Slope Instability in Ireland with Particular Reference to Peat Failures

Dr Paul Jennings

Applied Ground Engineering Consultants Ltd., Bagenalstown, Carlow, Co. Carlow, Ireland: pjennings@agec.ie

ABSTRACT

Recent large-scale peat failures in the autumn of 2003 at Pollatomish, County Mayo and Derrybrien, County Galway have focused attention on to such events. However, peat failures are not a recent phenomenon with possible evidence of peat failures in Ireland having been identified as far back as the Early Bronze Age. The paper examines the various peat types found in Ireland and the typical characteristic properties of peat. Peat strength is reviewed, as peat strength plays a primary role in peat stability. The variability of peat strength, particularly with depth is examined and the various methods used to assess strength discussed. Definition of peat failure is classified into bog flows and bog slides. Examples of both are given and differences between them highlighted. A review of historical failures is given and an assessment made of the hazards and risks associated with peat failures. Likely casual factors attributed to peat failures are presented using examples of failure, including the recent failures at Pollatomish and Derrybrien both of which have been investigated by the author.

1 INTRODUCTION

Recent large-scale peat failures in the autumn of 2003 at Pollatomish, County Mayo and Derrybrien, County Galway have focused attention on to such events. However, peat failures are not a recent phenomenon with possible failures in Ireland being dated as far back as the Early Bronze Age at about 4200 BP (Murray, 1997), and with written accounts of peat failures in Ireland having been traced back to the 1400s (Feehan and O'Donovan, 1996).

There is an estimated over 70 reported events of peat failures in Ireland, and more than likely a significant number of unreported events. The Irish Geological Survey is currently preparing a nationwide database of landslide events, which includes peat failures (Creighton, 2004). An indication of the distribution of reported peat failures is shown in Figure 1.

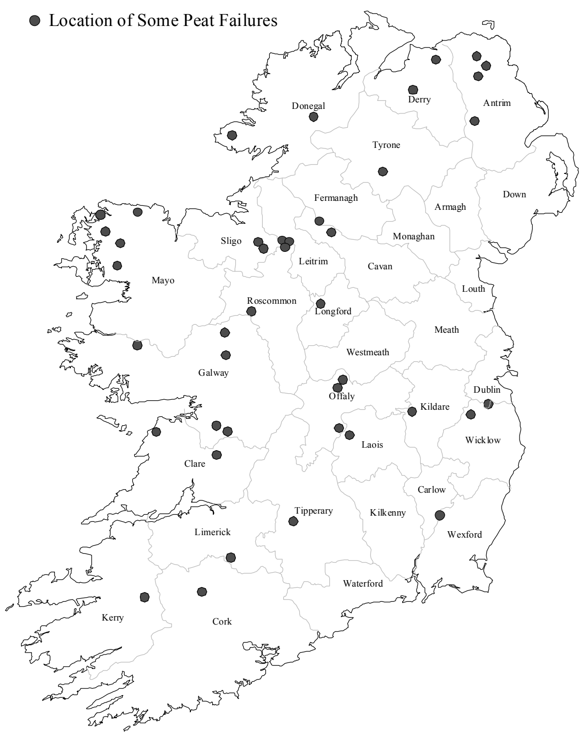

Figure 1 Location of Peat Failures in Ireland

2 CHARACTER OF PEATLAND IN IRELAND

2.1 Distribution and Types of Peat

Three type of peatland, or bog, occur in Ireland namely upland blanket bog, lowland (or oceanic) bog and raised bog. Peatland is generally found in areas of high rainfall under conditions of poor drainage. The distribution of peatland is shown in Figure 1 with altogether about 17% of Ireland covered in peatland (An Foras Taluntais, 1980).

The extent of each type of bog is controlled to a degree by rainfall and elevation. Upland blanket bog covers large expanses of most of the mountainous areas. In the west, due to the wet climate, blanket bog occurs down to sea-level; and this explains why low-lying bog is also referred to as oceanic bog. Raised bogs are commonly found in the Midlands, and are called raised bogs because of their characteristic domed profile. Details of formation of bogs are provided in numerous publications (for example see Feehan and O'Donovan, 1996 and Moore and Bellamy, 1974).

Raised bogs generally tend to be 3 to 12m thick, with an average of about 7m. Blanket bog would typically be about 3m thick, but as the underlying surface is irregular, locally thicker deposits of bog are commonly present. Blanket bog thickness typically thins at greater elevations. A limiting slope angle for deep blanket peat is given as 20^o (Hobbs, 1986).

Peat formation would have started in Ireland following the end of the Ice Age, some 10, 000 years BP. Initially peat would have formed in water-logged hollows as raised bogs, which would have been prevalent in the low-lying Midlands. The spread of upland blanket bog appears to have accelerated following the appearance of farming some 3,000 to 4000 years BP. As bogs form over previously existing ground surfaces it is therefore not uncommon to find evidence of relict topsoil horizons particularly under blanket bog. Other evidence of previous ground surface include remnant plant life, notably tree stumps, and more rarely human occupation. Typically soils found below bogs would include glacially derived soils, lacustrine deposits and weathered rock.

2.2 Nature of Peat

Peat consists of the remains of decaying plant life found growing on the peat, such as mosses, sedges and grasses. The uppermost peat layer contains actively growing bog plants and virtually undecayed fibrous plant matter. This uppermost layer, commonly referred to as the acrotelm, varies in thickness from about 0.3m to 1m and though waterlogged, the water level in this layer would vary seasonally. Deeper peat is notably less permeable and would remain effectively waterlogged year round.

In deeper peat below the acrotelm, the waterlogged conditions result in an oxygen deficient environment where the normal processes that bring about decay of plant matter are inhibited which results in the accumulation of plant remains – and hence peat This deeper pest layer is referred to as the catotelm. Within deeper peat plant matter essentially putrefies in situ resulting in plant matter slowly humifiying. As the humification proceeds, plant matter slowly decomposes with the detritus becoming finer until all vestiges of the original fibrous structure are lost (Landva and Pheeney, 1980).

The humification process results in the appearance of peat varying from a light coloured mass of leaves, stems and fresh plant matter to dark brown or black amorphous mass of low strength. A qualitative assessment of the degree humification can be assessed using for example the von Post Classification (see Hobbs, 1986) which ranks peat from H_1 (no decomposition) to H_{10} (complete decomposition), see Table 1.

Degree of Humification	Decomposition	Plant Structure	Amorphous Material Present	Material Extruded on Squeezing	Nature of Residue
H_1	None	Easily identified	None	Clear, colourless water	
H_2	Insignificant	Easily identified	None	Yellowish water	
H_3	Very Slight	Still identifiable	Slight	Brown, muddy water; no peat	Not pasty
H_4	Slight	Not easily identified	Some	Dark brown, muddy water; no peat	Somewhat pasty
H_5	Moderate	Recognisable, but vague	Considerable	Muddy water and some peat	Strongly pasty
H_6	Moderately strong	Indistinct (more distinct after squeezing)	Considerable	About one third of peat squeezed out; water dark brown	Fibres and roots more resistant to decay
H_7	Strong	Faintly recognisable	High	About one half of peat squeezed out; any water very dark brown	
H_8	Very Strong	Very indistinct	High	About two thirds of peat squeezed out; also some pasty water	
H_9	Nearly Complete	Almost unrecognisable	Very High	Nearly all peat squeezed out as fairly uniform paste	
H_{10}	Complete	Not discernible	Complete	All peat passes between fingers; no free water visible	

Table 1 Degrees of Humification based on von Post Classification (Hobbs, 1986)

The degree of humification provides an indication of the engineering characteristics of peat; with a low degree of humification there is a relatively high tensile strength and higher permeability compared to higher degrees of humification where peat tends to exhibit lower shear strength and lower permeability. Complete decomposition (H_{10}) is considered rare, as there is invariably some fibrous material present (Landva and Pheeney, 1980). Profile of humification with depth for a lowland bog is shown in Figure 2(a).

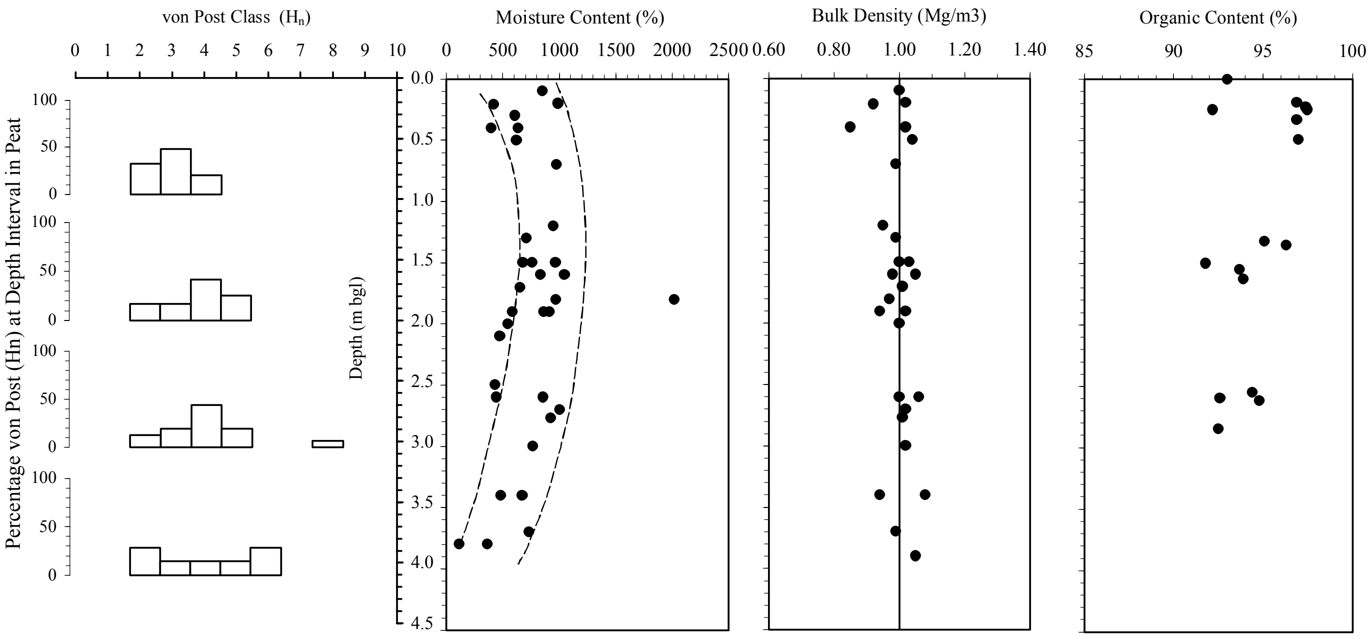

Figure 2 Typical Index Properties for Blanket Bog

Moisture content of peat can be more than 90%, yet given the small amount of solid plant matter that is present the peat possesses relatively significant shear strength. The water present within peat is considered to be held in 3 states (MacFarlane and Radforth, 1964), namely (a) free water in large cavities in the peat, (b)

capillary water in narrow cavities within plant matter, or (c) water bound (adsorbed) physically/chemically. Most water is contained within states (a) and (b), with water under state (a) removed by drainage, and water under state (b) removed by consolidation. Profile of moisture content with depth is shown in Figure 2(b) for lowland blanket bog. Typically moisture content decreases with humification, and humification generally increases with depth.

Bulk density of peat is variable but as a whole is typically similar or less than water. The low bulk density is attributed to the presence of entrapped gases in the peat (Hobbs, 1986). Typical plot of bulk density with depth for lowland blanket bog is shown in Figure 2(c).

Organic content of peat can be used as measure of the purity of peat, for example a peat that is completely free of extraneous mineral matter may have an organic content in excess of 98%. Mineral matter can find its way into peat by several ways, for example bogs formed in basins will be subject to runoff which will carry mineral soil particles, similarly natural drainage pipes, streams or up-welling waters will also carry in mineral soil particles (Lefebvre et al, 1984). Atmospheric dust, volcanic dust (Clymo, 1983) or grazing and burning of a bog over a period of time (Pearsall, 1950) will all contribute to mineral matter content of peat. An example of organic content of a lowland bog is shown in Figure 2(d).

2.3 Shear Strength of Peat

A primary controlling factor in peat failure is the shear strength of peat. An understanding of the shear strength variation through a peat mass will provide an indication of the likely stability of the peat. Shear strength of peat will vary with several factors, such as degree of humification, water content and depth. Typically peat strength can vary from less than 4kPa in more humified peat to in excess of 20kPa in fibrous peat.

Strength testing of peat is considered difficult for several reasons, namely (a) retrieving samples for laboratory testing can result in undue sample disturbance unless sampling is carried out with great care, (b) in situ testing results using vanes or cone penetration testing can be difficult to interpret due to the presence of fibres, and (c) applicability of routine geotechnical models may not wholly apply to fibrous peat (Magnan, 1994).

Notwithstanding the above, both laboratory and in situ testing of peat are commonly used to determine strength and routine geotechnical models applied to derive strength. The preferred approach is to obtain peat strength from several methods in order to corroborate results (MacFarlane , 1969).

2.3.1 In situ Vane Testing

In situ vane testing is commonly used to obtain undrained strength of soft soils, and has been used in many cases in peat (for example Helenelund, 1980, Piggott et al, 1992, Jones et al, 1995, Farrell and Davitt, 1996, Loughrey, 1996). A vane comprises cruciform-shaped metal blades typically less than 75mm in width that are pushed into the soil by pressure applied to connecting rods. At the test depth the vane is rotated and the torque required to rotate the vane is a measure of the shear strength of the soil. An example of vane tests results for blanket bog is shown in Figure 3(a). Results generally show a scatter, with an increase in scatter in the more fibrous zones. Interpretation of vane results can be problematic, as firstly the applicability of vane testing in fibrous peat remains questionable (Landva, 1980), and secondly there is inconsistency in the use of correction factors to vane results (Larrson, 1986, Mangan, 1994).

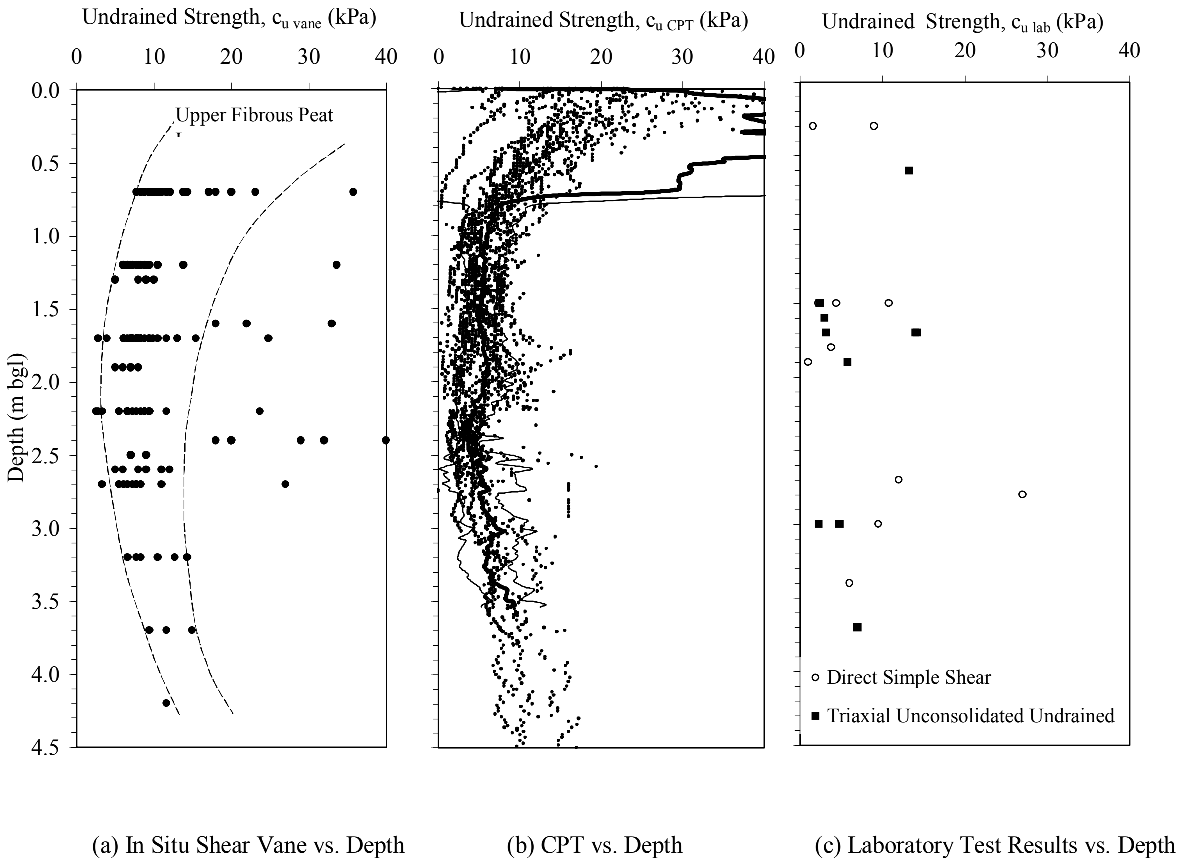

Figure 3 Undrained Shear Strength of Blanket Peat with Depth

2.3.2 Cone Penetration Testing

Cone penetration testing (CPT) involves pushing a metal cone into the ground at a constant rate of penetration. Pressure sensors at the tip and sleeve of the cone provide a near continuous record of cone tip resistance, sleeve friction and pore water pressure. CPT is commonly used for providing a detail profile of ground conditions. The pressure sensor readings are converted to undrained strength using established relationships. An example of peat CPT undrained shear strength with depth for a lowland blanket bog is shown in Figure 3(b). The detail obtained from the CPT clearly defines for example the sharp difference in strength between the upper fibrous layer and more humified layer below. Interpretation of results can provide a good correlation with vane undrained shear strength (Rodgers, 1992, Faulkner, 1998), though the applicability of CPT in more fibrous peat is questionable (Landva et al, 1986).

2.3.4 Laboratory Testing

There are numerous laboratory testing techniques that have been applied to determine the shear strength of peat, such as triaxial, simple shear, direct simple shear and ring shear testing. There are limitations and advantages to most techniques, see Landva et al (1986). The main limitations with laboratory testing would be for example the effects of sampling disturbance and the relatively high cost required to provide a comparable number and coverage of results that would be possible with in situ testing. An example of peat laboratory undrained shear strength with depth for a lowland blanket bog is shown in Figure 3(c).

The approach of using several of the above strength testing techniques to establish the strength profile in peat is considered possibly the best approach. An example of combining several strength testing techniques to determine peat strength is shown in Figure 4. Laboratory results can tend to show lower strength compared to in situ tests due to disturbance of samples during retrieval.

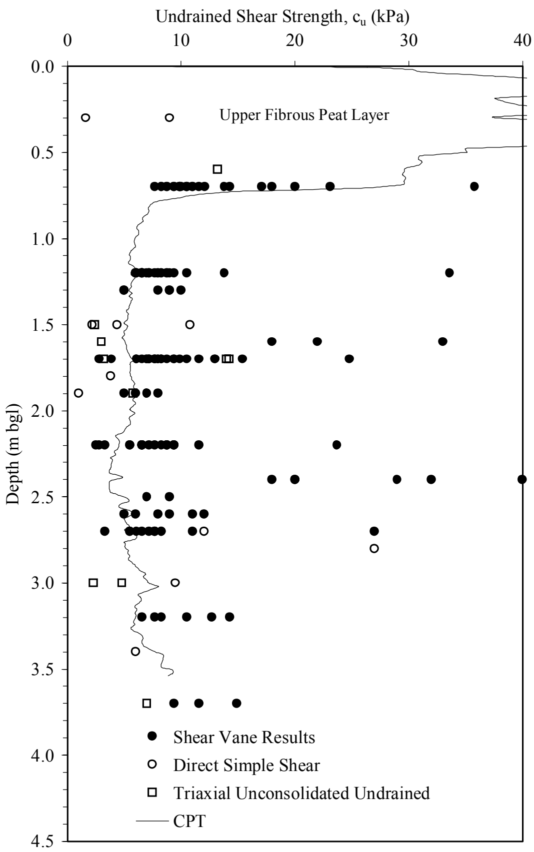

Figure 4 Determination of Undrained Strength Profile in Blanket Bog

2.4 Comparison of Peat Strengths from Different Bogs

As mentioned above peat strength will vary depending on many factors, and it is not possible to assume that all bogs will have a similar strength profile. For example where a bog is drained, there will be an increase in strength as a result of reduction in moisture content and possibly consolidation settlement of the bog. Figure 5 shows strength with depth profiles for an Irish west coast blanket bog and a Scottish east coast blanket bog. The Scottish bog is dissected by numerous deep drainage channels, which is the likely principal reason behind the increasing strength with depth profile, whereas the Irish bog has no deep drainage.

The strength profile within a bog will have a significant influence on the likely failure mode should a peat failure occur.

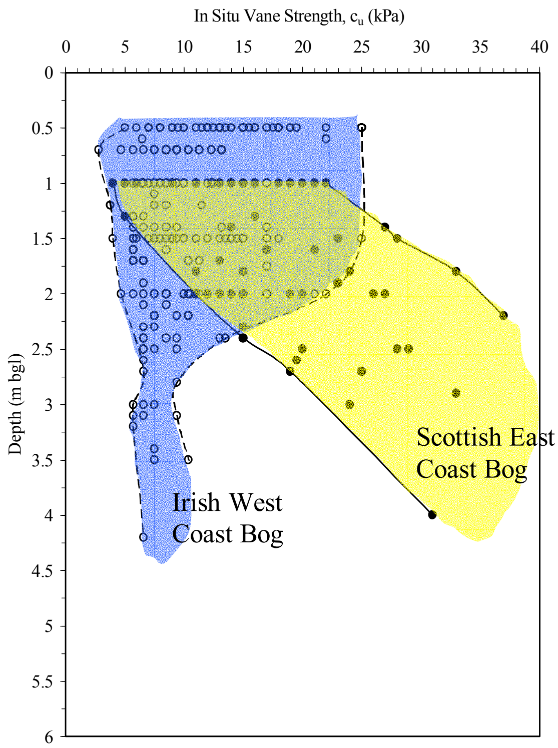

Figure 5 Comparison of Peat Strength for Different Blanket Bogs

3 TYPES OF PEAT FAILURE

Large-scale peat failures are known to occur elsewhere in the world, for example Canada (Hungr and Evans, 1985), England (Carling, 1986), Scotland (Acreman, 1991). Countries like Russia and Canada have extensive peatland areas, and it is considered very likely that peat failures occur in these places but due to remoteness and sparse populations such events go unreported. Notwithstanding the above, there appears to be more reported peat failures from Ireland than other countries. Failures have been reported from both blanket and raised bogs.

Classification of mass movement defines two dominant types of failure in peat (Hutchinson, 1988), namely:

(1) Bog flows, or more commonly referred to as bog bursts. This is a type of debris flow which involves large quantities of water and peat debris which flow down-slope usually following existing surface water channels. Large-scale bog bursts are usually associated with raised bogs where there is an upper fibrous layer over a lower body of weak amorphous peat. It would appear that peat within the bog is possibly in a near-fluid state prior to failure, possibly due to build-up of hydrostatic pressure within the bog.

    In many bog flows there is likely an initial shear failure on a discrete sliding surface prior to peat rapidly breaking-down into slurry. However the dominant movement would be by flow. The morphology of a typical bog flow scar would be a wide crater depression with a bottleneck exit. An example of a bog flow is the Boleynagee failure (Delap et al, 1932).

(2) Bog slides. Bog slides comprise a mass of intact peat that moves bodily downslope, usually over a comparatively short distance. Slides occur on a discrete shear plane usually located at depth and generally close to or at the base of the peat. The peat above the shear plane moves as an intact mass, which usually breaks into smaller pieces. Records indicate that slides usually affect blanket bogs.

Accounts of historical peat failures suggest that many large-scale peat failures originated as slides. As the sliding mass moves downslope it becomes disaggregated breaking into successively smaller pieces. Furthermore, the weaker deeper peat within the basal shearing zone becomes highly disturbed and is reduced

to slurry. Generally the further the peat mass travels the greater the disaggregation of the sliding peat mass. Eventually the moving peat behaves as a thick viscous fluid containing peat slurry within which there are pieces of intact peat. A recent example of this is the Derrybrien failure in 2003 (AGEC, 2004)

A schematic cross-section through a typical peat failure is shown in Figure 6. This shows the main features of a failure. The actual length of a failure from the head to the downslope extent of the deposited debris can vary from several tens of metres to many kilometres, this is discussed below. Photographs showing the various elements of a peat failure are shown in Plates 1 to 5.

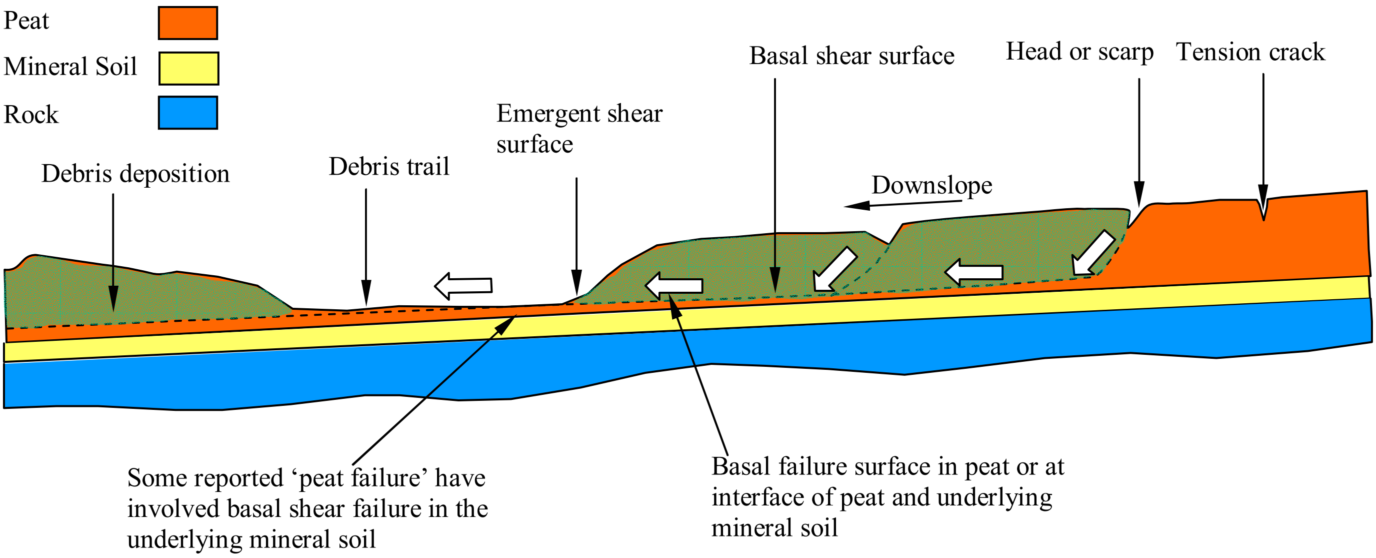

Figure 6 Schematic Cross-section through Typical Peat Failure

In this paper a peat failure is defined as failure within or at the basal interface of peat. There are many recorded ‘peat failures’ where failure has not occurred in the peat but within the soil beneath the peat, this includes for example most of the failures that occurred at Pollatomish in 2003 and the 7 failures in Antrim in 1982 (Tomlinson and Gardiner, 1982).

Photographs showing peat failure scars are given in Plates 6 to 9. Some of the older scars, such as the Glencastle Hill Failure of 1867 (Plate 6) can be difficult to identify with the main indicator of a previous failure being a sharp 1m to 2m step in the slope profile marking the head of the failure. The recent failure on Mount Lenister (Plate 9) occurred on a peat covered slope, however closer examination of the scar showed only a thin peat cover with the basal failure surface located in the underlying mineral soil.

4 HISTORICAL REVIEW

4.1 General

Some of the earliest possible peat failures recorded in Ireland have been dated to the Early Bronze Age at about 4200 BP (Murray, 1997). There are reports in historical literature of peat failures dating back as far as the 1400’s, see Colhoun et al (1965), Feehan & O’Donovan (1996). The early reports of failures were mostly subjective descriptions of the event and provide generally little useful scientific fact. From about 1800s onwards there was an increase in reported failures with an accompanying improvement in the factual and scientific reporting.

The aim of this review is to assess the hazard and risk that peat failures present in terms of frequency of occurrence, failure volumes, return periods and run-out distances. The review is based on over 70 reported

events. There are considered to many more unreported events, and indeed many of the reports refer to previous failures at the site of a failure.

4.2 Occurrence and Scale of Peat Failures

Figure 8 shows the number of peat failures from 1600 to the present. Historical records show 50 to70 failures in last 400 years, which is an underestimate of the actual number. There is a notable increase in reported failures from about 1800. This may in part be due to an increased awareness of the problem as development possibly encroached further into peatland. An increase in high intensity rainfall events, known to be a primary trigger of landslides, may also be associated with the greater number of events particularly towards the latter part of the 1900s. The high incidence of failures in 2003 includes the 11 peat failures at Pollatomish; alternatively this could be considered as one event.

Over the period 1600 to the present the estimated number of fatalities is 36 (Figure 7), which equates to a probability of 0.1 fatalities per year. The number of fatalities has been estimated, as it is unclear from early records as to the exact number of deaths.

The risk of a fatality associated with peat failure in Ireland, taking into account the exposure of the population likely to be at risk, is of the order of a probability of 10^{-7} fatalities per year. In developed countries where there are landslide problems the acceptable risk threshold is typically 10^{-3} to 10^{-4} fatalities per year. At lower risk values intervention would be required to mitigate the landslide risk.

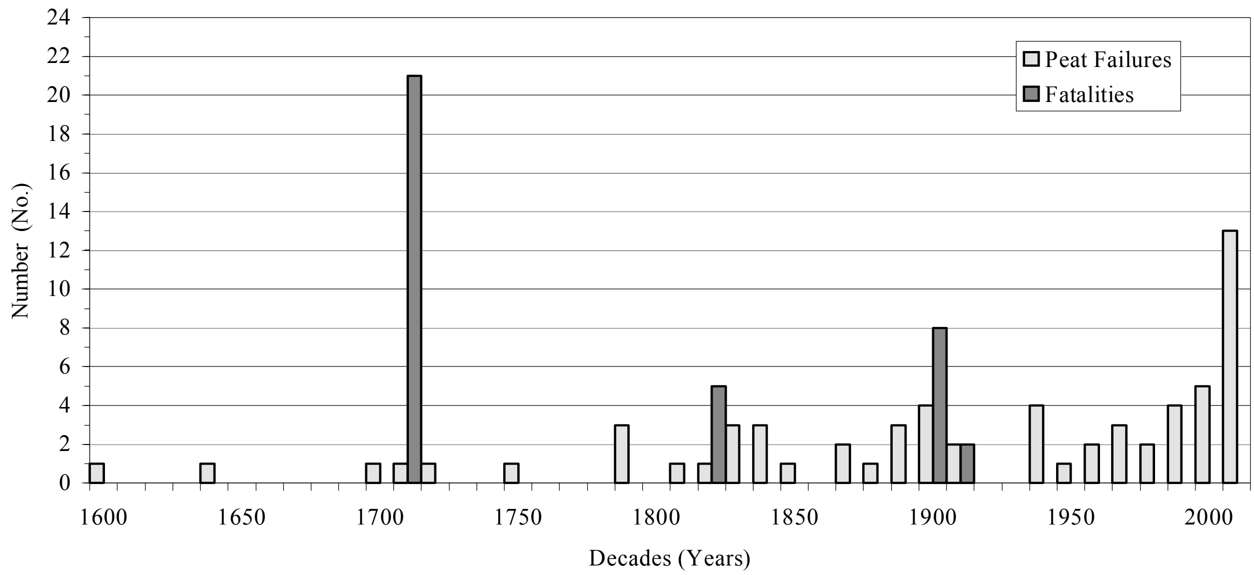

Figure 7 Histogram Showing Number of Peat Failures from 1600 to Present

Figure 8 shows the scale of peat failures measured in failure volume from 1600 to the present. The failure volumes are based on accounts given in the relevant reports, of which some at best are indicative. In some cases the credibility of accounts has been considered dubious and the failure volume not included. As can be seen there are 3 notably large failures which occurred in 1708, 1821 and 1896. The latter, and largest failure occurred at Knockmageeha, northeast of Killarney (Sollas, 1897), where a bog flow inundated a house with the death of 8 people. Fatalities are generally associated with larger failures.

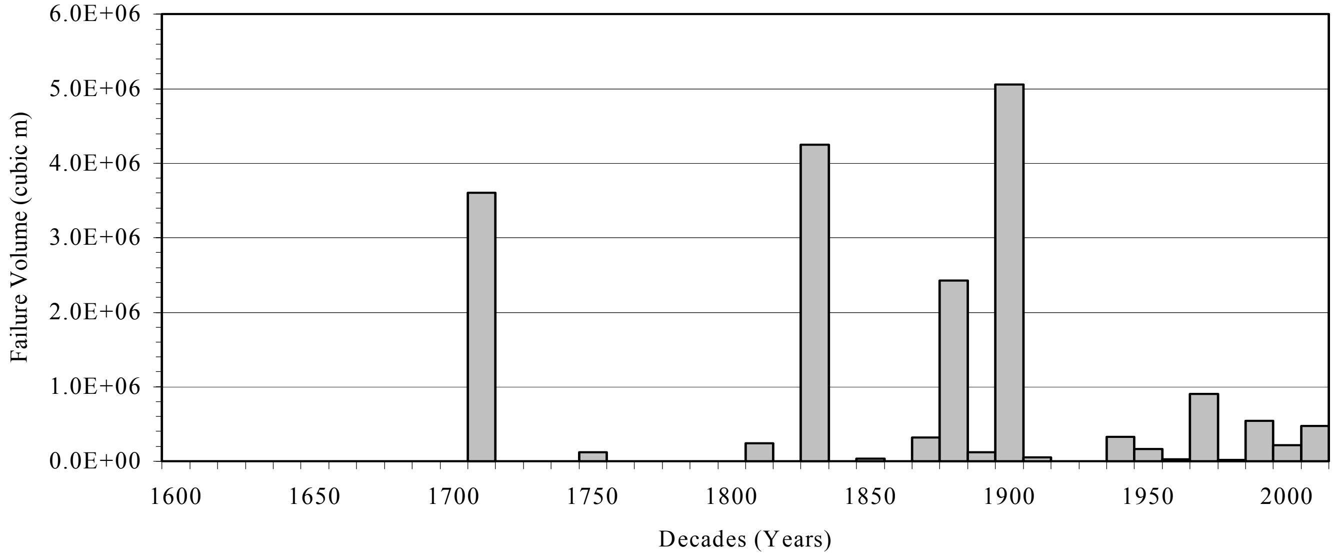

Figure 8 Histogram Showing Volume of Peat Failures from 1600 to Present

4.3 Mobility of Peat Failures

The mobility of peat failures is well documented with recoded instances of peat debris travelling many kilometres from the failure source. For example peat debris from the 1896 failure at Knockmageeha was recorded in excess of 15km from the failure source. Following initial failure, peat debris tends to rapidly break-down into slurry, which behaves as a viscous fluid. In many cases peat debris becomes confined and flows within a drainage line. Once peat debris has entered a drainage line it mixes with any water that may be present and becomes diluted which further increases its mobility.

Run-out distance versus failure volume for 44 reported peat failures is shown in Figure 9. Run-out distance is defined as the horizontal distance from the downslope edge of the failure scar to the downslope limit of failure debris. As peat debris is notably mobile and can be relatively easily transported in water it is difficult in many peat failures to determine exactly where the downslope limit of peat debris is.

There is a general trend showing that run-out distance increases with failure volume, though there is a large scatter of results at larger failure volumes. The scatter may be attributable to many factors, such as degree of topographic confinement, presence of entrapped water in failure mass, wash-out of debris along river courses. Further scrutiny of previous failure records would identify the likely extraneous mobility factors and possibly improve the relationship. Recent work with 'rapid landslides', which excludes peat failures, shows a relationship between run-out distance and failure volume (Hunter and Fell, 2003).

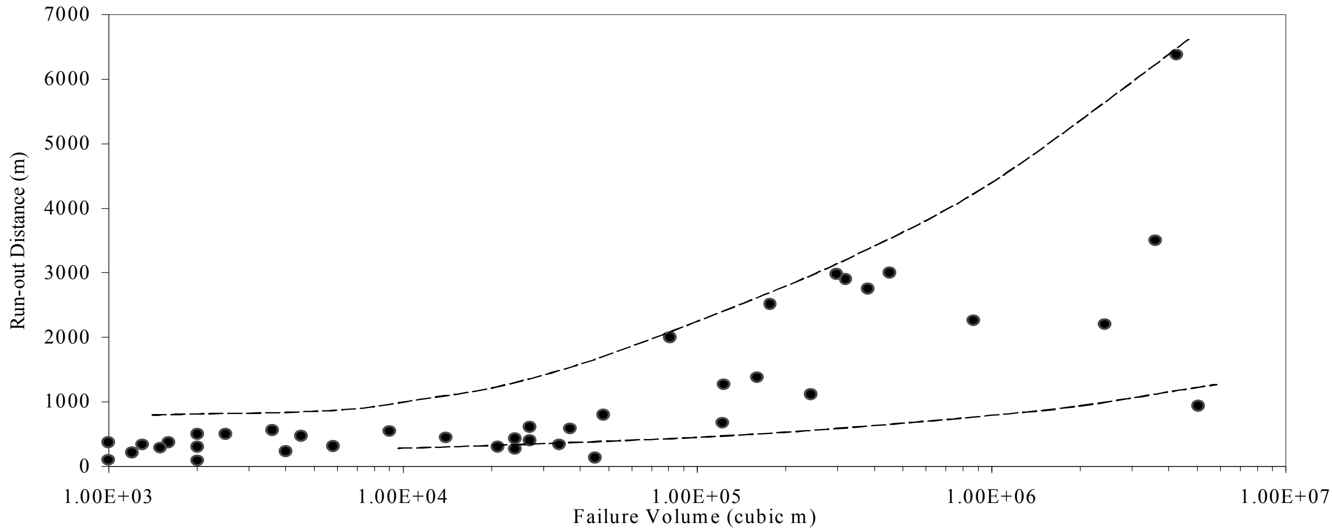

Figure 9 Failure Volume versus Run-out Distance

4.4 Return Period for Peat Failures

The return period for peat failures can be estimated from a cumulative frequency-volume curve (see Hungr et al., 1999 and Tse et al., 1999) as shown in Figure 10. This is based on 44 reported failures where failure volumes could be determined. As there are considered to be many more unreported peat failures the return period given is likely to underestimate the return period, particularly for smaller failures which are more likely to go unreported. For failures of about 1000 m^3, the return period is about 1 in 7.5 years, for larger failures the return period is greater, for example failures with volumes of 1 million m^3 are likely to have a return period of 1 in 60 years.

Prediction of return periods is based on past records, and as such it is assumed that factors that caused failures in the past will be present at the same intensity and frequency in the future. This may not be the case.

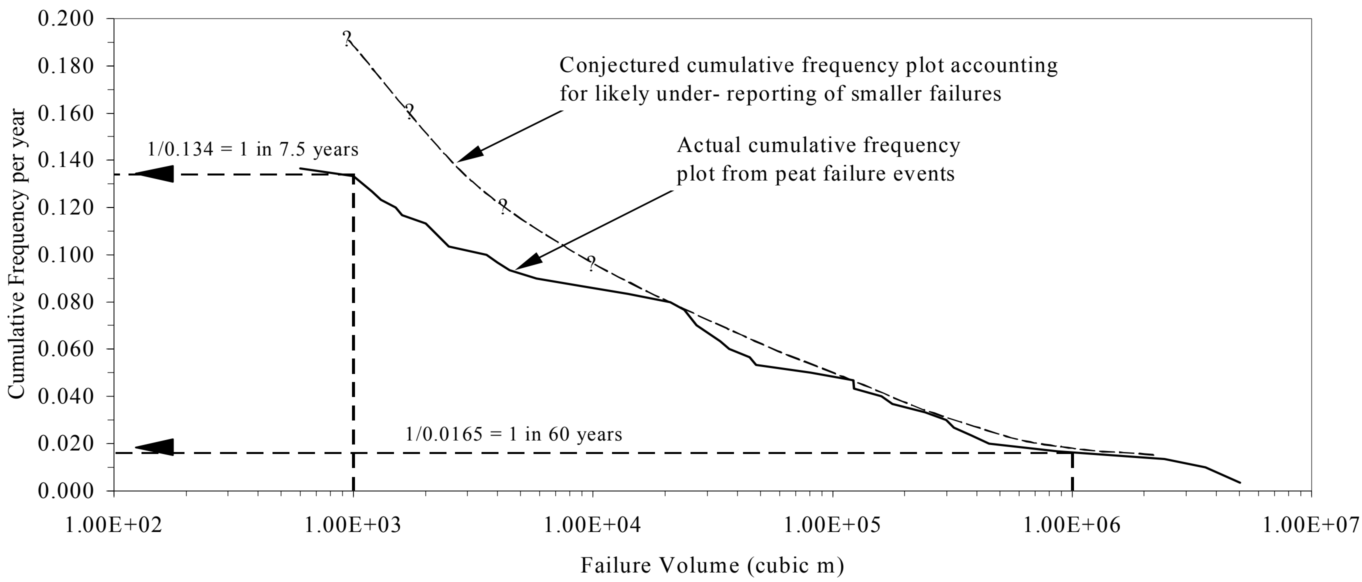

Figure 10 Cumulative Frequency versus Failure Volume based on Reported Failures

5 LIKELY CAUSAL FACTORS

Failure occurs due to a combination of contributory factors. In most cases the factor that initiates failure is given pre-eminence such as rainfall, loading, excavation. However in many cases there may be significant existing factors at a site prior to failure that over perhaps a considerable time predisposes a site to failure. For a peat site these predisposing factors may include the slow decomposition and weakening of peat, the increase in peat thickness, development of weaker layers due to creep/seasonal movement.

The main contributory causal factors based on reported Irish peat failures are given below and highlighted where appropriate with examples.

(1) High Intensity Rainfall. This is the most common reported triggering mechanism for peat failures with many reported failures occurring during or after a high intensity rainfall event. The most recent reported being at Pollatomish, County Mayo and on the Shetland Islands on the same night in September 2003 (Tobin, 2004 and AGEC, 2003).

It is commonly reported that there is a prolonged spell of relatively dry weather prior to the triggering high intensity rainfall event. This dry weather may have the effect of partly drying out particularly thinner peat resulting in cracking of the peat surface. The drying of peat would reduce somewhat the unit weight

of peat. This, in combination with cracking that would allow the relatively rapid ingress of water into the peat mass would reduce the effective strength of the peat.

(2) Slope Angle. A review of reported failure data against slope angle (Figure 11) shows a cluster of failures from 4 to 8 degrees. With a few failures at 2 degrees. There are a number of failures at high slope angles, but based on the author's inspection of such failure sites peat cover is generally thin and failure tends to involve underlying mineral soils.

The results suggest that there is a possible critical range of slope angles at which peat failures may be more common, that is 4 to 8 degrees. This critical range may correspond to the slope angles which allow a significant thickness of peat to develop, which over time becomes potentially unstable. At steeper inclinations peat would not develop to a great thickness; and at lower inclinations whilst peat thickness may be greater the destabilising downslope forces not sufficient enough to initiate failure.

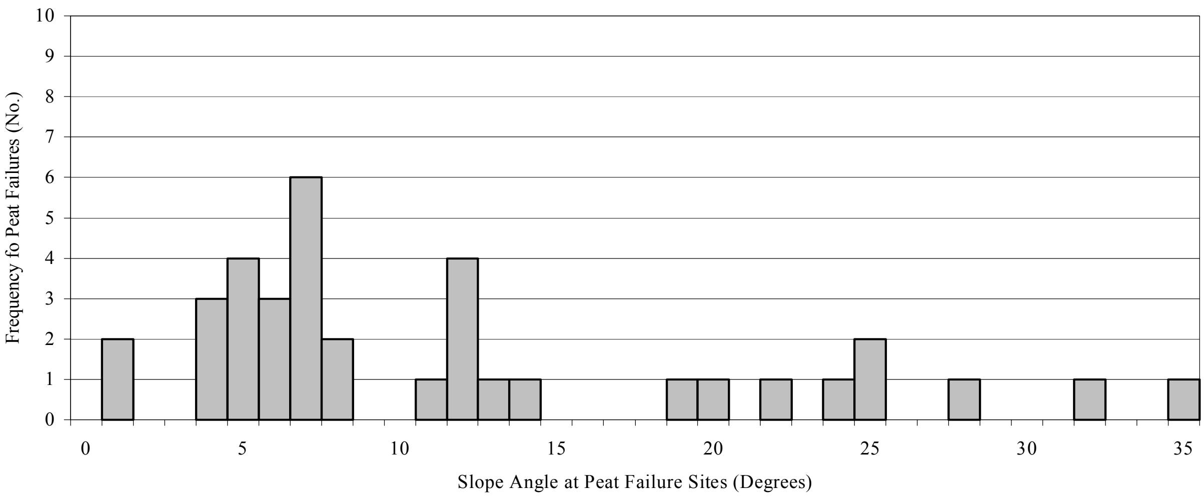

Figure 11 Distribution of Slope Angle with Peat Failures

(3) Peat Thickness. Within thicker peat there is the likelihood that the degree of humification at depth is greater. This would result in the absence of vegetative fibres and reduced shear strength at depth in the peat. Where a significant peat thickness can develop on a slope provided there is continued decomposition within the peat then over time the peat would become potentially unstable. Hence the critical combination between slope angle and significant peat thickness.

(4) Loading of Peat. Loading of peat has been reported in several cases as being the triggering factor. For example it has been reported that the recent failure at Derrybrien was as a result of loading of peat (AGEC, 2004). Possible sequence of events leading to failure as a result of loading is given in Figure 12.

Failure due to loading appears to occur as an undrained failure resulting in initially bearing type failure in peat below the loaded ground. The loss of peat strength as a result of bearing failure results in load being transferred to adjacent peat downslope. Where this load cannot be resisted by peat downslope a progressive failure of peat downslope occurs resulting in a larger-scale failure. A similar such incident was reported from Prince Rupert Island, Canada (Hungr and Evans, 1985).

The natural growth of peat also contributes to an increase in loading, which over time could also lead to destabilising of the peat mass.

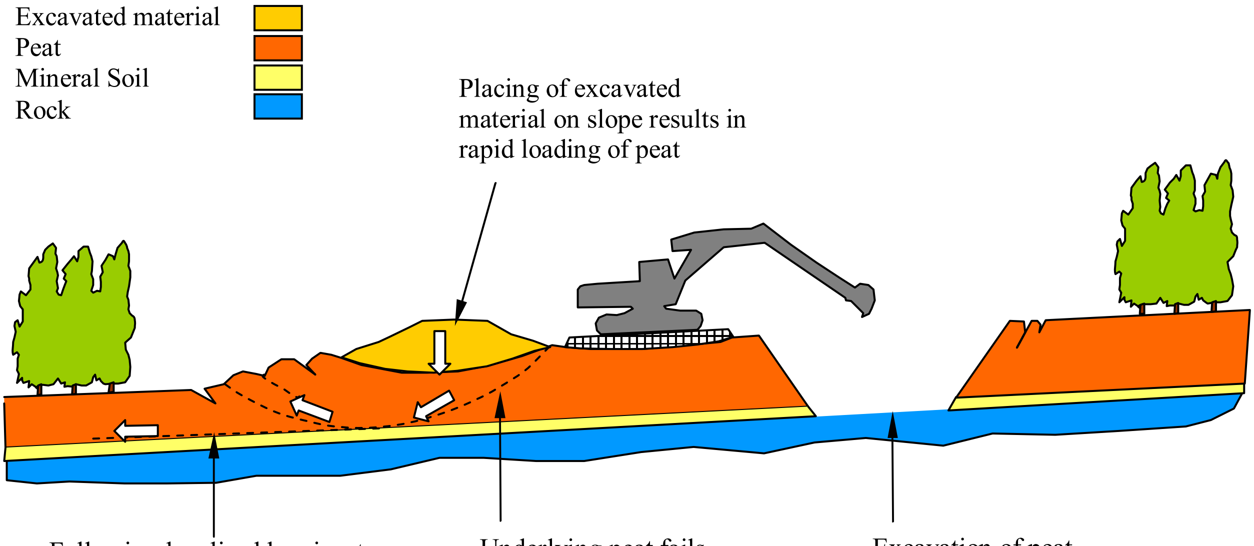

Figure 12 Possible Failure Mechanism Associated with Loading of Peat

(5) Unloading of Peat. There are several reported cases where unloading of peat has caused failure. Unloading can be as a result of excavation or natural drying-out of peat during prolonged dry spells. Typically peat cuttings or construction of roadways, for example the Early Bronze Age roadway has the effect of removing downslope lateral support to peat upslope. This can result in initially localised failure of the peat into the excavation, which under certain conditions can lead to retrogressive failure.

(6) Change in Internal Water Regime. A change in internal water regime can result in a reduction in normal stresses working in the peat leading to a reduction in effective stress. Examples which have led to reported failures include inundation/blockage of natural pipes within peat, change in vegetation, prolonged period of wet/dry weather, inappropriate or poorly maintained drainage.

A detailed review of hydrological factors affecting peat stability is given in Warburton et al (2004).

(7) Slope Morphology. In a number of cases a convex break in slope has been identified as a location where peat failures may be initiated. The possible mechanism given for this type of failure is that peat upslope of the convex break is notably thicker, and weaker, than and not as well-drained as peat below the convex break. Removal of support or rupture of the peat at the break point can result in retrogressive failure of peat upslope. The failure subsequently gains impetus as it passes onto the steeper slope below.

Shallow topographic depressions have also been cited as morphological features where peat failures may be initiated (AGEC, 2004). In this instance the possible presence within the depression of a large body of peat with a greater depth and likely reduced shear strength would increase the potential for instability.

6 SUMMARY

The paper has examined the various types of peat in Ireland and its typical characteristic properties, in particular peat strength, with respect to peat stability. Peat failure is defined and classified into (1) bog flows and (2) bog slides with examples of both given.

A review of historical failures is given and an assessment made of the hazards and risks associated with peat failures. Hazard and risk assessment of peat failures in Ireland shows that:

(1) Historical records show 50 to70 failures in last 400 years, which is an underestimate of the actual number. There has been an increase in reported peat failures from about 1800 onwards. This is possibly due to an increased awareness of failures with an associated increased development in peatland areas.
(2) Failure volumes up to about 5 million cubic metres have been recorded. However most failures are generally much smaller, with in most cases smaller failures unlikely to be reported.
(3) Run-out distance is variable ranging from a few hundred metres up to many kilometres. In general larger failure volumes travel the greatest distances, with failure volumes in excess of 1 million m^3 likely travelling in excess of 4 km.
(4) Return period for failures varies with failure volume. Larger failures being a rarer occurrence than smaller failures. Based on historical records, failures of about 1000 m^3 have a return period of about 1 in 7.5 years, though this return period is likely to be notably less as most small failure are unlikely to be reported. Failures in excess of 1 million m^3 have a return period of about 1 in 60 years.
(5) Over the period 1600 to the present day the estimated number of fatalities are 36, which equates to a probability of 0.1 fatalities per year. Fatalities are generally associated with larger failures.
(6) Risk of a fatality associated with peat failure, taking into account the exposure of the population likely to be at risk, is of the order of a probability of 10^{-7} fatalities per year. In developed countries where there are landslide problems the acceptable risk threshold is typically 10^{-3} to 10^{-4} fatalities per year.

7 REFERENCES

Acreman, M. (1991). The flood of July 25th 1983 on the Hermitage Water, Roxburghshire. Scottish Geographical Magazine, 107, pp. 170-178.

An Foras Taluntais (1980). General Soil Map, scale 1:575,000. Second Edition.

Applied Ground Engineering Consultants (AGEC) (2003). North Mayo Landslides – Report on Preliminary Findings. Unpublished.

Applied Ground Engineering Consultants (AGEC) (2004). Final Report on Derrybrien Wind Farm Post-Landslide Site Appraisal.

Carling, P. A. (1986). Peat slides in Teesdale and Weardale, northern Pennines, July 1983: description and failure mechanisms. Earth Surface Processes & Landforms, 11, pp. 193-206.

Creighton, R. (2004). Landslides in Ireland. Abstract from Geohazards – Ireland at Risk Conference, Dublin Castle, 4 October 2004.

Colhoun, E. A., Common, R. and Cruickshank, M. M. (1965). Recent bog flows and debris slides in the north of Ireland. Sci. Proc. R. Dubl. Soc. A(2), pp. 163-74.

Clymo, R. S. (1983). Peat. Ecosystems of the world 4A. Mire: Swamp, Bog, Fen and Moor. Elsevier.

Delap, A. D. Farrington, A., Praeger, R. Li. and Smyth, L. B. (1932). Report on the Recent Bog Flow at Glencullin, Co. Mayo. Scient. Proc. Royal Dubl. Soc. 20 (17), pp. 181-92.

Faulkner, A, (1998). Application to Irish conditions of new field and laboratory testing techniques. MSc These, trinity College Dublin.

Farrell, E and Davitt, S. (1996). Bunratty Embankment – Overview of Performance. In Road Oxford.Embankments on Soft Ground in Ireland. Geot. Soc. Ireland/ Inst. Eng. Ireland, March 1996, pp.28-42.

Feehan, J. and O'Donovan, G. (1996). The Bogs of Ireland – An Introduction to the Natural, Cultural and Industrial Heritage of Irish Peatands.

Helenelund, K. V. (1980). Geotechnical properties and behaviour of Finnish peats. Valtion Teknillinen Tutkimuskus. VVT Symposium 8 reprint, pp. 85-107.
Hobbs, N. B. (1986). Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly Journal of Engineering Geology, London, 1986, vol. 19, pp. 7-80.
Hungr, O. & Evans, S. G. (1985). An example of a peat flow near Prince Rupert, British Columbia. Can. Geotech. J., 22, pp. 246-249.
Hungr, O, Evans, S. G. and Hazzard, J. (1999). Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. Can Geotech. Jl., 36, pp. 224-238.
Hunter, G. and Fell, R. (2003). Travel distance angle for rapid landslides in constructed and natural slopes. Can. Geotech. Jl, 40, pp. 1123-1141.
Hutchinson, J. N. (1988). General report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. Proc. 5th Int. Symp. Landslides, Switzerland, vol.1, pp. 3-35.
Jones, D. B., Maddison, J. D. and Beasley, D. H. (1995). Long-term performance of clay and peat treated by surcharge. Proc. Inst. Civil Engng. Geotech. Engng., 1995, 113, Jan., pp. 31-37.
Kilroe, J. (1907). Soil Geology of Ireland. Department of Agriculture and Technical Institute for Ireland.
Landva, A. O. (1980). Vane testing in peat. Canadian Geot. Jl., vol. 17, no. 1, pp. 1-19.
Landva, A. O. and Pheeney, P. E. (1980). Peat Fabric and Structure. Canadian Geotechnical Journal, No. 17, pp. 1-19.
Landva, A. O., Pheeney, P.E., LaRochelle, P and Briaud, J.L. (1986). Structures on peatland – geotechnical investigations. Proc. Advances in Peatlands Engineering, Ottawa, pp.31-52.
Larrson, R. (1986). Construction on soft soils. Report No. 29, Swedish geotechnical Institute, Linkoping.
Lefebvre, G, Langlois, P., Lupien, C. and Lavallee, J (1984). Laboratory testing on in situ peat as embankment foundastion. Canadian Geotechnical Journal, 21, pp. 322-337.
Loughrey, L. (1996). Soft ground Issues on the Curlew Mountian Road Project. In Road Embankments on Soft Ground in Ireland. Geot. Soc. Ireland/ Inst. Eng. Ireland, March 1996, pp. 91-105
MacFarlane, I. C. (1969). Muskeg Engineering Handbook.University of Toronto Press.
MacFarlane, I. C. and Radforth, M. W. (1964). A study of the physical behaviour of peat derivatives under compression. Proc. 10th Muskeg Conf., Technical Memorandum 85, Ottawa.
Mangan,, J. P. (1994). Construction on peat – state of the art in France. Advances in the understanding and modelling the mechanical behaviour of peat. Editors Den Hann et al., Balkema, Rotterdam, pp. 396-380.
Moore, P. D. and Bellamy, D. (1974). Peatlands. Elek, London
Murray, C. (1997). Tipperary 1997:539 DER218, Derryfadda. Database of Irish Excavation Reports. http://www.excavations.ie
Pearsall, W. H. (1950). Mountains and Moorland. Collins, London.
Piggott, P. T., Hanrahan, E. T., and Somers, N. (1992). Major canal reconstruction in peat. Proc. Inst. Civil Engng. Wat., Marit., 1992, 96, Sept., pp.141-152.
Sollas, W. J., R. L. Praeger, A. F. Dixon & A. Delap 1897. Report of the Committee appointed by the royal Dublin Society to investigate the recent bog-flow in Kerry. Sci. Proc. R. Dublin Soc.,8, pp. 475-508.
Tobin – Consulting Civil and Structural Engineers (2004). North Mayo Landslide – Report on the Landslide at Dooncarton, Glengad, Barnchuille and Pollathomais.
Tomlinson, R. W. and Gardiner, T. (1982). Seven bog slides in the Slieve-an-Orra hils, County Antrim. J. Earth Sci. R. Dubl. Soc. 5, pp. 1-9.
Tse, C. M., Chu, T., Lee, K., Wu, R., Hungr, O. & Li, F. H. (1999). A risk based approach to landslide hazard mitigation measure design. Proc. Geot. Risk Management. Geot. Div. Hong Kong Inst. of Engng., May 1999.
Warbuton, J., Holden, J. and Mills, A.J. (2004). Hydrological controls of surficial mass movements in peat. Earth-Science Reviews 67, pp 139-156.
Wilson, P. and Hegarty, C. (1993). Morphology and causes of recent peat slides on Skerry Hill, Co. Antrim, Northern Ireland. Earth Surface Processes and Landforms, vol. 18, pp.593-601.

Plate 1 Debris Trial

Comment: Most of the debris has evacuated from the debris trail which seen as a light coloured surface in the view. The peat failed at the interface of the peat and underlying mineral soil, and the light coloured surface is the exposed mineral soil.

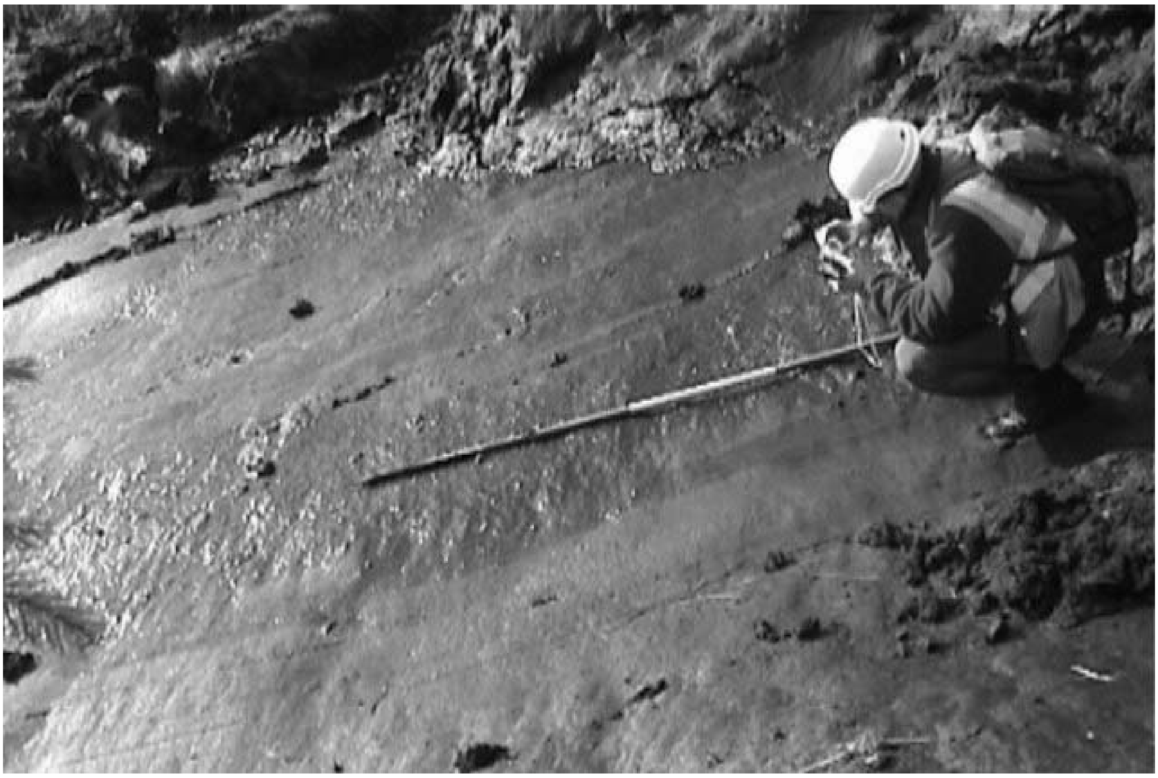

Plate 2 Basal Shear Surface

Comment: Basal shear surface comprises peat. The shear surface is located about 300mm above the base of the peat deposit. In this example some 2 to 3m of peat overlay the shear surface and failed as a translational slide moving to the left of the view.

Plate 3 Emergent Shear Surface

Comment: This is a view looking into the head of a failure where a discrete surface is visible (marked by tape measure in view) emerging from the apparently stable ground behind. In this example the failure surface is within mineral soil below the peat. The failure involved less than about 1m thickness of soil.

Plate 4 Tension Crack

Comment: This tension crack was one of many found around the periphery of a recent peat failure. Tension cracks provide an indication of the likely extent of distressed ground beyond the failure.

Plate 5 Debris Deposition

Comment: Peat debris from the failure at Derrybrien, County Galway travelled several kilometres before coming to rest. The view shows peat debris, shown as dark brown which flowed from left to right, depositing on level ground around a long-since disused dwelling. The peat debris has travelled nearly 2 km at this point.

Plate 6 Glencastle Hill Failure

Comment: Failure occurred in 1867 and involved the failure of peat over an estimated 16 ha. The view demonstrates the difficulty in identifying old failures; all the ground to the left of the black line has failed. The black line is co-incident with a 1.5m high step on the slope, which marks the head of the failure.

Plate 7 Boleynagee Lough Failure
Comment: Failure occurred in 1931 and was described as a bog burst. The view is looking from inside the failure scar upslope to the head of the failure, as marked by the black line.

Plate 8 Glenamoy Failure.
Comment: Failure year unknown but assumed in past few decades. The failure volume is estimated at 14,000m^3.Both views above are the same showing a long-distance look at the failure scar. This highlights the difficulties in observing some failure scars in the landscape. The view on the right has the scar highlighted.

Plate 9 Mount Leinster

Comment: Failure occurred in 2004. Though the slope is peat-covered, closer examination of failure (arrowed in view) showed that the basal failure surface was within mineral soil. Peat thickness was typically less than 0.5m and appeared in many cases to comprise essentially an organic mineral soil.