. (1971) I.R.P.I. Conf., Naples.

Hvorslev, M. J. (1937) Ingeniørvidenskabelige Skrifter, Copenhagen.

Mertz, E. L. (1928) Danmarks Geologiske Undersøgelse, Copenhagen.

Prior, D. B. et al. (1968) Geografiska Annaler, Stockholm.

Prior, D. B. and Stephens, N. (1971) Bull. Geol. Soc. America.

Prior, D. B. (1973) Geografisk Tidsskrift.

Schou, A. (1949) Atlas of Denmark, Copenhagen.

Skempton, A. W. and Hutchinson, J. N. (1969) Proc. 7th Int. Conf. Soil Mech., Mexico.

The overburden of highly permeable glacial sands and gravels facilitates the supply of water to the underlying Eocene clays. In this respect, attention must be drawn to the presence of former meltwater channels which will tend to concentrate the sub-surface water flow. It is hardly coincidental that the most active landslide areas truncate several of these channels. Also, the natural incorporation of layers of sand within the mudslides undoubtedly aids the mobility and concentration of water at distinct horizons within the accumulation areas and encourages their instability.

Local climatic conditions, through their effect on weathering processes also influence the stability of the Eocene clays. These are subject to seasonal and even daily rhythms of hydration and dehydration. Severe volumetric changes are also associated with freezing and thawing and these processes are particularly efficient in weathering swelling clays with natural fissures. Weathering is one of the most important processes determining the rates of clay supply to some of the mudslide systems.

In summary, marine erosion stimulates unloading and weakening of the Eocene clays. Climatic conditions provide seasonal pore water surpluses which contribute to the reduction of the capacity of the Eocene clay to resist stress. Different types of slope failure reflect variations in these fundamental processes and the effects of other local factors, such as topography, detailed stratigraphy and variations in these conditions since late-glacial times. Further work is continuing to evaluate the detailed geotechnical and geochemical properties of samples of the Eocene clay and aims at a more precise evaluation of the variables involved in landsliding, by conventional stability analyses.

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