Photographic feature

Peat slope failures and other mass movements in western Ireland, August 2008

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Abstract: Peat mass movements are relatively common in Ireland and potentially highly damaging. They are usually triggered by heavy rainfall but occasionally wind farm construction or other construction activities also cause significant peat slope failures. In August 2008, heavy rainfall in northwestern Ireland triggered several landslides near Geevagh, Co. Sligo, mostly involving peat-covered hillslopes, and a large peat flow occurred a few days later at the site of a new wind farm near Tralee, Co. Kerry. All were inspected very soon after they occurred to obtain visual evidence of site characteristics and conditions as little changed as possible from the time of failure. This paper reports the nature and implications of the landslides and highlights some of the difficulties of assessing potential landslide hazards from Irish blanket bogs.

On 13 August 2008, heavy rain across western Ireland triggered a spatially localized group of landslides in the uplands west of Lough Allen, similar to the landslide events at Dooncarton Mountain, Co. Mayo and the Channerwick area of the Shetland Islands, northern Scotland, on 19 September 2003 (Long & Jennings 2006; Moore *et al*. 2006; Dykes & Warburton 2007*a*, 2008*a*,*b*). The latest landslides, most of which involved hillslope blanket peat, were headline news as several hit country roads at night, in one case blocking all access to an elderly resident's home; however, he declined to be rescued, having 'witnessed such landslides before' (Fagan 2008). The 2003 landslides were followed 27 days later by the 450 000 m^3 Derrybrien wind farm peat flow in Co. Galway that was not associated with any rainfall, instead being attributed to site engineering works (AGEC 2004; Lindsay & Bragg 2004; Bragg 2007). The coincidence of the pattern of events being repeated 5 years later is worthy of note. The 2008 landslides, triggered by intense (late) summer rainfall as in 2003, were followed 9 days later by a very large peat flow that occurred within the site of a new wind farm development in Co. Kerry. As in 2003, there was no triggering rainfall event for this landslide but site construction works had recently begun.

We undertook site inspections of the landslides in Ireland between 15 August and 20 September 2008. At all of the landslides the primary record of site details was photographic, supplemented by estimates of failure sizes and volumes based on global positioning system (GPS) coordinates and measurement of *in situ* peat depths. Detailed geomorphological maps of the two largest failures, the 2008 Straduff Townland bogflow (hereafter referred to as SDF-08) and the Ballincollig Hill peat flow (BHW-08) were produced from detailed GPS surveys using the method of Dykes (2008*a*). Indicative measures of the strength and other properties of the peat were also obtained from these two sites. The different types of peat landslides observed, listed in Table 1, are identified according to the classification scheme of Dykes & Warburton (2007*b*). This photographic feature aims to report the nature and implications of these events and to highlight some of the continuing difficulties of assessing potential landslide hazards from Irish blanket bogs.

The NW Ireland landslides

During the night of 13–14 August 2008, landslides occurred at four locations within an area of 12 km^2 centred on the Arigna River valley, between Ballyfarnon, Co. Roscommon and Drumkeeran, Co. Leitrim. There may be other landslides within the same area that have not yet been found or reported. The known failure sites were on Carrane Hill (mostly within Co. Sligo) and Corry Mountain uplands that surround the Arigna River north of Geevagh. These uplands are known to be susceptible to peat landslides, with damaging bogflows occurring in 1831 (possibly as much as 10^6 m^3 of peat flowed from the far northwestern end of Carrane Hill completely destroying around 200 m of one of the local roads: Sollas *et al*. 1897) and 1984 (around two-thirds of 120 000 m^3 of failed peat flowed from Straduff Townland to Geevagh village: see 'Landslide 8', below). Other smaller bogflows occurred at Straduff Townland in 1945 and *c*. 1990 (see 'Landslide 8', below) and Tullynascreen Townland in 1985 (Alexander *et al*. 1985). Finally, in late September 2008 a further peat flow was apparently triggered by wind farm engineering works at the Garvagh Glebe (Northern) Windfarm (Anon. 2008*a*,*b*). Figure 1a shows the locations of the two largest

Quarterly Journal of Engineering Geology and Hydrogeology, **44**, 5–16
DOI 10.1144/1470-9236/09-020
1470-9236/11 $15.00

Table 1. *Characteristics of the landslides of August 2008 in western Ireland*

Landslide no.	Gradient downslope from head (°)	Maximum length (m)	Indicative average width* (m)	Failure depth (m)	Failure volume (m^3)	Failure surface position	Failure type	Impacts additional to pollution of watercourses
1	7 increasing to 15	70	20	0.8	1120	Peat–mineral interface	Peat slide†	
2	8–9 (planar)	120	50	1.0–1.4	7000	Peat–mineral interface	Peat slide†	
3	10	40	30	0.6	720	Soil–rockhead interface, 0.1–0.2 m below base of peat 0.4–0.6 m deep	Peaty-debris slide†	Blocked road
4	10 (20 m) then 20 (30 m)	50	30	0.7	1050	Soil–rockhead interface, *c.* 0.2 m below base of peat 0.4–0.6 m deep	Peaty-debris slide†	Blocked road
5	16–18	*c.* 40	10	0.4	160	Soil–rockhead interface	Debris slide	Blocked road
6	0 then 30	15	30	5?	2250	Within soil–rock debris on steep scarp slope below upland plateau	Rotational slide with minor translational debris slide at base of scarp slope	
7	30 then decreasing	<10	30	5?	1500	Within soil–rock debris at base of steep scarp slope	Incipient rotational slide	
8, SDF-08	5.5–3–6–23	220	65	2.5	35 000	Within lower–basal peat	Bog slide†	Blocked road; damaged community facilities
Ballincollig Hill, Co. Tralee: BHW-08	3	540	80	3	130 000	Within lower–basal peat	Peat flow†	Destroyed a bridge, blocked several roads and access to properties

* An estimated value from a few measurements of irregularly shaped landslides or from detailed plans (Figs 5 and 7) intended to communicate the size of the landslide as efficiently as possible.
† Types of peat failures as defined by Dykes & Warburton (2007*b*).

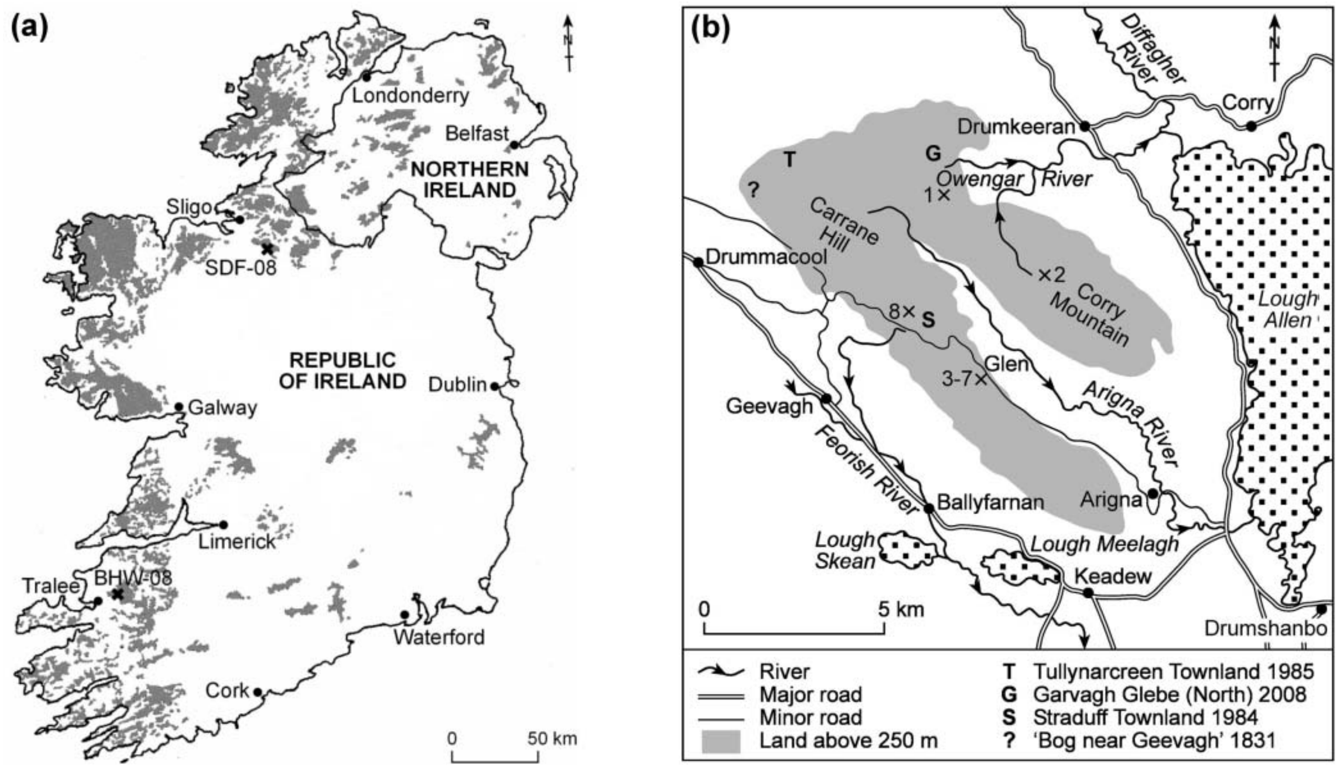

Fig. 1. (**a**) Distribution of blanket peat in Ireland, indicating locations of the landslides (after Tallis 1998). (**b**) Locations of the Corry Mountain–Carrane Hill landslides (identified by × and labelled as Numbers 1–8) and other peat landslides in this area. Landslide 8 is bogflow SDF-08 in (**a**).

failures in NW and SW Ireland respectively, and the proximity of the eight landslides near Geevagh to each other and to other significant peat landslides is indicated in Figure 1b. Details of all the landslides of August 2008, including geometries, classifications and impacts, are summarized in Table 1.

Landslide 1

This peat slide (Fig. 2a) was located above the western side of a mountain track adjacent to a small area of forestry (54°09.00′N, 08°11.8′W; 320 m altitude). It occurred around a natural drainage line near the head of a small tributary stream where surface and subsurface runoff converge, which is a common scenario for such peat failures (Warburton *et al.* 2004). The slope in this area was mantled with around 0.8 m deep blanket peat overlying a mineral substrate that may have comprised *in situ* weathered material.

Landslide 2

This peat slide (54°08.00′N, 08°09.9′W) occurred immediately NW of the Tullvnahaw Windfarm, on the summit of Corry Mountain, at an altitude of 405 m (Fig. 2b). The failure site was characterized by blanket peat up to 1.4 m deep overlying *in situ* weathered rock and/or till. Sub-horizontal seepage lines were visible as a plane of separation at the peat–mineral interface where shear failure occurred (Fig. 2c). These seepage lines resemble those recorded in many of the Dooncarton Mountain and Shetland Island landslides in 2003 (Moore *et al.* 2006; Dykes & Warburton 2007*a*, 2008*b*). This slide generated a flow of peat debris that entered a tributary stream course and was carried northwards an unknown distance towards the Owengar River.

Landslides 3–7

The main cluster of peat and soil landslides originated upslope of the Arigna to Glen road (around 54°06.3′N, 08°11.0′W) at altitudes of 300–350 m. Five landslides occurred within a distance of *c*. 500 m along the slope. These landslides blocked the road from Glen to Arigna that trapped the elderly resident in his home. Landslides 3 and 4, both peaty-debris slides, occurred above a sharp convex break of slope above the road (Fig. 3a and b) on a hillslope with blanket peat cover 0.4–0.6 m deep over a thin (up to 0.2 m) mineral soil horizon overlying rock. Both slides were associated with visible drainage lines upslope of the failure heads, and natural subsurface pipes and seepage lines were observed feeding water into the failures at the depth of the shear surface (i.e. at the base of the thin soil layer beneath the peat). Landslide 5 was similar to Landslides 3 and 4 in its slope and hydrological contexts but involved much less peat (<0.5 m depth) over the failed soil horizon, and exposed bedrock in the head of the failure revealed a small flowing spring that undoubtedly contributed to the generation of excess water pressures that triggered this

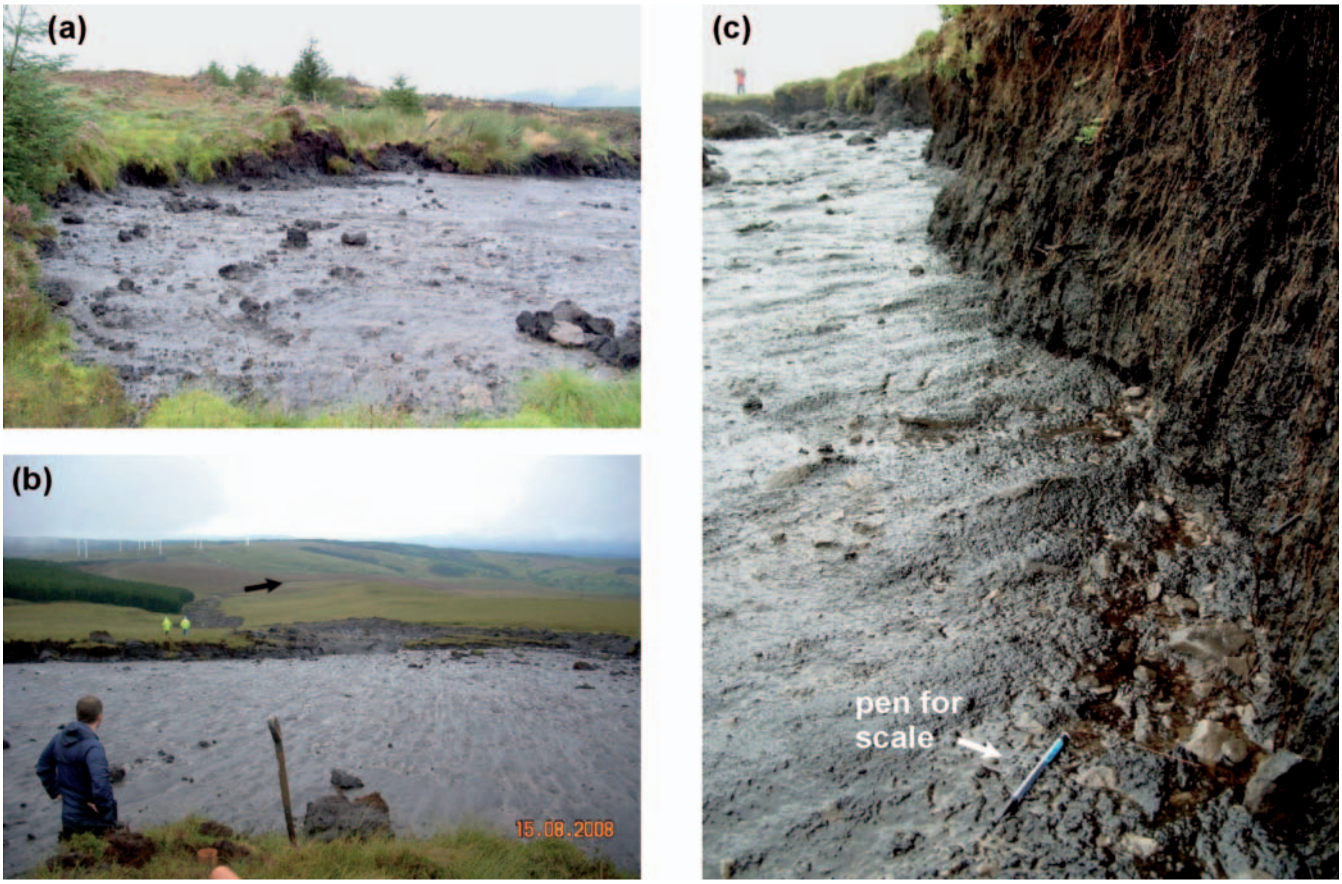

Fig. 2. (**a**) Head of Landslide 1. (**b**) View down Landslide 2 showing the debris runout extending into the head of a tributary stream. (**c**) Close-up of the failure surface at the peat–mineral interface in the head margin of Landslide 2. All photographs dated 15 August 2008.

failure. Landslides 6 and 7 were different in character, involving deeper rotational failure of glacial or colluvial debris on a steep scarp slope between the road and the summit plateau (Fig. 3c). Landslide 7 had not fully developed, being characterized only by a major tension crack 0.1–0.2 m wide at the surface, but the context is the same as that of Landslide 6 so a similar failure scenario can be reasonably inferred.

Landslide 8 (SDF-08)

This large failure occurred shortly before 22.30 h on 13 August 2008 when 'tonnes of black silt' inundated the grounds of the community centre in Geevagh village, which had been similarly devastated following a much larger bogflow in 1984 (Alexander *et al*. 1986). On this occasion an engineering assessment the following day reported that '600 tonnes of silt lie on top of the pitch' (Fagan 2008). The description of 'silt' reflect the smooth appearance, similar to soft silty mud, that liquified peat can possess following extensive remoulding during very wet flow.

The landslide originated on the summit ridge of Carrane Hill in Straduff Townland at 54°07.2′N, 08°13.0′W, at an altitude of 400 m (Fig. 4a). This ridge constitutes a gently sloping 'plateau' bounded by steep escarpments along either side (Fig. 4b), though containing subtle topographic variations. Large bogflows have occurred as a result of failure of the peat at the escarpment crest on the southern side of this plateau in 1945, 1984 and around late 1990–early 1991 (Alexander *et al*. 1986; Yang & Dykes 2006; Dykes 2008*a*). The latest failure involved the intact blanket peat between the 1945 and *c*. 1990 bogflows. Slope gradients and failure morphologies are shown in Figure 5. Although the lateral margins of the source area clearly show that lower catotelm peat flowed out from beneath the stronger, more fibrous acrotelm peat (the latter remaining as large, intact but subsided rafts as observed in all bogflows) (Fig. 4c), a shear surface within the basal peat at least 20 mm above the peat–mineral interface was exposed in the steeper head zone, with a small patch of shear surface also visible on the steeper slope near the escarpment edge (Fig. 4d). Shearing in the lower catotelm is a defining characteristic of bog slides, which tend to occur on slightly steeper slopes than bogflows (Dykes & Warburton 2007*b*). Boylan *et al*. (2008) hypothesized that all types of peat failure begin with this type of basal shearing, but morphological evidence from other sites suggests an alternative hypothesis for bogflows and bog

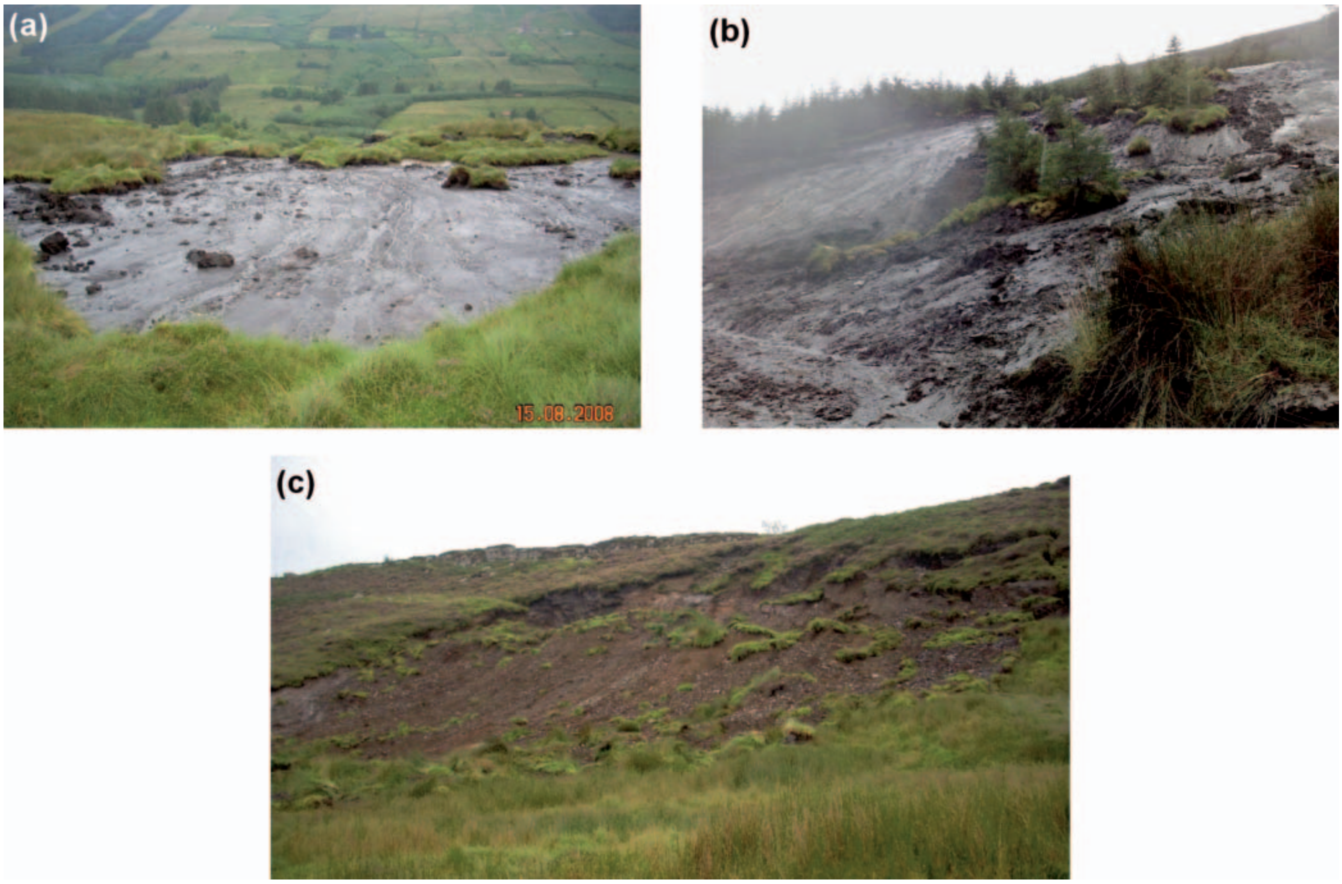

Fig. 3. (**a**) View down Landslide 3, above the convex break of slope. (**b**) Peat and soil debris from Landslide 4 descending to the road. (**c**) Landslide 6 on the scarp slope above the road. All photographs dated 15 August 2008.

bursts involving *in situ* collapse of peat structure, catastrophic loss of strength and outflow of basal peat (Dykes *et al.* 2009). Experimental testing of either hypothesis has yet to take place.

The peat was typically 2.5 m deep (varying between 1.8 and >3 m) (Fig. 4e), giving a failure volume of 35 000 m^3. However, following the failure, 1.0–1.5 m of semi-liquid peat slurry remained across much of the source area, with 0.8–1.2 m thick rafts of acrotelm peat floating in the slurry, typically 60% submerged with 0.3–0.5 m visible above the slurry surface. This means that *c.* 20 000 m^3 of (semi-liquid) peat was lost from the source area and moved down the escarpment slope towards and across the road (Fig. 4f and g), the mobility of the flow probably greatly enhanced by additional water from the heavy rain and associated surface runoff. Below the road (Fig. 4h) the flow followed the same stream channel for 4.5 km to the Geevagh sports field as in 1984 (Alexander *et al.* 1986). Interestingly, there is no report of a similar downstream inundation associated with the *c.* 1990 bogflow. Whereas this earlier, slightly smaller flow also crossed the road, it had first passed through an area of densely planted forest, which would have retarded the momentum of the flow as well as trapping peat debris above and between trees on the slope.

The SW Ireland landslide

Landslide BHW-08

The peat flow in Co. Kerry began on the NW side of Ballincollig Hill in the Stack's Mountains, 8 km NE of Tralee, in the afternoon of 22 August 2008. Although the potential risk of a landslide associated with wind farm development at this site had been identified in 2004, the developer is known to have addressed all of the issues raised by the relevant authorities (Lucey 2008). The site that failed is at an altitude of 295 m and is characterized by a planar 3° slope covered with typically 3 m deep blanket peat. The head of the source area coincided with the furthest extent of a gravel 'floating road' that was being constructed across the bog surface (Figs 6a and 7). A narrow belt of fully disrupted peat developed downslope from the head (Fig. 6b and 7), as observed in other peat flows (Dykes & Warburton 2007*b*). At the lower end of the main flow, a small patch of basal shear surface was visible (similar to Fig. 4d). However, peat extraction had previously occurred at the site using a peat-cutting machine, which extracts 'sausages' of peat from around 1.1 m deep through vertical slits or 'tines'. The tines effectively slice the upper metre of peat into strips, and within a few years of cutting they become almost invisible at the surface. Failure of the

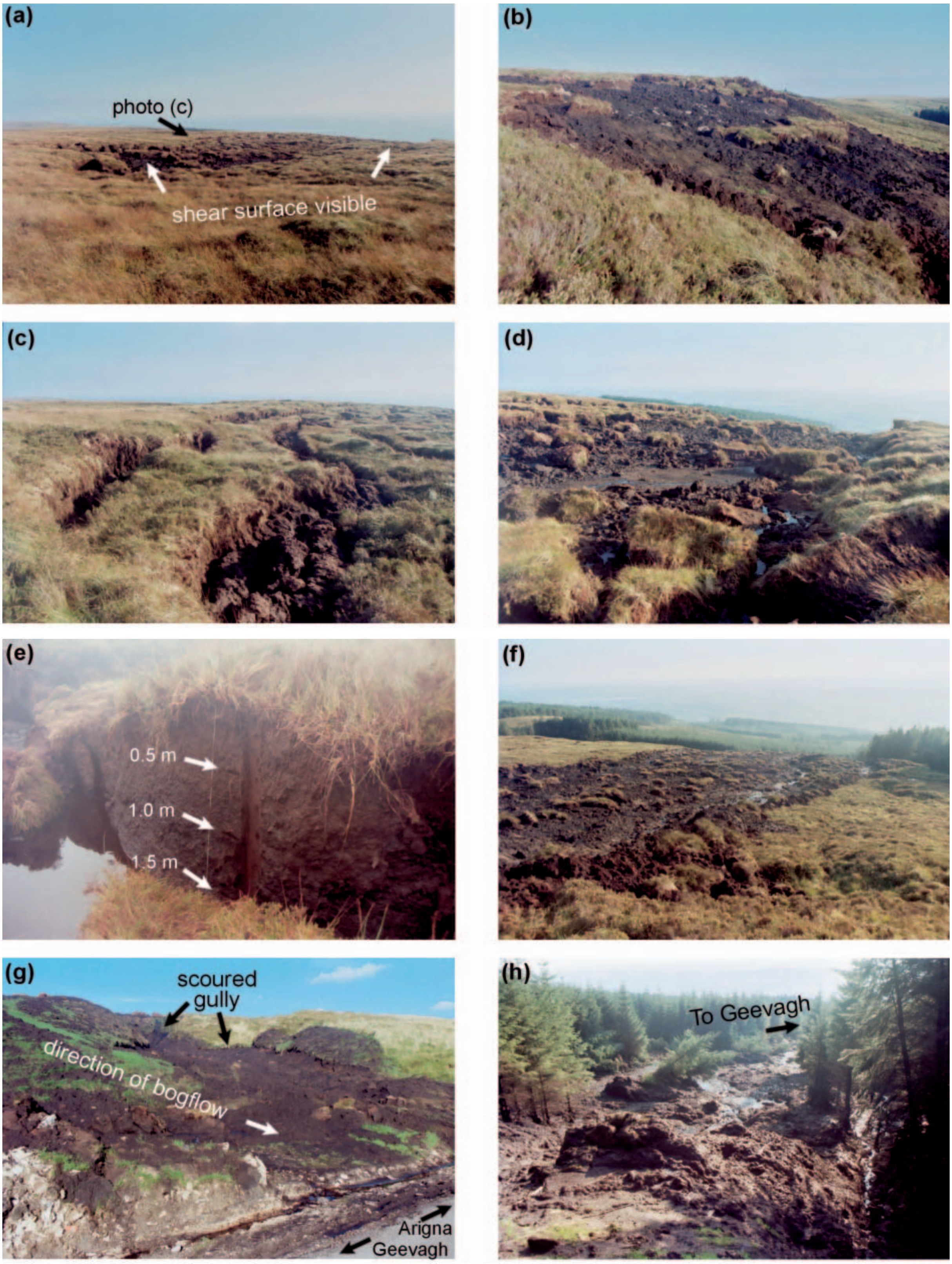

Fig. 4. Landslide 8 (SDF-08) on 20 September 2008 unless otherwise indicated. (**a**) View from above the head showing the whole landslide above the edge of the plateau. (**b**) The escarpment, the large peat rafts in the centre indicating the approximate downslope limit of peat failure. (**c**) The eastern margin showing displaced intact rafts of peat, each subsided by 0.5 m relative to the adjacent outer raft as a result of outflow of (semi-)liquid catotelm peat. (**d**) The lower 6° segment of the source area showing evidence of a shear surface within the basal peat. (**e**) The only accessible *in situ* undisturbed peat profile, from which samples were extracted, seen here in thick fog immediately prior to sampling on 19 September 2003. (**f**) The runout crossed a topographic bench below the escarpment, then flowed down the steep slope alongside the forest for 150 m before (**g**) pouring onto and across the road and (**h**) down through the forest below the road where it eventually fed into the stream that descends to Geevagh.

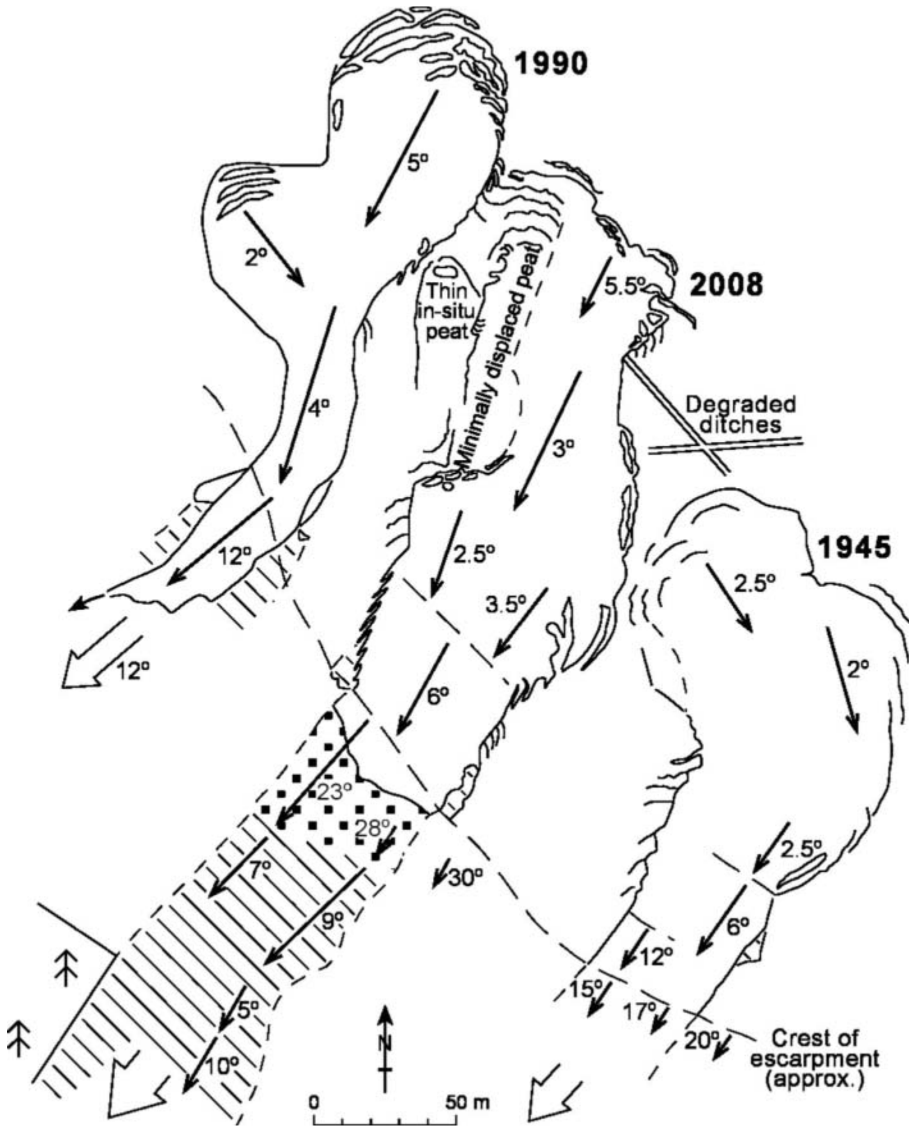

Fig. 5. Geomorphological map of landslide SDF-08 as surveyed on 19 September 2008, showing its location exactly between the *c*. 1990 bogflow (reference SDF-90) to the NW and the 1945 bogflow (SDF-45) to the SE. The outer extents of the respective source areas are mapped, with some interior details indicated. Coarse stipple indicates *in situ* peat or soil overridden by the flow; diagonal hatching indicates peat slurry and debris deposited on intact ground. Measured gradients are shown. The apparent northwards bias of source area development reflects the gently rising elevation of the ridgetop plateau in that general direction. The presence of the earlier bogflows, and another much larger one nearby, indicated an inherent instability of the blanket bog above this escarpment. The 2008 failure was therefore unsurprising, but the fact that it occurred precisely between the two older source areas without disturbing either of them was unexpected.

catotelm peat retrogressed outwards from the main flow, causing subsidence and separation of the acrotelm layer along the tines (Fig. 6c). This retrogression appears to have occurred in a similar manner to naturally occurring bogflows (Fig. 6d, compare Fig. 4c).

At the foot of the affected slope is a stream channel in the bottom of a small ‘valley’ around 3 m deep and 15–20 m wide (Fig. 6e). Adjacent and parallel to this valley on the side of the failure is a slight ridge of probably slightly drier and firmer peat (Fig. 6f), similar to conditions found near the edges of escarpments or other convex breaks of slope (e.g. Mitchell 1935; Tomlinson 1981; Alexander *et al*. 1986). This ridge may have caused failed peat to overflow the eastern margin to create the 0.25 ha deposit on *in situ* peat (Fig. 7). Failure of this ridge allowed peat debris to enter the stream valley, temporarily blocking the stream and diverting the flow of peat slurry and debris downstream. The total volume of failed peat was 130 000 m^3, of which possibly as much as 40 000 m^3 was lost from the failure site and formed the damaging flow that extended down the length of the Glashoreag River (*c*. 6 km along the valley) and sent peat fines onward into the Smearlagh River and, subsequently, the Feale River.

Additional observations

The potential and recorded impacts of peat landslides in Ireland and elsewhere are well known and the impacts of

Fig. 6. Landslide BHW-08 on 16–17 September 2008. (**a**) View down the peat flow from above the head. The dark course of the main flow is clear, but much of the failed peat extends some distance beyond this zone. (**b**) View across the main flow approximately halfway along the failure showing some acrotelm blocks chaotically mixed with fully disrupted catotelm peat. (**c**) The western margin showing a displaced intact raft of peat subsided by 0.5 m relative to the adjacent *in situ* peat, and displaced strips of acrotelm peat defined by tine cuts and dragged downslope by the outward flow of (semi-)liquid catotelm peat. (**d**) Catotelm peat squeezed upwards by rotation and sinking of a failing strip of acrotelm peat (compare Fig. 4c). (**e**) View downstream across the toe of the landslide (right). (**f**) The upper half of the landslide seen from the opposite side of the 'valley', showing the slight ridge of peat across the slope adjacent to the stream.

these recent landslides are outlined below. However, the difficulties of reliably assessing the stability of peatlands with respect to natural events such as extreme rainfall or engineering works associated with wind farms, forestry, or other types of projects, remain. There have been calls in Ireland for a 'best practice guide' for construction on peatlands (Anon. 2008*b*). A publication produced by the Irish Government entitled *Planning Guidelines for Wind Energy* (DoEHLG 2007) provides some guidance on wind farm development in peatland. A more detailed document specifically concerned with peat instability has been produced in the UK (Scottish Executive 2007) although some engineers find this guide difficult to follow in practice (several personal communications

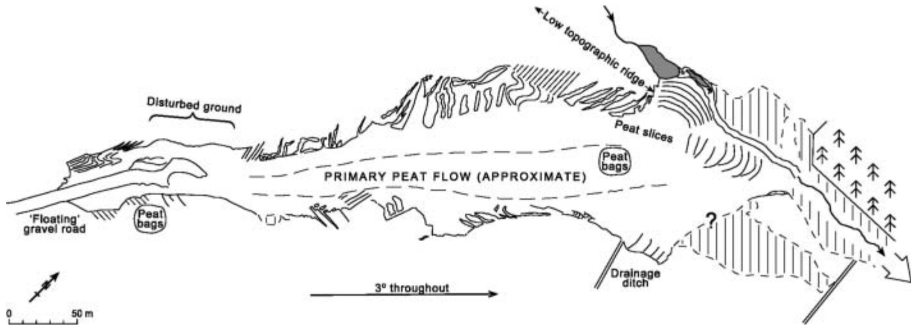

Fig. 7. Geomorphological map of landslide BHW-08 as surveyed on 16 September 2008. The road had been partially rebuilt to allow recovery of machinery from the peat flow. Broad vertical hatching indicates peat debris deposited on intact ground (i.e. undisturbed peat). Narrow parallel diagonal lines indicate (schematically) tine cuts in the peat showing minimal displacement. Curved parallel lines indicate displaced strips of acrotelm peat that separated along tine cuts. All markings indicate the outermost extent of visible disturbance of the peat. 'Peat bags' are white plastic sacks filled with cut and dried peat awaiting collection. Some of the bags that had been lying on the ground near the 'floating' road were moved 350 m downslope by the main flow of the failed peat. Grey shading indicates ponded stream water.

Table 2. *Peat profile properties at Ballincollig Hill peat flow (BHW-08)*

Depth (m)	Vane strength (kPa)	Tensile strength (kPa)*	Field water content (mass fraction %)	Saturated water content (mass fraction %)	Humification (von Post scale)†	Von Post classification of the peat†
0.25	‡	16.0	896	990	H 3–5	B_3 F_3 R_1 W_0 N_1
0.50	1–40	9.2	1276	1716	H 5–7	B_4 F_3 R_1 W_0 N_1
0.75	16	3.8	1275	1821	H 8–9	B_4 F_3 R_1 W_0 N_1
1.00	4–12	4.4	1137	1588	H 8–9	B_4 F_3 R_1 W_0 N_1
1.25	4–8	3.0	1152	2052	H 9–10	B_4 F_3 R_1 W_0 N_0

No *in situ* peat between 1.25 and 3 m deep was exposed in profile anywhere within the landslide area.
* Mean of two measurements from each test sample.
† von Post classification: H, humification (1 = no decomposition to 10 = complete decomposition); B, field water content (1 = dry to 5 = very high); F, fine fibres <1 mm diameter or width; R, coarse fibres >1 mm diameter or width; W, wood content; N, shrub content (F, R, W, N: 0 = nil to 3 = high content) (Landva & Pheeney 1980; Hobbs 1986; after von Post 1922).
‡ No data obtained.

2007–2008), not least because the recommended stability analyses require geotechnical parameters that cannot yet be reliably determined. Measurement of the tensile strength of peat appears to offer a potential solution to this fundamental problem, and research is continuing to evaluate existing approaches to these issues and to develop and test other new strategies and techniques (e.g. Boylan & Long 2007; Dykes 2008*b*–*d*). Two sets of additional observations of the landslides reported above, which relate to these issues, are briefly discussed here.

Peat strength measurement

The assessment and analysis of peat stability for engineering or hazard assessment purposes typically relies on the determination of peat strength properties. This remains a critical stumbling block (Winter *et al*. 2009), some of the difficulties of which have been examined by Moore *et al*. (2006) and Dykes (2008*d*). Furthermore, the variety of site factors that may give rise to failures of blanket bogs is very wide and the shear strength may be controlled by subsurface materials and features not apparent from inspections of intact ground (e.g. Warburton *et al*. 2004; Dykes 2008*c*). As part of our continuing work to understand the precise nature of peat failure and to successfully manage engineering works on peatlands, we measured the strength of the peat at the two largest failure sites SDF-08 and BHW-08 using a standard hand-held four-blade shear vane (e.g. Geonor H-60) and a laboratory tensile strength apparatus as described by Dykes (2008*b*). Although the sampling resolution was much lower than ideal or anticipated because of very limited safe access to exposed *in situ* and undisturbed peat profile faces (e.g. Fig. 4e), each shear vane reading was obtained from the same depth as, and within 0.2 m of, each tensile strength test sample.

Tables 2 and 3 show the peat data obtained from these sampling sites. The discrepancies between the vane and tensile strengths below 0.25 m depth at SDF-08 in particular are striking yet clearly support early accounts identifying the shear vane as being unreliable for measuring the (shear) strength of peat because of the influence of fibres wrapping around the vanes (Helenelund 1967; Landva 1980). At both sites the *in situ* and sampled peat

Table 3. *Peat profile properties at the 2008 Straduff Townland bogflow (SDF-08)*

Depth (m)	Vane strength (kPa)	Tensile strength (kPa)*	Field water content (mass fraction %)	Saturated water content (mass fraction %)	Humification (von Post scale)†	Von Post classification of the peat†
0.25	16	15.0	760	933	H 4–5	B_3 F_3 R_1 $W_{0\text{-}1}$ N_0
0.50	27	4.3	1036	1399	H 8–9	B_4 $F_{2\text{-}3}$ R_1 W_0 N_0
0.75	17	4.3	999	1231	H 6–7	B_4 F_2 $R_{0\text{-}1}$ W_1 N_0
1.00	19	2.8	997	1413	H 7–8	B_4 $F_{2\text{-}3}$ $R_{0\text{-}1}$ $W_{0\text{-}2}$ N_0
1.25	15	1.4	850	1108	H 9	B_4 F_2 R_0 $W_{0\text{-}1}$ N_0
1.50	18	1.4	959	1335	H 9–10	B_4 $F_{2\text{-}3}$ R_0 W_1 N_0
1.75	19				H 10	B_4 $F_{1\text{-}2}$ $R_{0\text{-}1}$ W_0 N_0
2.00	27			base of peat under water		

* Mean of two measurements from each test sample.
† von Post classification as in Table 2.

was noted to be extremely fibrous throughout (Tables 2 and 3), even in association with von Post (1922) humification scores of H_9–H_{10} (see Hobbs 1986). The shear vane can perhaps be used to indicate relative strength variations within a peat profile (MacFarlane 1969; Kirk 2001; Boylan *et al.* 2008) but these results support our view that shear strength values obtained using a shear vane should always be regarded as overestimates with the error increasing as the fibre content and measured strength increases. Notwithstanding this, where the peat fibre content is limited, such as in the more highly humified peat found at depth within the peat profile, then the vane test results would tend to be more representative of the *in situ* undrained shear strength of the peat.

Using an infinite slope analysis the measured tensile strengths are consistent with values of cohesion required for stability with respect to basal shearing within the peat. For BHW-08 using slope = 3°, depth = 3 m, unit weight = 10 kN m^{-3} and the water table at the ground surface, the cohesion required for factor of safety (FS) = 1.0 was c' = 1.2 kPa (with ϕ' = 30°) in terms of an effective stress analysis or c_u = 1.6 kPa assuming undrained failure conditions. These values are slightly lower than the measured tensile strengths, but the actual strength is expected to decrease further at depths below the sampling limit. For SDF-08 the average slope from the head to the escarpment edge was 4.27° and the average of the measured *in situ* peat depths surrounding the failure was 2.57 m. Using these values and unit weight = 10 kN m^{-3} with the water table at the ground surface, the cohesion required for FS = 1.0 was c' = 1.6 kPa (with ϕ' = 30°) in terms of an effective stress analysis or c_u = 1.9 kPa for undrained failure conditions. The measured tensile strength in the lower portion of the peat profile was lower than these values. Based on the above, the measured tensile strength appears to provide an indicator of the likelihood of the occurrence of failure, although this approach needs to be further examined.

Impacts of peat failures

Historical records of runout and fatalities from bog failures in Ireland were outlined by Boylan *et al.* (2008). Although there have been no such fatalities for almost a century, the potential for a fatal bog failure and certainly a highly damaging failure is clearly demonstrated by the nature of these recent landslides. Bog slide SDF-08 sent a 50 m wide torrent of peat slurry down an escarpment and across a road, at night. Likewise, debris from the smaller Landslides 4–6 hit a road. The latter cases are similar to many recent examples in the British Isles of peat or debris slides hitting roads, houses and other infrastructure located immediately below the slopes that failed (e.g. Moore *et al.* 2006; Winter *et al.* 2006; Dykes & Warburton 2007*a*, 2008*b*). On the other hand, larger flow-type peat failures such as bogflows and bog bursts are renowned for their extensive runout of peat slurry or debris (Boylan *et al.* 2008). These events can have damaging impacts far from the original source areas of the failures (e.g. Sollas *et al.* 1897; Colhoun 1966), which adds a significant complication to the already difficult task of assessing the potential hazard from peat mass movements. At Straduff Townland, it was clear following the *c.* 1990 bogflow (Yang & Dykes 2006), which occurred in close proximity to the 1945 and 1984 failures (Alexander *et al.* 1986), that future such landslides from the same escarpment should be expected and that the peat debris could follow the same course to Geevagh village as in 1984. This assessment has been validated and reinforced by the 2008 failure. However, assessing the susceptibility of apparently intact blanket peat on other uplands remains problematic because of the wide variety of natural and anthropogenic contributory causal factors that have been identified previously (Dykes & Kirk 2006; Dykes 2008*c*).

The other major impact of these and other recent peat failures in Ireland has been the contamination of water courses. The Ballincollig Hill peat flow sent peat slurry many kilometres downstream into the Smearlagh and

Feale Rivers, both important water resources and angling rivers. It was reported that up to 30 000 people in and around Listowel in northern Kerry had their water supplies interrupted to minimize more damaging contamination of the distribution system and a boil notice had to be issued for a period of at least several days. At the same time, the upper reaches of the Smearlagh River constitute an important spawning ground. According to the Shannon Regional Fisheries Board (SRFB), 5000 juvenile salmon and sea trout were killed in the Glashoreag River (the major tributary into which the peat initially flowed) and a further 3000 adult fish were killed in the Smearlagh River (Hickey 2008). The SRFB reported similar major fish-kills in 2003 caused by a small peat flow on Slieve Bearnagh (into the Annacarriga River) as well as the Derrybrien Wind Farm peat flow (SRFB 2003).

Conclusions

The landslides reported in this paper include several types of peat mass movements as well as slides involving thin soil and deeper failures of superficial sediments. The peat landslides displayed typical characteristics of their types, including extensive runouts of remoulded or liquified peat. The two largest landslides displayed features important to improved understanding of natural failures and to landslide risk assessments. Both examples highlight the critical importance of detailed examinations of potential failure sites, to identify subtle topographic controls such as the gently sloping plateau of deep peat at Straduff Townland with a (slightly) steeper upslope side and a steeper downslope side, or previous disturbance of the peat such as mechanical extraction that left the tines at Ballincollig Hill. At both of these sites, the role of tensile strength within peat, largely owing to presence of fibres, was examined as a possible indicator of the occurrence of failure. The results showed a reasonable correlation between measured tensile strength and theoretical cohesive strength derived from back-analyses. Finally, the need to extend hazard assessments and environmental impact assessments beyond the immediate vicinity of any potential site of blanket peat instability is clearly reinforced by our examination of these landslides.

Acknowledgements. P.J. inspected all of the landslides (except SDF-08) under contract for clients. Interpretations of single landslides beyond the statement of observable facts are therefore the views and responsibility of A.P.D. alone. The maps were prepared by C. Ivison.

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Received 22 April 2009; accepted 9 October 2009.