

Peat slope failure in Ireland

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Abstract

Recent peat slope failures in Ireland in the autumn of 2003 at Pollatomish, County Mayo and Derrybrien, County Galway have focused attention on such events. However, slope failures involving peat are not a recent phenomenon, and possible evidence of peat failures in Ireland has been identified as far back as the Early Bronze Age. This paper summarizes the issues surrounding peat slope failure in Ireland that would be of interest to an engineer or engineering geologist assessing this geohazard. The distribution of peat throughout Ireland, its formation, and its typical characteristic properties are discussed. A review of historical failures shows that there is a relationship between run-out distance and failure volume, and that the majority of the failures are clustered at slope angles between 4° and 8°. It seems that the risk of fatalities from peat slides is relatively low. The likely causal factors of peat slope failure are presented using examples including the recent failures at Pollatomish and Derrybrien, both of which have been investigated by the authors. Particular attention is paid to shear strength properties of peat and the applicability of traditional soil mechanics. Given the uncertainties that exist about peat strength, a cautious approach to slope stability assessment is advocated together with identification of potential causal factors to mitigate against this geohazard.

Peat, or bog as is it commonly referred to, is a material that consists of partly decomposed or undecomposed organic material derived from plants. Recent peat slope failures in the autumn of 2003 at Pollatomish, County Mayo (see Fig. 1) (Long & Jennings 2006; Dykes & Warburton 2007) and Derrybrien, County Galway



Fig. 1. Failures at Pollatomish, Co. Mayo; September 2003.

(AGEC 2004) have focused attention on such events and the risk of future failures. However, slope failures involving peat are not a recent phenomenon: possible failures in Ireland have been dated as far back as the Early Bronze Age at about 4200 BP (Murray 1997), and written accounts of peat failures in Ireland have been traced back to the 1400s (Feehan & O'Donovan 1996). There are over 70 reported events of peat slope failure in Ireland, and there are probably a significant number of unreported events. The Geological Survey of Ireland Landslides Working Group has recently prepared a nationwide database of landslide events, which includes peat failures (Creighton *et al.* 2006). An indication of the distribution of reported peat slope failures is shown in Figure 2.

The objective of this paper is to summarize the issues surrounding peat slope failure in Ireland that would be of interest to an engineer or engineering geologist assessing this geohazard. A review of previous failures is undertaken and the range of likely causal factors discussed. Particular attention is paid to the shear

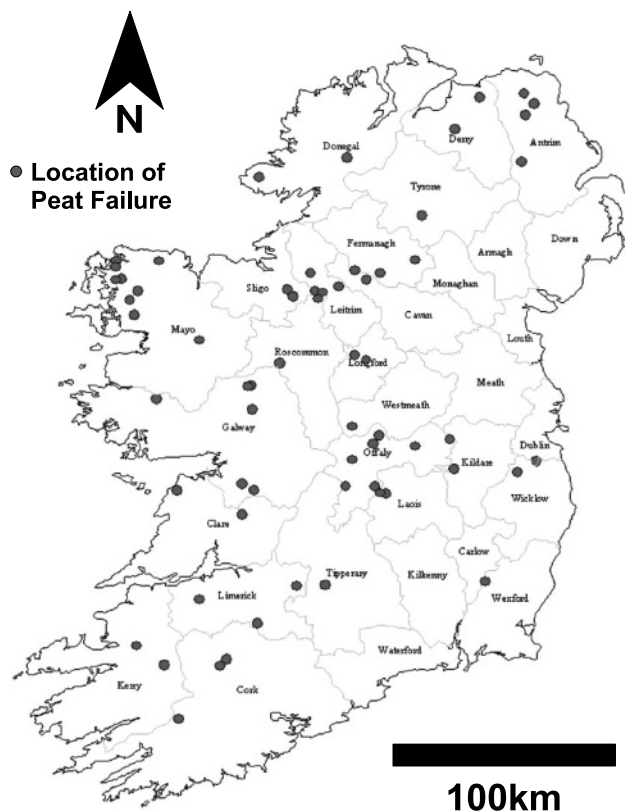


Fig. 2. Location of peat failures in Ireland (Creighton *et al.* 2006).

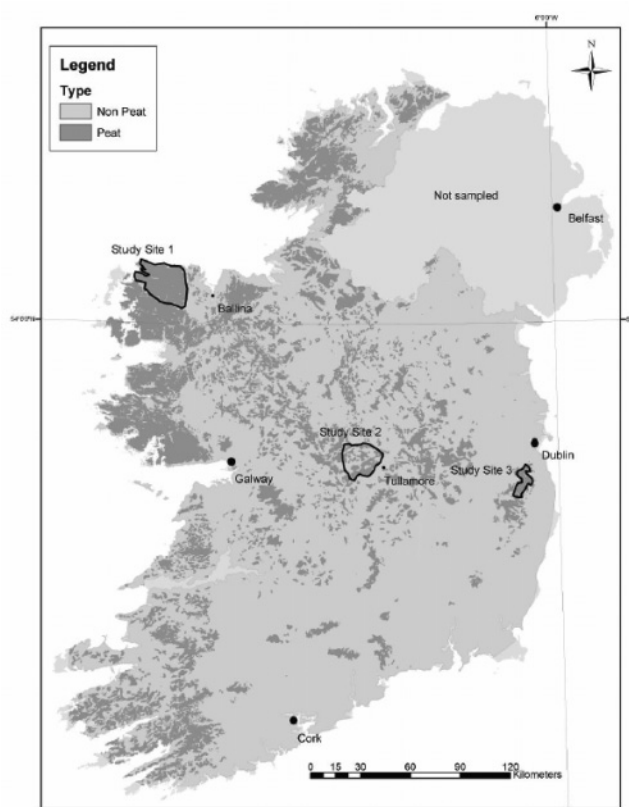


Fig. 3. Peatland map of Ireland (from Connolly *et al.* 2007).

strength properties of peat and the assessment of slope stability.

Character of peatland in Ireland

Distribution and types of peat

Three types of peatland occur in Ireland: upland blanket bog, lowland (or oceanic) bog and raised bog. Peatland is generally found in areas of high rainfall under conditions of poor drainage. According to a 1980 study about 17% of the Republic of Ireland is covered in peatland (An Foras Taluntais 1980). More recently, Connolly *et al.* (2007) have revised this estimate using a rule-based approach and digital data (e.g. the analysis automatically removes areas with slopes greater than 25° and industrial peatlands where peat deposits have been removed) and have concluded that 13.8% of Ireland is overlain by peatland. Their map is reproduced in Figure 3 and has a stated reliability of 75%, which is higher than that for the previous peatland maps.

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, because of the wet climate (typically rainfall >1250 mm per year compared with 750–1000 mm in raised bog areas), blanket bog occurs down to sea level; this explains why low-lying bog is also referred to as

oceanic bog. Raised bogs are commonly found in the Midlands, and are so called because of their growth above the level of the horizontal water table. Details of formation of bogs have been provided in numerous publications (Moore & Bellamy 1974; Feehan & O'Donovan 1996; Tallis 1998).

Raised bogs generally tend to be 3–12 m thick, with an average of about 7 m. Blanket bogs can be up to 5 m and are typically about 3 m thick, but as the underlying surface is irregular, locally thicker deposits of bog are commonly present. Blanket bog thickness typically thins at greater elevations. Peat can form on slopes up to 20–25° (Tallis 1998) although the authors have observed small localized deposits of peat on slopes as steep as 32°.

Peat formation

Peat formation started in Ireland following the end of the Ice Age, some 10 000 years BP (An Foras Taluntais 1980). Initially, peat formed in waterlogged hollows and developed into raised bogs across the low-lying Midlands. The spread of upland blanket bog appears to have accelerated following the appearance of farming some 3000–4000 years BP. Because bogs form over previously existing ground surfaces it is not uncommon to find evidence of relict topsoil horizons, particularly under blanket bog. Other evidence of previous ground surface includes remnant plant life, notably tree stumps, and more rarely human occupation. Typically, mineral soils below peat include glacially derived soils, lacustrine deposits and weathered rock.

Properties of peat

Classification of peat

Various definitions exist throughout the world differentiating peat from other soils (Carlsten 1988) but for geotechnical purposes Landva *et al.* (1983) defined peat as a soil with an ash content <20%. As peat exists in various stages of decomposition, further classification of peat deposits can be carried out by describing the constituents of the peat and the level of decomposition (von Post & Granlund 1926; Radforth 1969). In physical terms, decomposition in peat is the breakdown of the structure of organic plant materials and transformation into amorphous material. Large fibres are broken down and the pore space decreases while the proportion of fine material increases (Blackford & Chambers 1993). The method of von Post & Granlund (1926), which is the most widely used, classifies peat using a simple hand squeeze test and examination of the material to describe the wetness, level of decay, as well as fibre and shrub constituents. The level of decomposition of the material is classified by determining a humification number (H) between one and 10, where H1 refers to a peat that has

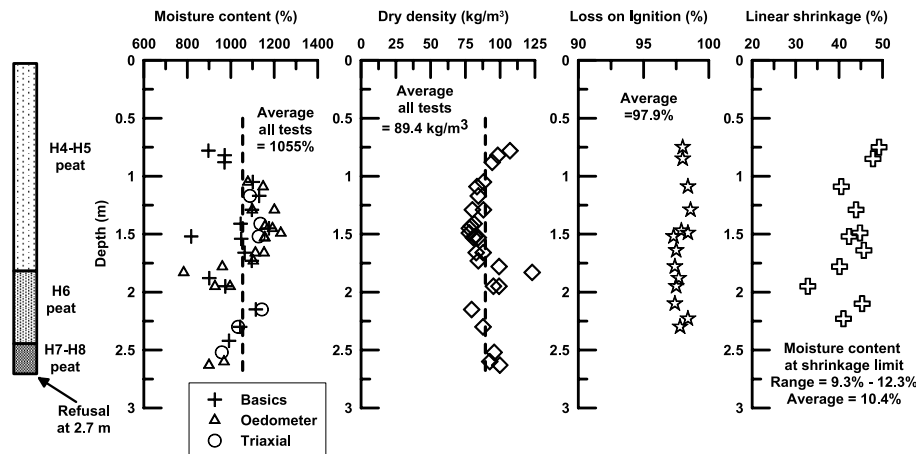


Fig. 4. Typical index properties for a lowland blanket bog study site in Co. Mayo: (a) humification; (b) moisture content; (c) dry density; (d) loss on ignition; (e) linear shrinkage.

undergone no decomposition and H10 is a peat that is completely decomposed. Although the term humification strictly means the content of humic substances in peat, it is taken to mean, in this context, the same thing as decomposition. Hobbs (1986) further extended this method to include properties such as tensile resistance, organic content, plasticity and smell. Figure 4a shows a profile of decomposition with depth for a lowland blanket bog in western Mayo using the method of von Post & Granlund (1926). The study site is underlain by about 1.8 m of H₄ to H₅ (somewhat to moderately humified) peat, over about 0.6 m of H₆ (moderately humified) peat, which in turn overlies a thin 0.2 m layer of H₇ to H₈ (fairly well- to well-humified) material. Fibres and roots are still easily identifiable. They comprise a mixture of coarse and fine elements and are orientated and spaced randomly. The material shows little evidence of plasticity. Weathered rock was encountered at 2.7 m. The level of decomposition can provide an indication of the likely engineering properties, with shear strength and permeability typically reducing with increasing decomposition (Baden & Eggelsman 1963; Helenlund 1980). Because of the subjective nature of these classifications, results can vary widely and can only be treated as an indication. Quantitative measurement of the fibre content of peat (Lévesque & Mathur 1979) and measurement of the extracted humic substances (Schnitzer 1967; Rochus & Sipos 1976) have been noted as the most reliable indicators of peat decomposition.

Fabric of peat

Before looking at the engineering properties of peat, it is important to consider the nature of the peat fabric and how it compares with mineral soils (e.g. clay, silt and sand) for which many geotechnical theories have been developed. Figure 5a shows a typical scanning electron microscope image of peat from a blanket bog site in western Ireland. The material is moderately to strongly

decomposed (H7 on the Von Post scale). The overall fabric is an assemblage of decaying plant cellular structures interconnected with frequent fibres and large leaves in a less decayed state. A closer view of the micro-fabric, in Figure 5b, shows the connectivity between the elementary structures creating the open cellular structure. Pore spacing is large, with regular pores up to 10 μm evident in these images, reflecting the high permeability of the material. Particle thickness ranges from 0.03 to 0.2 μm , which is at the lower end of the range when compared with kaolinite clay particles, which range between 0.05 and 2 μm (Mitchell 1993). Peat has significant fabric differences from mineral soil: (1) elementary particles are connected to each other, unlike the frictional contacts of mineral soils; (ii) elementary particles of the decaying plant material are most likely to be compressible; (3) plant material is continually decaying with time.

Hydrological properties

Peatland hydrology will be shown later in this paper to play a significant role in many of the peat failures that have occurred in Ireland. To understand the hydrological processes in peat, a diplotelmic system of an upper acrotelm layer and lower catotelm layer is used (Ingram 1978, 1983; Holden & Burt 2003). The active acrotelm is affected by a fluctuating water table, a high hydraulic conductivity and a variable water content. The transition to the lower catotelm occurs at the lowest level of the water table beneath which anaerobic conditions exist. Water contents are static with time and hydraulic conductivities tend to be small. Macropores (pores with diameter greater than 1 mm) and soil pipes (larger and more continuous forms of macropores) have also been shown to exist in peatlands and provide pathways for significant amounts of runoff (Holden & Burt 2003). Holden (2006) has provided a review of all aspects of peatland hydrology and the role played by macropores and soil pipes.

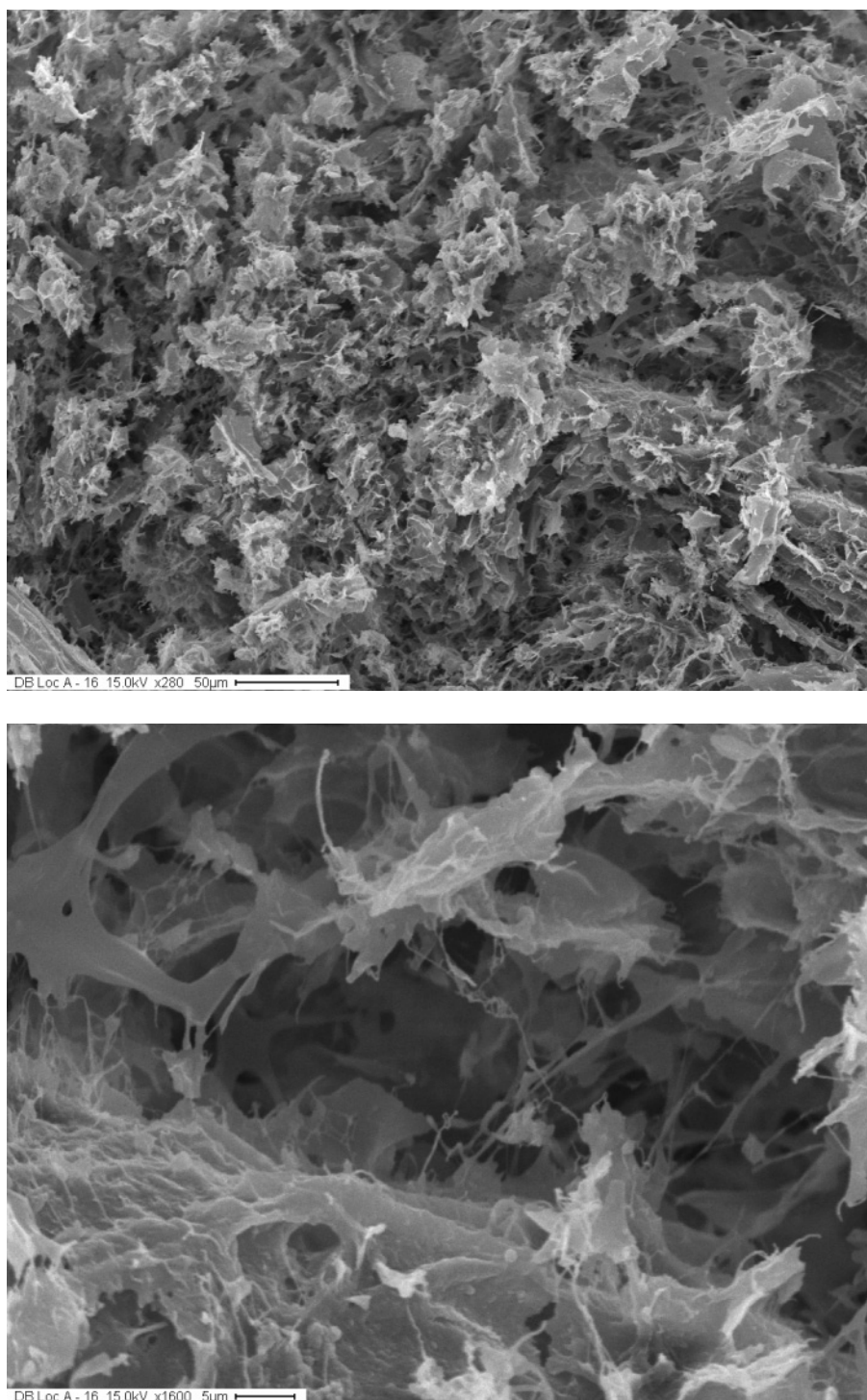


Fig. 5. (a) Scanning electron microscope image of peat microstructure; (b) close-up SEM image of microstructure and particle connections.

Geotechnical index properties

Moisture content of peat can be more than 900%, 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 three states (MacFarlane & Radforth 1964): (1) free water in large cavities in the peat; (2) capillary

water in narrow cavities within plant matter; (3) water bound (adsorbed) physically or chemically. Most water is contained within states (1) and (2), with water in state (1) removed by drainage, and water in state (2) removed by consolidation. A profile of moisture content with depth for the lowland blanket bog study site is shown in Figure 4b. Moisture contents range from 800% to 1300%, with some variation occurring at the transition

in decomposition at 1.8 m. Typically, moisture content decreases with increasing humification (Hobbs 1986), and in blanket bogs the humification generally increases with depth, but variations do occur as a result of preferential path flows and geomorphological variations in the peat mass.

The application of Atterberg limit concepts to peat is doubtful. Plastic limits are difficult to obtain for peat and are generally not reported. The liquid limit strictly describes, for fine-grained soils, the water content at which the particles lose contact and behave like a liquid. As the contacts between particles in peat are connections and peat frequently occurs intact above its liquid limit, this concept does not seem appropriate to peat. In spite of this, various researchers have reported liquid limit values for peat (Skempton & Petley 1970; Hobbs 1986). Linear shrinkage values determined from intact peat samples seem to provide an indication of changes in decomposition. Figure 4e shows linear shrinkage values from the study site that reduce from close to 50% at 0.75 m to about 40% at 2 m depth, possibly reflecting the reduction in fibre content with depth; however, there is significant scatter in the data. Moisture content at the shrinkage limit is about 10%, confirming the large potential for shrinkage in the material.

Bulk density of peat is typically similar to or less than that of water. The low bulk density is attributed to the presence of entrapped gases in the peat (Hobbs 1986). Values of bulk density tend not to vary with the peat properties and instead remain relatively constant (1.03 Mg m^{-3} in this case). Instead, dry density is often a more useful parameter to reflect variations in moisture content and degree of humification (see Fig. 4c).

Organic content (by loss on ignition at 440°C for 5 h (Arman 1971) 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% (see Fig. 4d). Mineral matter can find its way into peat in 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 upwelling waters will also carry 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.

Types of peat failure

Peat failures are known to occur throughout the world but 80% of reported events have occurred in the British Isles (Dykes & Kirk 2006). Countries such as Russia and Canada have extensive peatland areas, and it is considered very likely that many peat failures occur in these regions but because of remoteness and

sparse populations such events go largely unreported. Notwithstanding the above, there appear to be more reported peat failures from Ireland than other countries. Failures have been reported from both blanket and raised bogs.

There are a number of mass movement classifications that include a description of peat failure (Hutchinson 1988; Dykes & Warburton 2006). Hutchinson (1988) defined two types of failure in peat: bog flow (or more commonly referred to as bog burst) and peat slide. Bog flow involves large quantities of water and peat debris that flow down-slope usually following existing surface water channels. Large-scale bog flows are usually associated with raised bogs where there is an upper fibrous layer over a lower body of weak amorphous peat. It appears that the peat is in a near-fluid state prior to failure, possibly as a result of build-up of hydrostatic pressure within the peat mass (Colhoun *et al.* 1965; Alexander *et al.* 1986).

Peat slides comprise a mass of intact peat that moves bodily down-slope, usually over 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 (Mitchell 1938; Dykes & Kirk 2001).

Some early accounts of peat failures tended not to differentiate between bog burst and slide so it is not possible to determine with accuracy the actual mode of failure from them (e.g. Kinahan 1897). Several relatively recent reports described bog flows (e.g. Tomlinson 1981; Alexander *et al.* 1986) based on post-failure landforms. However, it is considered in many bog flows that there was probably an initial shear failure on a discrete sliding surface prior to the failed peat mass breaking down into slurry, following loss in mass strength caused by disturbance, and developing into a flow. For example, inspection of the scar left by the 1896 reported bog flow at Knocknageeha Bog, County Kerry (Sollas *et al.* 1897) clearly shows large detached rafts at the edge of the failure, which have moved as translational slides. As such, in the authors' opinion, many of the historical large-scale peat failures are likely to have originated as slides, with the sliding mass becoming disaggregated and breaking into successively smaller pieces as it moved downslope. To observers downslope the failed peat mass would appear as a flow of thick viscous fluid of peat slurry within which were pieces of intact peat. A recent example of this is the Derrybrien failure in 2003 (AGEC 2004), which originated as a slide but degraded into a debris flow as it moved downslope. Figure 6 shows the basal failure surface of the failure at Derrybrien, where it originated as a slide.

More recently, Dykes & Warburton (2006) have reviewed numerous peat failures and suggested a formal classification scheme that groups peat failures into six



Fig. 6. Basal shear failure surface of Derrybrien peat failure.

distinct types based on several failure and morphological characteristics.

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; these include, for example, most of the failures that occurred at Pollatomish in 2003 (Long & Jennings 2006) and the seven failures in the Slieve an Orra hills, Co. Antrim in 1982 (Tomlinson & Gardiner 1982).

Historical review

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), and reports in historical literature of peat failures date back as far as the 1400s (see Colhoun *et al.* 1965; Feehan & O'Donovan 1996). The early reports of failures were mostly subjective descriptions of the event and generally provide little useful scientific fact. From about the 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 and run-out distances. The review is based on 70 reported events. There are considered to be many more unreported events, and indeed

many of the reports refer to previous incidents at the site of a failure.

Occurrence and scale of peat failures

Figure 7 shows the number of peat failures from 1600 to the present. Historical records show up to 70 failures in last 400 years, which is probably 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 where failure occurred within the peat mass; alternatively, this could be considered as one event. Figure 8 shows the monthly distribution of failures up to 1985 for which information on the month of occurrence is reported (from Alexander *et al.* 1985). It can be seen that the majority of failures on blanket bogs occurred during the wetter autumn and winter months, whereas failures on raised bogs are more evenly distributed throughout the year.

Over the period 1600 to the present the estimated number of fatalities is 36 (see Fig. 7), which equates to a probability of 0.1 fatalities per year. The number of fatalities has been estimated, as the exact number of deaths is unclear in early records. The risk of a fatality associated with peat failure in Ireland, taking into account the exposure of the population likely to be at

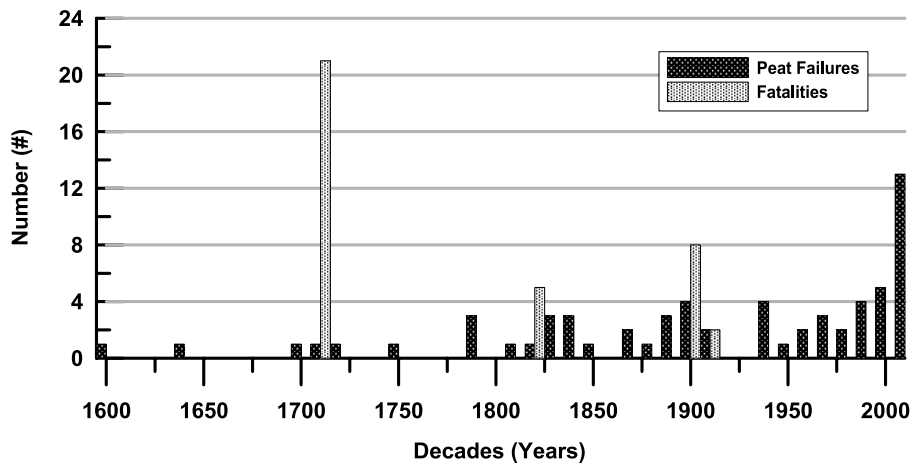


Fig. 7. Number of peat failures and fatalities in Ireland from 1600 to present.

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 (Fell & Hartford 1997; Reeves *et al.* 1999). At higher risk values intervention would be required to mitigate the landslide risk.

Figure 9 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 is not included. As can be seen, there are four notably large failures, which occurred in 1708, 1821, 1873 and 1896. The largest failure occurred at Knockmageeha, NE of Killarney (Sollas *et al.* 1897), where a bog flow inundated a house with the death of eight people. Fatalities are generally associated with larger failures.

Mobility of peat failures

The mobility of peat failures is well documented, with recorded 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 15 km 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 v. failure volume for 44 reported peat failures is shown in Figure 10. Run-out distance is defined as the horizontal distance from the down-slope edge of the failure scar to the down-slope limit of failure debris. The relationship between run-out distance and volume is based in part on information contained in historical publications, which were not subjected to the same level of scientific scrutiny as applies today. As evidence of down-slope extent of historical peat failures, and to a lesser degree failure scars, has long since been removed by nature it is not possible to verify this data. The objective is not to make definitive conclusions but to indicate likely trends. It is recognized that mobility is affected by many factors such as topography, degree of confinement (ranging from open slope to steep-sided gully), water content, slope inclination and roughness of travel path (Hunter & Fell 2003). The historical records generally do not report these factors and as such the effect of these factors is not included in the relationship. Furthermore, failure volume is based on the size of the failure scar and it is assumed that all debris evacuates the scar; this may not be the case. As peat debris is notably mobile and can be relatively easily transported in water it is difficult in many peat failures to define exactly the limit of the down-slope debris.

There is a general trend showing that run-out distance increases with failure volume, although there is a large scatter of results at larger failure volumes. Larger failure volumes seem to be associated with failures at raised bog sites, which is consistent with the fact that raised bogs

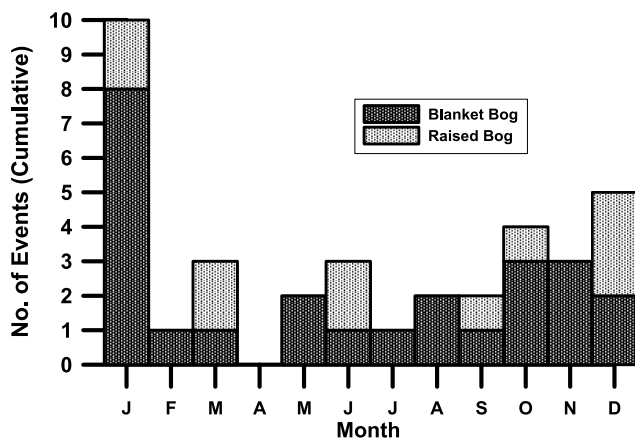


Fig. 8. Reported peat failures per month up to 1985 (Alexander *et al.* 1985).

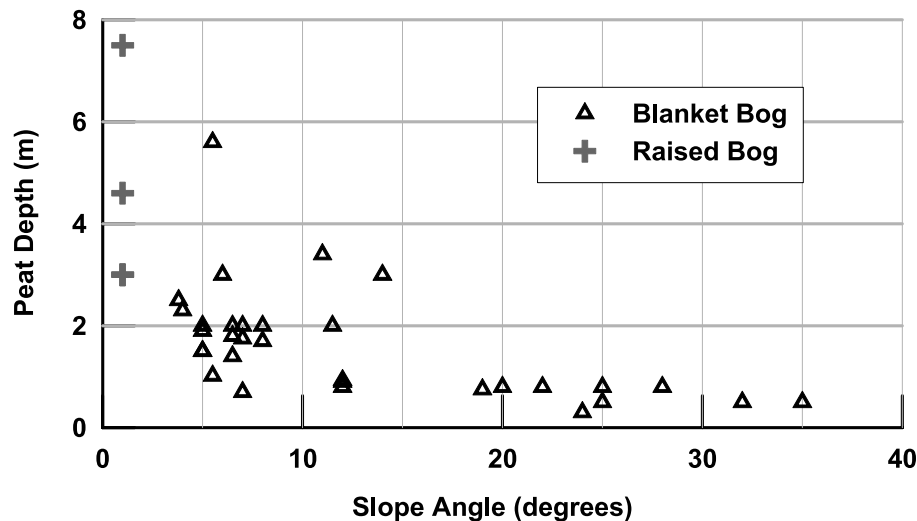


Fig. 11. Slope angle at failure site v. peat thickness.

encouraged water to flow, which eventually caused the failure.

Slope inclination is a significant factor in controlling the occurrence of peat failure. Further analysis of the peat failures reported in the historical review (see Fig. 11) shows a general trend of increasing peat thickness with reduction in slope angle. The vast majority of the failures are clustered between 4° and 8°. This may correspond to the slope angles that allow a significant amount of peat to develop that over time becomes potentially unstable. Mitchell (1938, p. 54) suggested that 'in all cases where bursts in mountain bogs have been investigated there are indications that growth had rendered the bog unstable, and that the burst acted as a safety valve to restore equilibrium'. There are a number of failures at high slope angles (>20°) but, based on the authors' inspection of such failures, peat cover is generally thin and failure tends to involve underlying mineral soils.

Slope morphology has been shown to provide possible initiation points for failures. A convex break in slope has been cited as a feature in a number of failures (Mitchell 1935; Bishop & Mitchell 1946; Tomlinson 1981). It is postulated that the peat upslope of the convex slope is notably thicker and weaker than the well-drained peat below the break. In the event of rupture at the break this leads to a retrogressive failure of peat upslope with little passive resistance provided by the lower slopes. At the other extreme, concave slopes have been noted at failure locations (Mitchell 1938; Alexander *et al.* 1986) but the failures are characteristically different. Mitchell (1938, p. 52) described a failure in Co. Wicklow, where the peat on the upper slope 'may have tended to slide slowly downhill, and as this movement was checked by the flatter slope of the spur, the peat may have welled up into a ridge'. It is postulated that tearing at the base of the ridge allowed the upper peat to move up on top of the intact peat surface below the concave break and the

failure evolved. Evidence was found of possible earlier failures further down-slope, and these may have been the causal factor rather than the concave break in slope.

A common feature of many failures is for slides to be initiated in depressions and watercourses of rivers (Delap *et al.* 1932; AGECE 2004). During the early stages of peat development, peat formed first in waterlogged depressions and in channels where water flowed. This peat formed under high nutrient conditions from rainfall and the contribution from the surrounding mineral soils causing an increased level of humification in these depressions. The degradation of peat strength with increased decomposition may make these locations more prone to failure. The susceptibility of these channels to failure would be exacerbated by the concentration of runoff waters within the peat mass at these locations.

The hydrology of blanket bogs and interference with it has been seen to be significant in a vast majority of peat failures. With the permeability of catotelm peat being moderate to low, in the range of 10^{-5} to 10^{-10} m s⁻¹ and decreasing significantly with humification (Ingram 1983), blanket bogs use a network of macropores and pipes to transport water within the peat mass (Holden 2006). The presence of natural pipes at the level of the failure surface is a common feature of slides, most recently at Pollatomish (Long & Jennings 2006; Dykes & Warburton 2007), where Murphy (2004) used ground penetrating radar (GPR) to identify pipes at the level of a failure surface. Nichol *et al.* (2007) similarly reported the presence of a natural pipe at the level of the failure surface for a peat slide that occurred in Wales. Warburton *et al.* (2004), who reviewed a number of hydrological aspects of peat mass movements, concluded that a better understanding of the basic hydrology of peat and peat slopes is still required before it can be realistically modelled.

The influence of the underlying mineral soil on the occurrence of peat failures is generally studied from the



Fig. 12. Dislocated organic matter beneath mineral soil; Pollatomish.

point of view of its permeability. Alexander *et al.* (1986) described a failure at Straduff, Co. Sligo where the impermeable clay-rich drift underlying the peat was identified as a potentially significant factor. With many failures occurring at or close to the interface between the peat and the mineral soil, the interaction between the two may be a significant factor in many failures. Warburton *et al.* (2004) observed various types of contacts at the peat–mineral soil interface ranging from a sharp contact to a complex connection. Many of the mineral failures at Pollatomish, Co. Mayo described by Long & Jennings (2006) occurred on a plane of organic material beneath the mineral soil (see Fig. 12). Humic acids in the peat would have leached the mineral soil of soluble minerals and organic material by a process known as podzolization, creating well-defined horizons of depletion and accumulation (Tan 1994). The leached humus and minerals would have translocated to create the layer of organic material and poorly developed iron pan observed at the failure scars. The excess pore water pressure from the extreme rainfall event would have easily dissipated through and eroded this weak organic layer, mobilizing the failures. It is also postulated that the impermeability of the poorly developed iron pan made these locations susceptible to failure (Dykes & Warburton 2007). The formation of this podzol profile would have been facilitated by the alternate wetting and drying cycles (O'Dubhain 1978) encountered on the thinly covered steep slopes of Pollatomish. Callier & Visser (1988) studied the effect of humic substances in peat on clay–sand mixtures and found varying types of aggregation depending on the type of clay particle. Aggregation may have positive benefits for soil, strengthening bonds and increasing shear strength. Söderblom (1974) conversely reported varying amounts of dispersion for a number of humic substances, which reduces the effective contact between soil particles and thus reduces soil strength. Pusch (1973) pointed out that the composition of humic substances suggests various

types of interaction with clay particles, and both dispersion and aggregation take place depending on the chemical composition of the environment. This is an area that deserves consideration in failures that occur at or below the peat–mineral interface.

Shear strength of peat

A primary controlling factor in peat failures is the shear strength of peat. An understanding of the strength variation through a peat mass will provide an indication of the likely stability of the peat.

Classical soil mechanics and peat

Although peat is a decaying mass of soft organic material, soil mechanics strength models that were developed for mineral soils are routinely applied to peat. Figure 5a and b shows that the fabric of peat is significantly different from that of mineral soils, which makes the direct application of these classical soil mechanics models doubtful.

Drained strength. The drained strength of a soil refers to the shear strength of a soil when the pore pressures generated by shearing dissipate rapidly or are not present at all. It is usually determined using the Mohr–Coulomb failure criterion by the equation

$$\tau = c' + \sigma' \tan \phi' \quad (1)$$

where τ is the shear strength, c' is the apparent cohesion and ϕ' is the effective angle of shearing resistance. The effective stress (σ') is the portion of stress in the soil mass carried by the solid skeleton and is determined from the effective stress principle (von Terzaghi 1923) using the equation

$$\sigma' = \sigma - u \quad (2)$$

where σ is the total stress in the soil mass and u is the pore water pressure.

Bishop & Eldin (1950) have shown that for equation (2) to be valid it is required that the particles are incompressible, which is unlikely to be the case in peat. Furthermore, the contacts between particles in peat are connections rather than frictional contacts, which makes it unlikely that an effective angle of shearing resistance (ϕ') exists in peat. The combination of these two factors makes the applicability of equation (1) in its present form to peat soils questionable.

In any case, effective friction angles (ϕ') for peat are regularly reported in the literature with values ranging from less than 18° to as high as 58° (Hanrahan *et al.* 1967; Den Haan *et al.* 1995; Farrell & Hebib 1998), with apparent cohesion values (c') having a equally scattered range. Landva (1980a) found from ring shear tests that

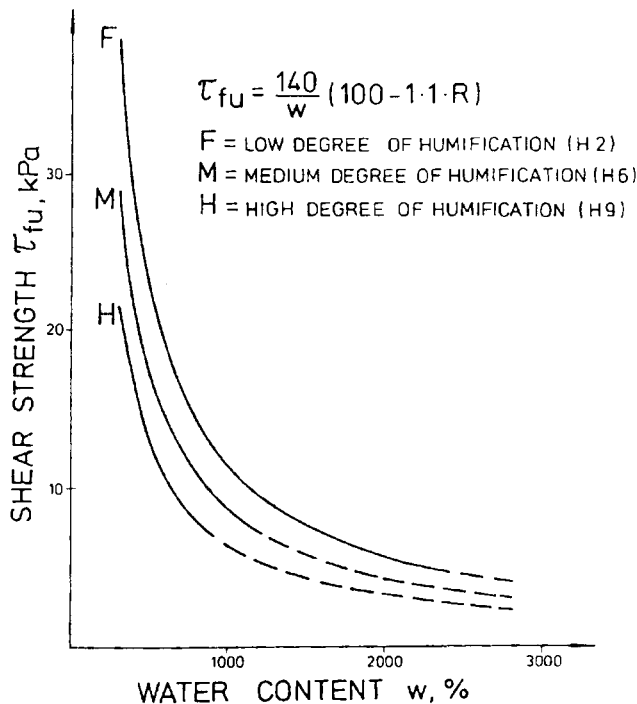


Fig. 13. Relationship between shear strength, moisture content and degree of humification (Helenlund 1980).

at low normal stress levels, the value of ϕ' tended to decrease while c' values increased, possibly as a result of fibre entanglement in the peat. At higher stress levels c' values decreased and ϕ' values increased. The type of laboratory test apparatus used has been shown to have a significant effect on the measured effective strength properties (Landva *et al.* 1986; Farrell & Hebib 1998). The high effective friction angles are believed to be due to the reinforcing effects of the predominantly horizontally aligned fibres, and attempts have been made to unravel their contribution by using a combination of tests utilizing different modes of deformation (Landva & La Rochelle 1983) and calculating the part of the friction angle related to the fibres (Long & Jennings 2006). Cola & Cortellazzo (2005) have attempted to measure the contribution of fibres by carrying out tests on intact and reconstituted samples without fibres.

Undrained strength Undrained shear strength (s_u) refers to the strength of soil in situations where the excess pore water pressures developed during shearing cannot dissipate and failure takes place. In mineral soils, failure occurs as a result of a reduction in effective stress brought about by the increase in pore water pressure. The fact that the very application of the effective stress principle in its classical form to peat is doubtful makes the application of undrained shear strength correspondingly doubtful. Undrained shear strengths (s_u) have been reported to vary from 20 kPa in fibrous peat to below 4 kPa in more humified peats (Long 2005). s_u been shown to vary with several factors, such as degree of humification and water content (see Fig. 13, from

Helenlund 1980). Undrained strength ratios (s_u/σ'_{vo}) are generally higher than for mineral soils, with values scattered between 0.3 and 0.8 in the normally consolidated range (Carlsten 2000; Edil 2001), and values are less scattered for laboratory tests than for field vane testing. Lechowicz (1994) found that s_u/σ'_{vo} values showed a bilinear relationship with effective stress level with a marked increase in the over-consolidated region. The higher permeability of some peat compared to clay soils makes it uncertain whether undrained conditions would exist for many *in situ* strength tests and design situations.

Shear strength testing

In situ vane

In situ vane testing is commonly used to obtain undrained strength values of soft soils and has been used in many investigations of peat in Ireland (Farrell & Davitt 1996; Loughrey 1996). Although the vane is routinely used in design, interpretation of results is complicated by the presence of fibres. Landva (1980b) studied the deformation of peat during shearing by the vane and noted a void opening up behind the blade into which the compressed peat drained. The measured strength was also found to decrease with increasing vane size as a result of the fibre action relative to the size of the vane. It was concluded that the *in situ* vane test in peat is of little engineering use and that it can, in fact, be directly misleading. Hanrahan (1994) acknowledged the limitation of the vane, but felt that it still remains a useful method to assess the variability with depth and presence of soft layers (see, e.g. Piggot *et al.* 1992). In the authors' opinion, *in situ* vane strength values are of use only as an 'index' property of the peat.

Cone penetration testing

Cone penetration testing with pore pressure measurements (CPTU) is routinely used to assess the undrained shear strength variation of soils by correlating tip resistance profiles with laboratory strength tests or *in situ* vane tests. The use of CPTU in peat is complicated by the presence of fibres that cause scatter in the profile and difficulties in measuring resistance in very soft peat because of resistance values being close to the accuracy of the equipment. Factors such as the variation of temperature between the surface and in the ground can have a significant influence on the operation of the cone, because of the small resistances being measured (Lunne *et al.* 1986). Landva (1986) studied the deformation pattern of model cones in the laboratory and found it to be one of varying compression and tearing that does not resemble any real mode of deformation under structures

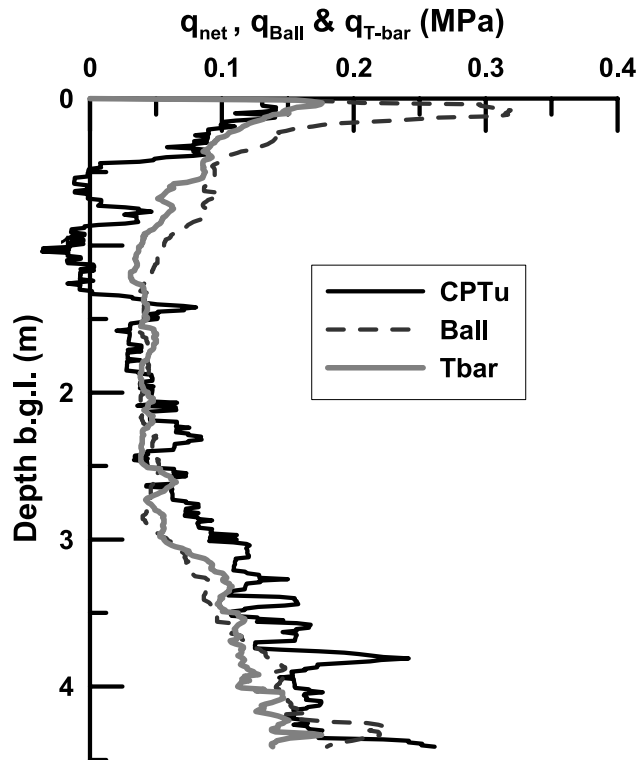


Fig. 14. Comparison of penetrometers in peat (Boylan & Long 2006). b.g.l., below ground level.

on peatland, and concluded that CPTU was of little engineering use. From the authors' experience, pore pressure parameter (B_q) values from CPTU in Irish peat are generally less than 0.3, which would indicate that the material behaves in a partially drained to drained manner (Schnaid *et al.* 2004). CPTU can, however, provide a good vertical profile of the peat, which can detect general variations in peat condition and layering using the friction ratio (R_f) and pore pressure parameter (B_q) (Long 2005).

Advanced penetrometers

Uncertainty about the deformation around the CPTU cone and the level of corrections to be applied to results has led researchers to look at larger full flow penetrometers such as the T-bar and ball penetrometer (Chung & Randolph 2004). These devices have the advantages of a greater bearing area, very little correction of data and closely bracketed plasticity solutions. Recent research (Boylan & Long 2006) has shown that these penetrometers give a much more defined measure of the resistance than the CPTU probe in peat (see Fig. 14), and problems associated with CPTU measuring negative resistance as a result of temperature variations are eradicated because of the larger bearing areas of the T-bar and ball. The T-bar and Ball were found to yield a narrower range of bearing capacity factors than the CPTU, which correlate measured resistance with undrained shear strength from

other laboratory and *in situ* tests. Further research is required to understand the failure mechanism of these penetrometers in structurally anisotropic soils, relate measured resistance to shear strength parameters obtained by other test methods and establish whether the use of advanced penetrometers in peat has practical merit.

Laboratory testing

Laboratory testing methods to test for the shear strength of peat are generally the same as for traditional soils. Triaxial compression (TC), direct shear (DS), direct simple shear (DSS) and ring shear (RS) have been used to measure undrained and effective strength properties. Laboratory testing of peat strength properties is complicated by several factors, as follows.

(1) It is difficult to obtain and prepare samples because of the high water content and fibres.

(2) Difficulties are experienced in maintaining and measuring small stresses on samples so as to model *in situ* conditions.

(3) Corrections related to apparatus compliance and membrane stiffness can be a large percentage of the measured strength.

(4) Interpretation of actual failure is difficult because of the large strains involved and excessive deformation.

(5) Structural anisotropy as a result of the presence of fibres within peat can cause artificial reinforcement of the sample.

Farrell & Hebib (1998) carried out a detailed study of the shear strength of peat using various laboratory tests. Effective friction angles (ϕ') measured in triaxial compression (TC) were found to be higher than those measured in direct shear (DS), ring shear (RS) or direct simple shear (DSS). It is thought that the difference reflects the orientation of the fibres in relation to the direction of shearing. The undrained strength ratios (s_u/σ'_{vo}) were comparable for TC and DSS testing.

Landva *et al.* (1986) found that standard triaxial testing of peat is not particularly useful, with samples deforming without reaching any maximum stress value. DS testing was not recommended either, owing to the uncertain stress distribution and mode of deformation. RS testing was found to be useful to eliminate the effect of fibres and study peat at large strains. DSS testing of peat has been used routinely by a number of researchers (Farrell & Hebib 1998; Farrell *et al.* 1999; Carlsten 2000), and it is believed that its results are relevant to potential sliding surfaces in a layered soil such as peat. Long (2005) has carried out a detailed review of the problems associated with laboratory testing of peat and the trends reported by various researchers, and concluded that RS and DSS tests are the most useful laboratory tests for understanding the behaviour of peat in landslides.

Slope stability analysis

Peat failures in upland blanket bogs for the most part resemble translational planar slides and several researchers (e.g. Hendrick 1990; Dykes & Kirk 2001; Warburton *et al.* 2003; Long & Jennings 2005) have used a relatively simple infinite slope analysis to back-analyse these slides. Other approaches to slope stability that search for curved and wedge type failure surfaces can result in over-conservative results, as a result of the dominant failure in peat being planar. Assumptions about inter-slice forces in limit equilibrium analyses may also serve to make analyses over-conservative.

According to Haefli (1948) and subsequently Skempton & DeLory (1957), the factor of safety (FOS) for a planar translation slide, if the peat is assumed to behave in an undrained manner, is given by the equation

$$\text{FOS} = \frac{s_u}{\gamma z \sin \beta \cos \beta} \quad (3)$$

where s_u is the undrained shear strength of peat, γ is the bulk unit weight, β is the slope angle on base of sliding and z is the depth of failure surface.

The following equation is used for effective stress strength analysis, assuming steady seepage of ground-water parallel to ground level:

$$\text{FOS} = \frac{c'}{\gamma z \cos \beta \sin \beta} + \frac{[\gamma - \gamma_w(z_w/z)] \tan \phi'}{\gamma \tan \beta} \quad (4)$$

where c' is the apparent drained cohesion of peat, ϕ' is the effective angle of shearing resistance, γ_w is the bulk unit weight of water and z_w is the height of water table measured from the failure surface upwards. Equations (3) and (4) both ignore the passive resistance provided by material at the toe of the failure volume, but this becomes less significant with increase in the ratio of length of failure to depth.

Figure 15 shows the sensitivity analysis of the c' and Z_w parameters on the calculated FOS for various bulk unit weights (γ) using equation (4). It can be seen that for low bulk unit weights, the values of c' and Z_w play an increasingly significant role in the calculated FOS. For a typical blanket bog site where the unit weight of peat is close to that of water ($\gamma \approx 10 \text{ kN m}^{-3}$) and the water table is high ($Z_w/Z \approx 1$), the c' parameter essentially dictates the resulting FOS. In these circumstances, equations (3) and (4) are largely the same and results are dependent on the values of c' and s_u .

As discussed above in the section on shear strength of peat, the applicability of both the undrained and drained strength methods to peat is highly questionable. In purely drainage terms it is likely that the mode of failure is in reality partially drained. Given the high degree of uncertainty associated with such analyses, current practice in Ireland, for an indication of the risk of peat slides,

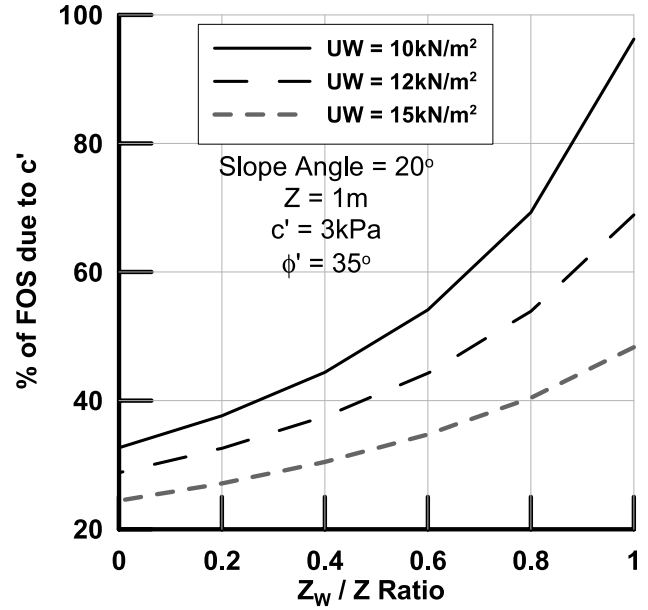


Fig. 15. Sensitivity analysis of equation (4).

is to utilize a pessimistic s_u value (e.g. the lowest value measured) and a relatively high safety factor (e.g. 1.4). The difficulties in determining a c' value mentioned above make equation (3) a much more practical option. *In situ* vane tests are typically used to derive an s_u value, but given the effects of fibres on the vane and the mode of deformation, this test can be directly misleading. Even with the doubts about undrained shear strength, the value of s_u should at least be from a test where the mode of deformation is comparable with the situation under analysis (i.e. direct simple shear for peat failures).

Rigorous finite-element techniques that allow for 3D analysis of the peat mass, modelling of the hydrological processes and accurate simulation of the stress paths followed by elements of peat during different events (i.e. elevated pore pressures, loading, excavation) could lead to a better understanding of peat failures and the risk of them occurring. Before this can happen, however, fundamental research on peat strength and how it is derived needs to be carried out and specific material models for peat developed.

Summary

This paper has examined the topic of peat failures in Ireland with emphasis on the areas that would be of interest to an engineer or engineering geologist assessing this geohazard. The distribution of peat throughout Ireland, its formation and its typical characteristic properties have been discussed. 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 the following.

(1) Historical records show up to 70 failures in the 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 $5 \times 10^6 \text{ m}^3$ have been recorded. However, most failures are generally much smaller, and in most cases smaller failures are unlikely to be reported.

(3) There is a general trend of increasing peat thickness with reduction in slope angle. The majority of the failures are clustered between 4° and 8° . This may correspond to the slope angles that allow a significant amount of peat to develop that over time becomes potentially unstable.

(4) There are a number of failures at high slope angles (above 20°) but, based on the authors' inspection of such failures, peat cover is generally thin and failure tends to involve underlying mineral soils.

(5) Run-out distance is variable, ranging from a few hundred metres to many kilometres. In general, larger failure volumes travel the greatest distances, with failure volumes in excess of $1 \times 10^6 \text{ m}^3$ probably travelling in excess of 4 km.

(6) Over the period 1600 to the present day the estimated number of fatalities is 36, which equates to a probability of 0.1 fatalities per year. Fatalities are generally associated with larger failures.

(7) 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.

Likely causal factors for peat slides have been reviewed. Understanding the reasons for past slides and prediction of future slides is a complex issue but the most significant factors appear to be the possibility of intense rainfall and the local morphology, geomorphology and hydrology.

The issue of peat strength has been discussed and is clearly an area where more fundamental research is required. Peat has significant fabric and structural differences that make the direct application of traditional soil mechanics strength models doubtful. Furthermore, there are many uncertainties and difficulties about the use of standard laboratory and *in situ* shear strength test methods.

The huge areas of uncertainty that exist about peat strength and causal factors of failure mean that slope stability analyses in peat cannot be relied on, and should be used only as an indication of stability. Current practice is to use cautious infinite slope stability methods with low values of undrained shear strength (s_u) and high factors of safety. The presence of any causal factors should also be identified in any stability assessment.

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