# GEOLOGICAL AND GEOTECHNICAL ASPECTS OF A LANDSLIP IN THE FREMINGTON CLAY, NORTH DEVON

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Cattell, A. 2003. Geological and geotechnical aspects of a landslip in the Fremington Clay, North Devon. *Geoscience in south-west England*, **10**, 397-402.

A landslip in the Fremington Clay at the A39 Lake cutting was investigated. The geology was similar to that found at the old clay pits to the east, but two novel features were noted. Firstly, the base of the clay was laminated on a millimetre scale. The laminated unit consisted of red clay with fine sand laminae at the base, passing up into interlaminated light-red (probably silt-rich) and red (silt-poor) clay, and finally into red laminated clay. The laminated red clay was overlain by unlaminated brown clay. Secondly, both the contact of the clay with the underlying gravel, and the clay laminae, dipped northward at about 11°. This suggests deposition of the clays in a quiet environment, probably lacustrine, draping an existing surface of the basal gravel, and probably marking the southern margin of the lake basin in which the Fremington Clay was deposited. Clay deposition was punctuated by a gradually declining periodic influx of fine sand and then silt. The geology has important geotechnical consequences. The clays of the upper part of the laminated unit have low frictional strength, high plasticity, and negligible cohesion across the laminations, that dip at an unfavourable angle out of the north-facing side of the cutting. A basal slip plane has formed along this horizon, above which a complex landslip has developed.

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## INTRODUCTION

The Fremington Clay is well known as the only likely glacial deposit on the South West England mainland. A general description of the deposit is given in the local memoir (Edmonds *et al.*, 1985) and their context is discussed in Cullingford (1981). Natural exposures are rare, and most descriptions are based on sections from clay pits, from where the clay was dug for use in pottery making. The most recent study was carried out by Croot *et al.* (1996), who created a large temporary excavation in order to expose the clay. Away from the area of the clay pits, the Fremington Clay was temporarily exposed during the construction of the A39 North Devon link road, to the south of Barnstaple, particularly in the Lake cutting. The temporary exposures in part of the cutting were described by Hawkins and Hawkins (1990).

The base of the Fremington Clay is marked by a coarse basal gravel which rests on Carboniferous bedrock. The basal gravel is up to 2 m thick, and consists of clast-supported subangular gravel in a sandy silt matrix, with clasts of local origin. The top of the gravel shows a sharp contact with the overlying clay. The clays overlying the gravel are usually clast-free, 3-6 m thick, and constitute the main pottery clays, but a thin (<1.0 m) discontinuous gravelly clay or 'till' is noted by some authors at the base of the clay (see sections on figures. 11.4 and 11.5 of Cullingford (1981)). Overlying the clast-free clay is a gravelly clay, shown by some authors to have a gradational contact (Croot *et al.*, 1996), and by others to be a distinct unit (Cullingford, 1981). All authors note beds, laminae and lenses of fine sand within the gravelly clay. The Fremington Clay sequence is overlain by a gravelly head deposit, typical of head deposits in the area, and not genetically connected to the underlying sequence. The possible origins of the various units are discussed by Croot *et al.* (1996). The basal gravels are considered to be of fluvial origin, although fluvioglacial or raised beach origins have also been proposed. The stoneless clays are concluded to be glaciolacustrine, although a glaciomarine origin is discussed. The occasional gravel-sized clasts are interpreted as dropstones. The fine sands are thought to have been contemporaneous with the clays, and thus also glaciolacustrine. The gravelly clays are thought by Croot *et al.* (1996) to be a weathered extension of the underlying clays, in contrast to previous interpretations of this unit as a till.

The engineering geology of the clay is not well known. Presumably the clay pit operators were aware in practical terms of the general stability of cut faces in the pits but it seems doubtful that any tests or quantitative analyses were carried out, and certainly none seem to have been published. Hawkins & Hawkins (1990) gave some geotechnical data on the exposures in the Lake cutting, mainly particle size distributions on various units and plasticity data from the clays. Croot *et al.* (1996) carried out some oedometer tests to determine the consolidation characteristics of the clay. Some particle size, plasticity, and shear strength data are recorded on the unpublished borehole logs from the North Devon link road site investigation; these are held by the British Geological Survey in Exeter.

## LANDSLIPPING

The outcrop area of the Fremington Clay has subdued topography, and no record of natural landslips on the material has been found. The outcrop area is blanketed by a metre or more of stony head deposits. Therefore slope stability problems related to the clay would only occur in deep excavations, such as Lake cutting, and presumably also in the old clay workings. Consequently little was known, because little needed to be known, about stability of slopes in the Fremington Clay.

Lake cutting lies some 2 km south of Barnstaple, where the A39 North Devon Link Road climbs westwards from the floodplain of the River Taw up onto the gently sloping plateau that overlies the Fremington Clay outcrop (Figure 1). A minor road crosses the midpoint of the cutting on Lake Overbridge. The cutting faces are at 1:3 (approximately 18°). At the overbridge the south face of the cutting is 10 m high. The cutting height gradually reduces westwards as the road climbs through the cutting, while the crest of the southern face stays roughly constant at 30 m above Ordnance Datum. The natural slope of the land prior to road construction was very gently toward the north-north-east.

Subsequent to the construction of Lake cutting, some landslipping occurred on the southern side of the cutting,

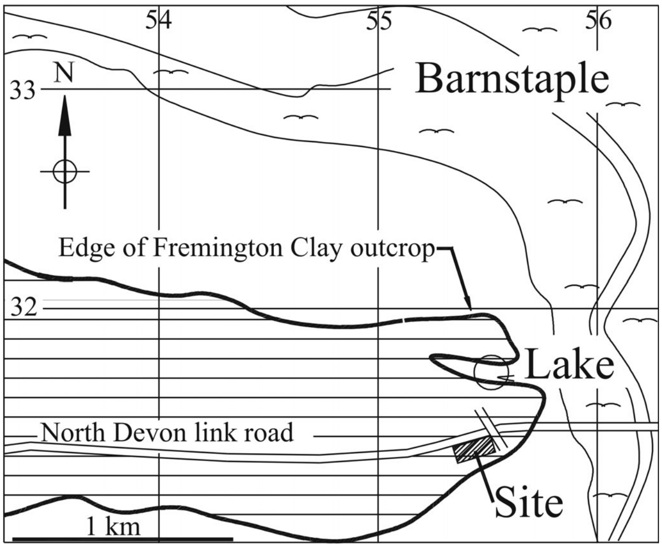

***Figure 1.*** *Map showing the location of the investigated landslip at Lake cutting.*

immediately west of Lake Overbridge. The slip has affected a 100 m length of road (Figure 2). Its surface expression is a series of arcuate backscarps, revealing a complex of several individual slips, probably formed progressively by retrogression up the slope. Areas of benching, back-rotation and graben structures are present immediately downslope of the backscarps. These features are accommodation structures which indicate that the failure surfaces are not circular in section, but that the steep failure surfaces revealed in the back scarps connect with one or more flatter-lying basal slip planes at depth. Movement at the toe was sufficient to carry spoil onto the highway, and features at the toe had been destroyed by temporary remedial works prior to this investigation. Movement on the slip continued each winter, and led to the decision to carry out works to stabilise the slip. The ground investigation into the landslip, prior to design of remedial works, forms the basis of this contribution. Large movements continued during and after the ground investigation in autumn 2001. Subsequent design and construction of the remedial scheme in 2002 was carried out by others.

## GEOLOGY

The ground investigation consisted of 4 trial pits and 6 window sample holes (Figure 2). The sequence revealed in the cutting is similar to that reported from the clay pits to the west (Croot *et al.*, 1996), and to that described by Hawkins and Hawkins (1990) from the cutting to the east of Lake Overbridge. It consists of the basal gravels, including some gravelly clay, overlain by red and brown clay, overlain by some gravelly clay with rare sand beds or laminae (Figure 3). At the exploratory hole positions the superficial gravelly head deposits had been fully excavated out during construction of the cutting, but 1.5 m of this material could be seen in the landslip backscarp.

Bedrock was not reached in this investigation, but an earlier borehole for the southern abutment of the overbridge proved mudstone and sandstone bedrock beneath 2.05 m of the basal gravels (recorded as gravelly sand and clay), and Hawkins and Hawkins (1990) recorded 2.5 m of sandy gravel over slate bedrock just to the east of the site.

The basal gravels consist of dense yellowish brown clayey gravel and sandy gravel. The gravel is generally coarse, both rounded and angular, and contains some cobbles and boulders. The clasts were not systematically identified, but most appeared to be of locally derived sandstone. Some gravelly clay bodies are present and were also recorded in the earlier site investigation boreholes for the road. The clay is yellow and of low plasticity, in contrast to the more plastic red and brown clays of the main clay unit.

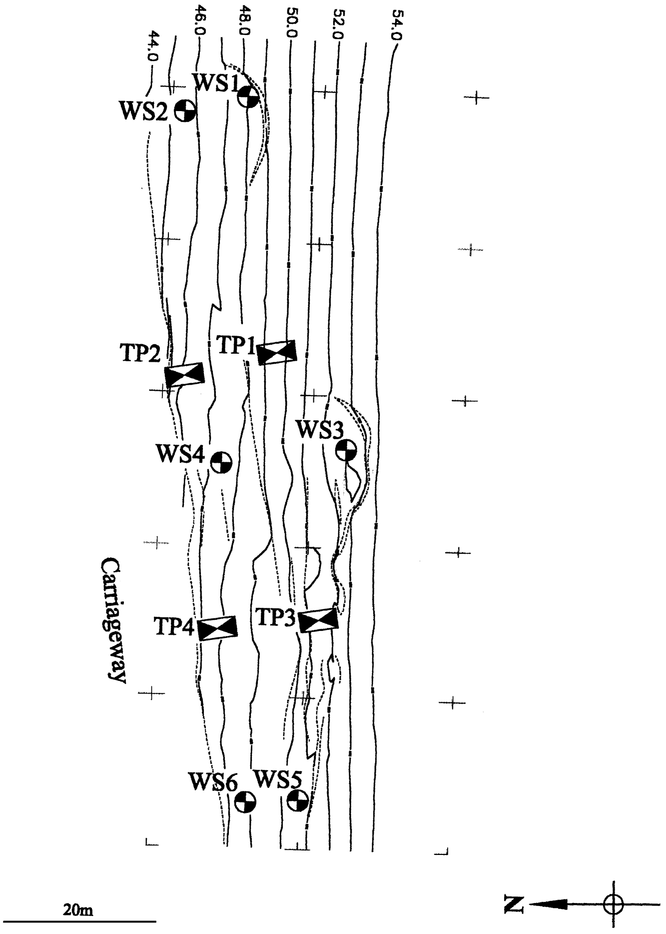

***Figure 2.*** *Site plan showing trial pit and window sample hole positions. Contours in 1 m intervals relative to local datum, not OD. Datum level is approximately 24 m above OD.*

The clay can be divided into a lower red unit and an upper chocolate brown unit. The red clay is between 0.25 m and 0.75 m thick, but the contact with the overlying brown clay is gradational so the exact thickness is difficult to measure. Nevertheless, there appears to be a general thickening of the unit to the south: five of the six pairs of exploratory holes show a greater thickness of red clay in the southern hole of the pair (Figure 2). The lower part of the red clay contains laminae of fine yellow sand, and in places a thin or very thin bed of sand marks the base of the unit. Hawkins and Hawkins (1990) also noted a 100 mm thick silty fine sand at the base of the clay, to the east of Lake Overbridge. Upward through the red clay the sand laminae become less common, and are not present in the top half of the unit. The middle part of the red clay shows thin laminae of lighter colour, probably indicating a variation in silt content. The uppermost part of the red clay is laminated.

The overlying brown clay lacks lamination or visible layering, and locally has poorly developed polyhedral fissuring. Secondary reduction (gleying) along the fissure surfaces produces a light greenish grey colour. The lower part of the brown clay is clast-free, but some gravel is present in the upper part. Thin beds of fine sand are common in the upper part of the brown clay at the eastern end of the site in WS1, but absent elsewhere. This appears to be a continuation of the material recorded to the east of Lake Overbridge by Hawkins and Hawkins (1990), where a 100 m long body of fine sand up to 3 m thick wedges out just east of the bridge.

The contact between the clay and underlying gravels, and also the laminations in the clay, dip toward 010° at about 11° (Figure 4). The base of the clays falls from 26 m above O.D. at the cutting crest to 20 m above O.D. at road level beneath the overbridge. The dip is consistent from west to east along the 100 m length of road, but does not continue northward far beyond the road, where earlier boreholes to the north of the road recorded the

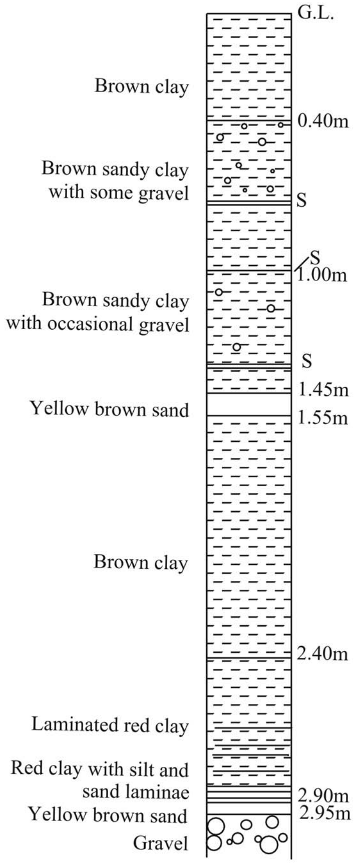

***Figure 3**. Stratigraphic section, based on WS1. S = thin sand horizon.*

clay-gravel contact at 19.9 and 20.4 m O.D., essentially the same level as the lowest levels at the site. The geology to the south of the cutting is not known, but if the strata continue to dip up at 11°, then they will be truncated by the base of the head deposits within 100 m of the crest of the cutting. The southern boundary of the Fremington Clay outcrop is approximately 200 m south of the site. Groundwater was not encountered in the exploratory holes, and groundwater monitoring found only a slight head of water above the top of the basal gravels in one hole in winter 2001/02.

Shear surfaces were searched for in the trial pits and window samples. Polished surfaces parallel to the laminations in the clay were noted in some trial pits, but could not always be found. Higher angle polished surfaces, dipping north towards the road, were also noted but could not necessarily be connected to backscarp features at the surface. Clear shear surfaces could not be identified in the window samples, despite the obvious presence of softened zones.

## ENGINEERING GEOLOGY

### *Plasticity*

Plasticity was determined on 22 samples as part of the investigation described here, and data are available for a further 32 samples from Hawkins and Hawkins (1990) and from the original road scheme site investigation logs. The plasticity data can be used to indicate the relative clay content of the samples since plasticity index varies proportionally with clay content. They also give an indication of the likely peak strength, as peak shear strength in clay soils varies inversely with plasticity.

Clays from within the basal gravels have a uniformly low plasticity index of 15-18% (Figure 5). Within the red and brown clays, the plasticity index is variable (25-40%) in the lower red clays, remains generally high at about 40% in the upper red clays and lower metre of brown clays, and then falls to about 20% in the upper part of the brown clays. These data indicate the varying proportions of fine sand and silt layers within the tested samples. The upper red clays and lowermost brown clays are the most clay-rich. The lower part of the red clays has a variable content of silt and fine sand, much of it present as layers too thin to separate out during sampling. The upper part of the brown clays also has an increasing proportion of silt, and possibly fine sand, but not as discrete layers. The peak shear strength of the clays is likely to be lowest in the upper part of the red clay and the lower part of the brown clay.

### *Undrained shear strength*

The undrained shear strength of the clay soils in the trial pits and window samples was measured using a hand vane and hand penetrometer. There is a general increase in shear strength with depth, from 50 kPa or less at ground level to 150 kPa at 2 m depth (Figure 6). The general correlation of increasing strength with depth below the cutting face shows that the clays have re-equilibrated through swelling and softening with the reduction in overburden pressure since the cutting was excavated. Softer zones are present at depth. These occur at 2.2 and 2.6 m in WS1, 1.5, 1.75 and 2.5 m in WS3, 0.95 m in WS4, and 1.50 m in WS5. In each case the lowest soft zone occurs in the upper part of the red laminated clay. These soft zones probably indicate shear zones in the clays, although discrete shear surfaces are not visible in the clay within the soft zones in the window samples from which the data shown on Figure 6 were obtained.

### *Peak drained strength*

Strength was tested in the laboratory using consolidated drained shear box tests, consolidated undrained triaxial tests, and ring shear tests (Figure 7). All tests were carried out on the red laminated clay. The shear box testing gave variable results because of the presence of laminations, some of which may also be shear planes, within the clay. The laminations are at a low angle

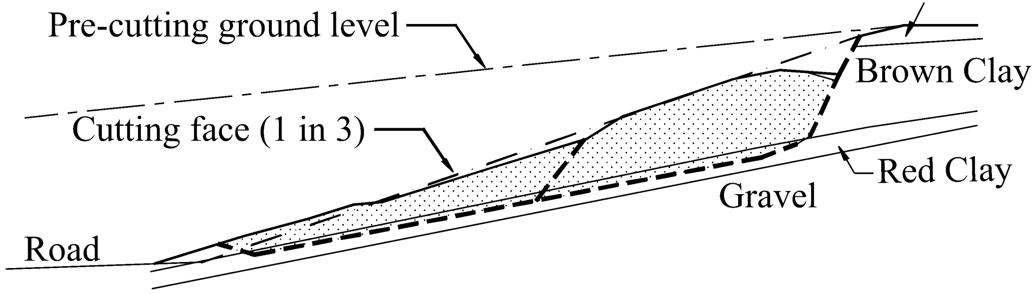

***Figure 4**. Cross section through cutting and landslip, based on section through WS4 and WS3. No vertical exaggeration. Dashed lines indicate slip planes. Further slip planes are probably present.*

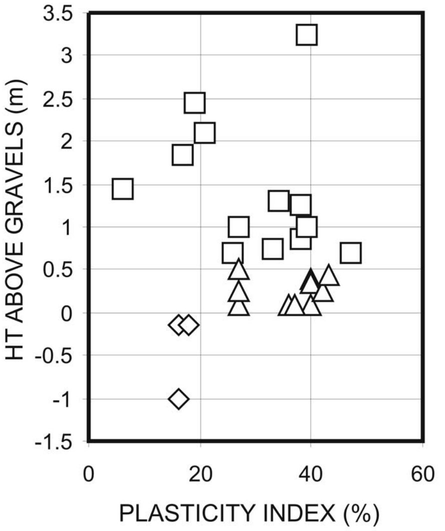

***Figure 5**. Plasticity index plotted as a function of stratigraphical height. Open diamonds are samples from clay lenses in the basal gravels, open triangles are of red clay, and open squares of brown clay.*

to the shear surface produced by the shear box tests, which were carried out on samples cut such that the induced shear surface was horizontal. Strengths ranging from peak down to residual might be expected, depending on whether the shearing induced by the shear box exploited the laminations present, and on the extent to which the strength of the clay along the lamination surface had already had its strength reduced toward the residual by shear along it prior to testing. The results cannot be used to define $c'$ and $\phi'$, but do show the natural variation in 'peak' strength present in the red clay. If $c'$ is assumed to be zero then the six specimens tested give $\phi'$ of 18 to 35°.

The triaxial tests do give good values for $c'$ and $\phi'$ because the triaxial samples were cut with the long axis vertical and thus at a high angle (80°) to the laminations. The laminations are at a high angle to the peak shearing stress induced by the test and are not exploited during the test. As a result, the test gives the peak strength of the intact red clays. The two tests samples gave very similar results: $c' = 4$ kPa and $\phi' = 28°$ for TP2, and $c' = 2$ kPa and $\phi' = 27°$ for TP4. These values represent the peak strength when the clay is sheared at a high angle to laminations. The shear box tests suggest that the peak strength is lower if the clay is sheared parallel to the laminations, as might be expected, and this needs to be considered in any stability analysis.

### *Residual strength*

The ring shear tests give the residual strengths of the clays. The material showed swelling behaviour at pressures up to 100 kPa and could only be tested at confining pressures greater than this. The residual strength envelope has to be projected back to the lower pressures applicable to the site. The test assumes that there is no residual cohesion ($c'_r = 0$), and based on this assumption, residual strengths of $\phi_r' = 10°$ for TP2 and $\phi_r' = 9°$ for TP4 are obtained. Best fit lines through the data give apparent $c'_r$ of 2 kPa for TP2 and –6 kPa for TP4, and –2 kPa when data from both samples are combined. The negligible apparent $c'_r$ values show that the assumption that $c'_r = 0$ is reasonable. They also show that the residual strength envelope cannot be significantly curved at low confining stress, and that the $\phi_r'$ values from the tests are applicable for the lower confining pressures at Lake.

## DISCUSSION

### *Geology*

This investigation was for geotechnical purposes, and the origin of the Fremington Clay is beyond the scope of this contribution. Nevertheless, some new features were noted which need to be considered when assessing the origin of the deposits.

The most obvious feature in the field is the presence of a red clay unit at the base of several metres of uniformly chocolate brown clay. However, it is unclear that the colour variation is primary, and it may not be of any genetic significance. At this site the colour change does approximately coincide with textural change (from laminated to polyhedrally fissured), but this may merely be coincidental or even consequent upon the textural change (because of the different bulk permeability properties of the different textures).

The presence of thin beds of fine sand at the base of the clay is important. Hawkins and Hawkins (1990) noted 100 mm of fine sand between the basal gravels and overlying clay, but commented on the sharp change in colour and lithology between the sand and overlying clay. Although not explicitly stated, this seems to imply an abrupt change in sedimentation, possibly associated with a significant time gap. The evidence from this investigation is that sand and clay deposition continued contemporaneously, probably in the form of background sedimentation of clay with episodic influxes of fine sand which became less common, and possibly siltier, with time. There remains the possibility of a significant time gap between deposition of the underlying gravels and deposition of the sand and clay. There appears to have been a significant hiatus in sand input as the main body of the clays were deposited, but sand bodies and layers again become common towards the top of the brown clay.

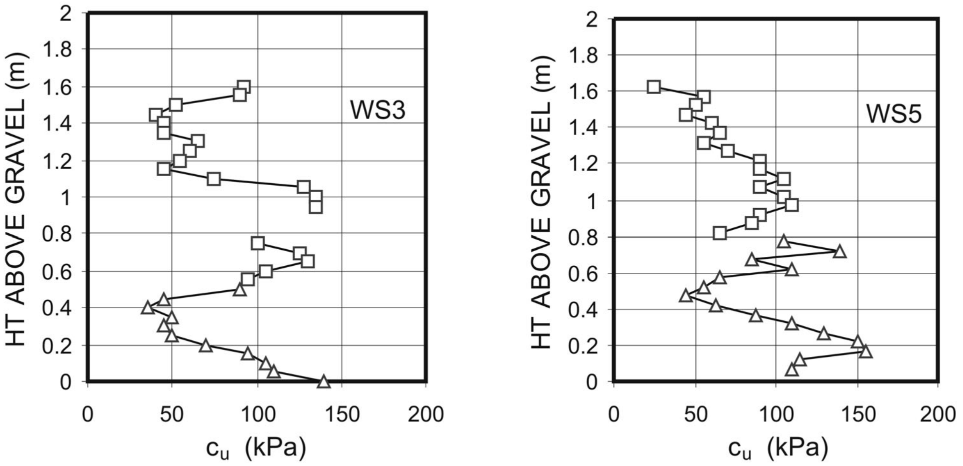

***Figure 6**. Undrained shear strength plotted as a function of stratigraphic height. Symbols as in figure 5. Data from hand penetrometer tests on window samples.*

The upper part of the red clay is laminated, and part of it is colour laminated, probably reflecting the presence of more and less silt-rich layers within the clay. The presence of laminated clay within the Fremington Clay does not appear to have been previously described, although the likelihood of it having originally been deposited in this way has certainly been considered. Croot *el al.* (1996) stated that the clay must have been deposited in a (sub-) horizontal or laminated manner, and that although traces could occasionally still be seen microscopically, it was strongly deformed by post-sedimentary processes and in most places lamination could not be observed.

In the area of the clay pits the unit is approximately horizontal, although somewhat uneven, as depicted in figure 6 of Croot *et al.* (1996). At Lake cutting the base of the clay and the laminations within it dip northward at 11°. It is assumed that this dip is not tectonic (although it remains possible that the Fremington Clay is Tertiary in age). Comparison with nearby boreholes shows that this dip does not continue northward into the centre of the outcrop area. It is more likely that the clay laminations reflect sediment draped over a northerly sloping surface of gravel. The site seems therefore to mark part of the southern boundary of the lake basin in which the clays were deposited. The geometry of moderately dipping sediments at the margin passing into flat lying deposits in the centre is similar to the glaciolucustrine deposits described by Wieczorek *et al.* (1998) from the Tully Valley of New York State.

## *Geotechnical*

The engineering geological evolution of the site is as follows. Following deposition, the clays were buried to several tens of metres, as indicated by the overconsolidation pressures of 250 to 350 kPa calculated from oedometer tests by Croot *et al.* (1996). Subsequently the clays were eroded to their present thickness and blanketed by head deposits. Pressure release probably led to polyhedral fissuring of the brown clays. Site investigation for the cutting in 1982 proved clays whose undrained shear strength increased progressively with depth below ground level, showing them to be in equilibrium with the then current conditions.

Excavation for the cutting would have immediately lowered the pore water pressures within the clays, leading to negative values (suctions) and consequently to high effective strength. For this reason the slope would initially have been stable. Subsequently, gradual infiltration of rainwater, and groundwater from the underlying gravels, would have brought the pore water pressures back up to levels in equilibrium with the new post-cutting profile, thereby gradually lowering the effective strength of the clays. This process is well known, and may take decades in cuts in thick sequences of impermeable clays. However, the clay sequence at Lake is thin, has permeable gravel beneath it, and sand layers and lenses within it. All these factors would accelerate the re-equilibration of pore water pressures, which probably only took a few years. The results of the 2001 site investigation show undrained shear strengths generally in equilibrium with the post-cutting, and not the pre-cutting profiles, indicating that re-equilibration of pore water pressures was complete. The factor of safety for the slope would have progressively fallen from the time of construction, as the pore water pressure rose. Initial failure would probably have occurred during high transient pore water pressures following heavy winter rainfall. The site must be particularly prone to this as the clays are underlain by a sloping layer of gravel, which can be recharged by infiltration of rainwater only a few tens of metres upslope from the cutting. Once a failure had occurred and a slip surface even partially formed, then further movement was inevitable because of the low residual strength of the clays along the slip surface, relative to the previous peak strength.

The form of the landslip was strongly controlled by the geology. The presence of the underlying gravels prevented the formation of a simple 'circular' (arcuate) slip surface, and instead a complex landslip developed, with a basal slip plane parallel to the gravel surface. This slip plane exploited the more clay-rich and plastic layers approximately 0.5 m above the gravels. The presence of laminations within the clay at this level is important, because the cohesive component of shear strength is lost across the laminae, i.e. shearing along the lamination is resisted only by the frictional component of the shear strength.

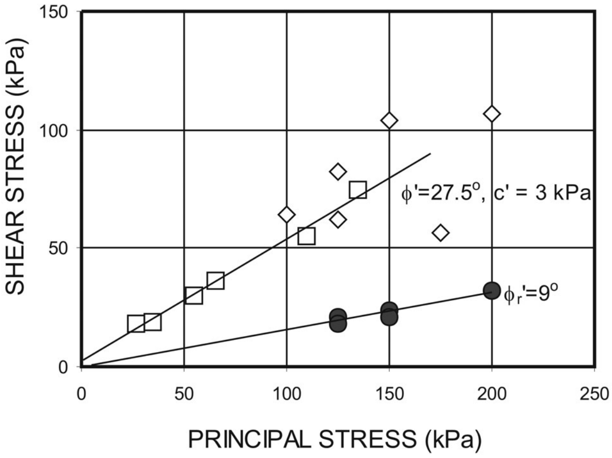

***Figure 7**. Laboratory shear strength data. Open diamonds are peak strength data from shear box tests, open squares are peak strength data from triaxial tests, and filled circles are residual strengths from ring shear tests.*

The 2D stability of the landslip was modelled by the Janbu method, using the average peak strength values of $c' = 3$ kPa and $\phi' = 27.5°$ for the clay. The observed geometry of the landslip was modeled using a simple 3 straight segment failure surface. Under 'summer' conditions, with water levels below the clays, a factor of safety (F) of 2.0 was calculated for the slope (first time failure of the slope should occur if $F<1.0$). Winter conditions were modelled by assuming groundwater levels were at the surface, and under these conditions, $F=1.14$ was calculated for an unlaminated clay. The effect of laminations in the clay was modelled by reducing the cohesion (c') from 3 kPa to zero for the section of the slip surface that ran parallel to the laminations. Under these conditions, F fell from 1.14 to 0.92.

The analysis above is not intended to be rigorous, since the pore water pressure distributions are not known. Nevertheless, the closeness of the calculated F value to 1.0 suggests that the assumptions are not unreasonable. More importantly, the analyses show the importance of the effect of the laminations in the clay, which reduce the factor of safety by over 20%. The effect is significant because of the orientation of the laminations, that dip out of the cut slope at 11°. As a test of this effect two other analyses were run, this time with the hypothetical situation that the clays extended down beyond the base of the slope, and that the basal slip plane was horizontal. For an unlaminated clay, the hypothetical factor of safety was essentially unchanged from the actual case of the sloping basal slip surface, i.e. $F=1.14$. For a laminated clay, the hypothetical factor of safety fell to $F=1.06$, a drop of only 8%.

In short, the slope has just about the worst possible set of characteristics. The slope was cut in clay, but underlain at shallow depth by gravel, allowing build up of pore water pressures in the clay through groundwater flow in the underlying gravel. Within the clay was a unit of relatively high plasticity, and thus relatively low shear strength, dipping out of the slope at about 11°. The clay was laminated and thus had no cohesive strength when sheared parallel to its layering. The clays also have a low residual strength, meaning that once movement has occurred, the factor of safety drops significantly. The effect of this is that movement can continue at lower pore water pressures.

The likely instability is obvious in retrospect. However, the original site investigation did not record any laminations in the clays, nor was any dip of the strata noted. Any stability analysis based on the original records would have yielded a misleadingly high factor of safety. The situation would be made worse because at least 80% of the slip surface lies within the more plastic red clay, and any analysis based on average strength results or strengths of samples elsewhere in the clay units would again overestimate the true factor of safety. The landslip highlights the need for careful investigation and understanding of the geology on which any geotechnical assessment is made.

## ACKNOWLEDGEMENTS

The author thanks the Highways Agency for permission to publish this work.

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