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AN INVESTIGATION OF TWO PEAT SLOPE FAILURES IN THE WICKLOW MOUNTAINS

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ABSTRACT

Although peat slope failures have occurred in Ireland for many thousands of years their causal factors and the triggering mechanisms involved are poorly understood. A particular barrier to quantitative assessment of the risk of failures is the lack of knowledge of the geotechnical properties of peat and its role in failures. In order to advance the understanding of these issues case history data is invaluable. This paper describes a case study from the Wicklow mountains where a desk and remote sensing based study was used to identify peat slope failures. Subsequently detailed field studies were carried out at two failure locations. It was found that although the full causal factors at the time of failure are unknown, a common factor was that the failure took place in a zone of highly decomposed and relatively low fibre content peat. A revision of the standard test method for fibre content for use in peat soils is proposed.

INTRODUCTION

Peat slope failures in Ireland have occurred for many thousands of years with archaeological records recording failures going back to the Early Bronze Age at about 4200 BP (Murray, 1997); more recently about 63 recorded failures in Ireland have been identified (Creighton, 2006). However, this is likely to be an underestimate as many of these failures occur in remote regions and will go unnoticed and unrecorded until specific landslide studies report their findings. In recent years, peat slope failures have received increased attention due to a number of high profile failures during 2003 (Long & Jennings, 2006, Dykes & Warburton, 2007) and a number of other peat slope failures since then. These failures represent a geohazard to communities, developments and the environment of upland peat terrains where they predominantly occur.

While peat failures have been occurring throughout the Holocene the causal mechanisms by which they occur are poorly understood. The bulk of literature on peat slope failures is largely made up of descriptions of the extent of the run-out, the likely conditions before the event and possible causal factors. Quantitative analysis of the geotechnical properties of the slide material is limited to a small handful of the reported slides that have occurred in recent decades (i.e. Alexander et al. (1986); Carling (1986); Long and Jennings (2006); Yang and Dykes (2006)). However, the geotechnical tests used in some of these studies were primarily developed for mineral soils and may not be applicable in peat soils which have significant microstructural and structural differences (Boylan et al., 2008).

In any study of the geotechnical properties of peat, careful consideration should be given to the application of tests to peat, the real meaning of the resulting parameters and in some cases adjustments to the test and interpretation procedures may be required. An understanding of the fundamental properties of the peat mass which make locations susceptible to failure and the effect of different factors (i.e. extreme rainfall, loading of the peat surface, cuttings) will

assist in quantifying the risk of future failures occurring and the impact of changing climatic conditions. However, the current lack of knowledge on this topic represents an impediment to realistic analysis of this risk of a peat failure and, as a result, risk analyses are highly qualitative in nature.

To begin to try and understand the mechanisms by which peat failures occur and develop realistic methods to assess the risk of failure in a particular scenario, it is first necessary to study the peat at failure locations and identify the characteristics which may make a particular location susceptible to failure. Accepting that other factors will also influence the triggering of peat slope failures at particular locations (i.e. rainfall, cracks in peat, peat pipes) it is the intention of this paper to focus solely on the basic geotechnical characteristics. Future research can then be targeted on particular features of the soil structure and the effect of other factors.

This paper describes a case study undertaken in the Wicklow Mountains to identify peat slope failures and the geotechnical characteristics of the failure locations. Firstly, a desk and remote sensing based study with field checks was undertaken to identify failure locations. Following this, field studies were carried out at a number of failure locations, including basic geotechnical characterisation as well as topographic and peat depth surveys.

METHODS

Case Study Location and Geology

The Wicklow Mountains (Figure 1) are an approximately 15 km wide area of upland terrain on the east coast of Ireland that stretch from the suburbs of south Dublin for about 40 km in a south-southeast direction through the length of county Wicklow. The bedrock in the centre of this upland area is dominated by igneous intrusions of the Leinster Granite (McConnell et al.,

1995). At the Silsean site (B in Figure 1) this comprises pale grey fine to coarse granite, weathered at the surface to a coarse granular material. The geology of both the east and west flanks of the igneous intrusion comprises of Lower Ordovician rocks. Specifically at the location of the Kilbride failure (C in Figure 1) these deposits comprise dark slate-schist and quartzite. A thin cover of glacial deposits was laid down on the Wicklow uplands during the last glaciation (Warren, 1993). Subsequently the great spreads of blanket bog, which cover approximately 140km² of the Wicklow Mountains formed in the last 11,500 years during the Holocene. Figure 1 shows the present extent of blanket bog peat with a depth greater than 0.3 m in the region of the Wicklow Mountains (Connolly et al., 2007).

Peat Slope Failure Identification

Peat slope failure identification was undertaken using a combined desk and remote sensing based study with field checks undertaken to calibrate the process. This portion of the study took place at the Geological Survey of Ireland (GSI) and utilised a number of data sources located there. Initially, a literature review of landslides within the case study region identified a number of slope failures involving peat (Mitchell, 1938, Delap & Mitchell, 1939). Following this initial desk study, various mapping, orthophotographic, and satellite imagery sources were studied to identify further failures. Table 1 lists the different sources which were utilised in this study and their resolutions.

Analysis of satellite imagery to detect peat failure scars was carried out using LANDSAT ETM+ imagery from 2001 using ERDAS Imagine version 8.7 software. LANDSAT ETM+ (Enhanced Thematic Mapper) is a multi-spectral satellite which collects data across six spectral bands, one thermal band and one panchromatic band. Interpretation of physical features on the earth can be done by viewing a specific combination of bands as a False Colour Composite (FCC) which highlights certain features. Mathematical transformations can

also be applied to the bands to further enhance features. O’Loingsigh (2004) had previously shown that analysis of LANDSAT ETM+ satellite imagery was useful for identifying healing scars from old landslide locations, particularly Principal Component Analysis (PCA) of bands 4,3,2. Analysis of FCC images of bands 5,4,2 (used to identify disturbed ground) was found to be too coarse to identify landslide scars.

Initial analyses focussed on the methods suggested by O’Loingsigh (2004). Imagery was sharpened to a resolution of 15m x 15m ground resolution using the panchromatic band 8. Analysis was first carried out using PCA of bands 4, 3 and 2 but was found to be of little use, being highly sensitive to the spatial extent of the analysis region. Imagery was also viewed using FCC images of bands 5, 4 and 2 (FCC 542). Locations where failures were known to have already occurred were initially viewed to ascertain the spectral signature of failure locations which could then be used to identify new failures.

Figure 2 shows an example of the spectral signatures in the vicinity of a peat slope failure. It can be seen that the spectral signature of the slide location and a location where the peat has been cut are broadly similar for bands 5, 4 and 2 while undisturbed peat has a slightly different signature especially bands 4 and 5. Generally, it was observed that the spectral signature of peat failure locations is similar to areas of upland erosion, locations where the peat has been altered by burning, cutting or drainage. In addition to this, as peat tends to regenerate in failure surfaces, especially in failure surfaces within the peat mass, exposures of subsoil and bedrock which would influence the spectral signature become hidden. However, in this study, the usefulness of FCC 542 images was enhanced by applying a high pass convolution filter to the imagery which enhances edges and helps delineate subtle changes in the peat surface. Figure 3 shows a comparison of LANDSAT ETM+ imagery for a location in terms of (a) FCC 542 and (b) FCC 542 with convolution filtering. The use of convolution

filtering in this case emphasised the location of a failure in the Garryknock townland (indicated by red circle).

While the usefulness of the LANDSAT ETM+ imagery is limited in isolation, it is a useful tool to identify possible peat failure sites which can be further examined using the other sources in Table 1. For example, anomalies such as bedrock and drift exposures were identifiable using appropriate geological field maps. Application of convolution filtering to LANDSAT ETM+ imagery also emphasised locations of peat cuttings and upland erosion, but side by side analysis of orthophotographic images allowed these latter areas to be identified. Field visits were carried out to identify features which could not be delineated from any of the other desk study sources.

Photographic imagery of the study area from the Ordnance Survey of Ireland (OSI) in the form of black and white (1995), and colour (2000) digital orthophotographs were studied to identify possible failures. In addition, black and white stereo-photography from an earlier period (1973-1977) held at the GSI was examined. The use of photography from different time periods allowed identification of temporal changes in the landscape and provided an indication of the time period in which failures would have occurred. Peat failures were found to be much more identifiable from black and white photography as the scars appear more contrasting to the surrounding landscape than in the colour photographs. Figure 4 shows an example of the difference between a peat failure in both black and white and colour orthophotographs.

Peat Failures

From the combined desk, remote sensing and field studies, four peat slope failures were identified within the case study location. Figure 1 and Table 2 show the locations of the identified failures and provide information on the extent of each failure. For this study, peat

slope failures were only classified as peat failures if the organic content of the failure material had an organic content greater than 80% which is consistent with the classification of peat soils suggested by Landva et al. (1983). In addition, peat failures were only considered if the depth of peat was greater than 0.3 m. Other failures identified in the case study location which did not meet these criteria have been omitted.

Field Studies

Field studies were carried out of two of the larger failures identified at Silsean and Kilbride (B & C in Figure 1). Initially a survey of the slide extent was undertaken to estimate the volume of slide material and run-out length. Soils were sampled at the head of each failure scar and at stable locations nearby (less than 50 m from slide location) of similar slope and peat depth. Sampling at the failure locations was conducted within 2 m of the failure scar and it was assumed the peat this close to the failure scar was similar to that of the slide material which had previously failed. Sampling at the stable locations was carried out for comparison to the failure locations and to provide an indication of the characteristics which may make a particular location prone to failure. The samples were obtained using a peat corer similar to the one described by Jowsey (1966). This sampler took 5 cm diameter half barrel samples of 50 cm length which were retained behind a plate during extraction lessening disturbance to the sample. Samples were sub-divided into 100 mm sections and an initial assessment of the state of decomposition was made using the method of von Post and Granlund (1926) for comparison to laboratory assessments. The samples were stored in air-tight containers in a humid, cool (10°C) room and laboratory testing was carried out within 24 - 48 hours of the sampling in the field.

Geotechnical Characterisation

Water content was determined by oven drying at a temperature of 80°C until equilibrium mass was achieved. This temperature was used to prevent charring of solid material which would lead to apparently higher water contents.

Organic content was determined by burning off all the organic matter in a furnace and measuring the loss on ignition (N). Skempton and Petley (1970) suggested burning the organic matter at 550°C for 3 hours as a method to determine the organic content of peat. However, at temperatures above 450°C, clay minerals loose fixed water during ignition and this increases the apparent organic content. Therefore, the organic content (OC) is calculated using Eq. 1:

$$OC(\%) = 100 - C(100 - N) \quad (1)$$

where C is a correction factor for organic carbon losses (typically 1.04 (Skempton & Petley, 1970)). To overcome this problem, Arman (1971) recommends calculating N by igniting the soil at 440°C for 5 hours. The advantage of this method is that no correction for organic carbon losses is required and the organic content can be calculated directly from the loss of ignition (i.e. C = 1). In this paper, organic content was calculated by igniting the soil at 440°C for 5 hours and measuring the loss on ignition.

Bulk Density (ρ) and Dry Density (ρ_d) were calculated directly from the mass of samples of known volume and water content.

The degree of decomposition defines the state of transformation and destruction of the organic matter in peat (Davydik, 1987). For engineering purposes, the state of decomposition is traditionally determined using the method of von Post and Granlund (1926). This method was adopted as it is commonly used in engineering practice and has been used to correlate

with engineering parameters (e.g. Carlsten (1988)). The method classifies peat using a simple hand squeeze test where a small sample of peat (typically 20g) is squeezed and the residue is examined to describe the wetness and the level of decay. The level of decomposition is classified by determining a humification number (H) between 1 and 10 using Table 3, where H1 refers to a peat which has undergone no decomposition and H10 is a peat which is completely decomposed. While 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. Also, the user dependency of this method leaves the reliability of results open to question and they should not be considered in isolation.

Quantitative measurement of the fibre content of peat (Lévesque & Mathur, 1979) combined with measurement of the extracted humic substances (Schnitzer, 1967, Rochus & Sipos, 1976) have been noted as the most reliable properties to assess the level of peat decomposition. However, McDonnell (2002) pointed out that the amount of humic substances present in a soil can be affected by many environmental, topographic, and climatic and land management factors. For this reason, measurement of the fibre content was the only quantitative indicator of decomposition considered in this study. It is recognised that fibre content is not always an indication of the level of decomposition as some peats may have few or no fibres, or be composed primarily of wood. However, from an engineering point of view fibre content is likely to heavily influence the behaviour of peat soils.

The fibre content of peat can be determined using the method described in the ASTM standard D1997-91 (ASTM, 2002). This method requires the peat sample to be saturated in a dispersion agent, a solution of 40g/l of sodium hexametaphosphate, to loosen the peat fibres followed by wet sieving. The sample is placed on an ASTM No.100 sieve (150µm) and water is gently washed through before drying the retained material at 103°C in an oven until all

moisture is removed. The fibre content is expressed as the mass of dry material as percentage of the original dry mass. However, this method does not capture the true fibre content as amorphous matter still adheres to the fibres after the saturation in dispersion agent and sieving. Cohen (1983) points out that this method neglects to account for the inorganic material (sand, shell fragments, sponge spicules) greater than 150µm which could have a significant influence on the mass of the retained material. Also, the fibre content measured in this method is more analogous to the “unrubbed” fibre content where fibres in a state of high decomposition have not broken down and light rubbing of the peat material in ones hands would break them down. Lévesque and Mathur (1979) also found that the “rubbed” fibre content correlated better with indicators of decomposition than the “unrubbed” value.

To overcome these problems, an alternative method was developed. At least three samples at each depth were tested. Each sample of peat of known volume and water content was saturated in a solution of sodium hexametaphosphate at a concentration of 40g/l overnight to loosen the fibres. Following this, the sample was placed on a 150µm sieve and gently washed with water. The retained material was then lightly rubbed by hand and the remaining fibres with a diameter greater than 0.5mm were removed using a tweezers. The fibres removed were then dried in an oven at a temperature of 80°C until a constant mass of dried fibres was achieved. Fibre content was determined using Eq.(2) where $M_{\text{Fibres-Dry}}$ refers to the dried mass of fibres and $M_{\text{Original-Dry}}$ is the original dry specimen mass.

$$\text{Fibre Content (\%)} = \frac{M_{\text{Fibres-Dry}}}{M_{\text{Original-Dry}}} \times 100 \quad (2)$$

RESULTS

Silsean Peat Failure

The peat failure on Silsean was previously described by Mitchell (1938). Figure 5 illustrates the extent of the slide from surveys undertaken in the field study. This failure, which occurred early in 1937, took place on a flank of Silsean where a convex break in slope runs into a flatter spur orientated in a south easterly direction. Within the source area of the failure where the peat would have been between 1.8m – 2m deep, there is a convex break in slope where the slope changes from between 12° – 14° to 8° – 10° . Mitchell (1938) postulated that the thicker peat on the upper slope may have tended to slide downhill, and as this movement was checked by the flatter slope downhill, the peat may have welled up in a ridge. Contemporaneous field evidence suggested that the base of the ridge may have torn, allowing the base of the peat to slide up onto the intact peat surface ahead of it. The run-out material from the slide flowed downhill either side of the spur. Based on the measurements taken during the field study, the volume of material from the source area is estimated to be of the order of 12000 m^3 while the longest run-out from the head of the failure to the toe is approximately 550m. It is likely that additional material was entrained during the run-out of the slide material. The locations where the slide material was sampled at the head of the source area and an undisturbed location are also indicated in Figure 5.

Figure 6(a) to (d) present the results of characterisation tests conducted on peat from the Silsean failure. Results are compared between the slide location and an undisturbed location. Moisture contents are broadly similar for both locations ranging between 500% and 1000%. As bulk densities (ρ_b) are relatively constant at both locations between $1000 - 1040 \text{ kg/m}^3$, dry densities (ρ_d) have the inverse trend of the moisture content and are similar for both locations. Decomposition assessed using the method of von Post and Granlund (1926) suggests the peat at the slide location is less decomposed than the undisturbed location throughout the majority of its depth. However, at the deepest depth (1.5m – 1.7m), the slide location is slightly more decomposed (H9) than the undisturbed location (H8). In contrast, measurements of peat

fibrosity show the slide locations to have lower fibrosity throughout compared to undisturbed location, suggesting that the peat at the slide location is more decomposed. At the base of the peat, where the failure surface of the slide occurred, the fibrosity at the failure location is 2% compared to over 6% in the undisturbed peat.

Kilbride Peat Failure

The Kilbride failure was identified through examination of orthophotographic images which were described earlier in this paper. This failure occurred prior to 1995 and based on the state of the run-out in the orthophotographs from 1995, it is likely that it occurred close to the time when this imagery was obtained.

Figure 7 illustrates the extent of the slide from measurements taken in the field study. The slope within the source area is relatively uniform ranging from 9° – 11° while the peat depth would have ranged from 1.2m – 2.1m with the deeper peat located at the head of the source area. The extent of the slide is not too dissimilar to the Silsean failure with the volume estimated to be approximately 10900m^3 while the longest run-out from the head to the toe of the failure is around 400m. Large portions of the debris material remained within the source area after the failure which is evident in Figure 4(b) and blocks of the decaying peat were still present at the time of the field study (2006). The blocky nature of the failure and the exposure of the subsoil beneath the peat suggest that the failure occurred on a failure surface close to the base of the peat or at the interface with the subsoil below. During the field study, a number of peat pipes (See Figure 8) were identified at the head of the failure close to the interface beneath the peat and subsoil. These pipes which typically have diameters between 100 mm – 150 mm, suggest that there may have been a hydrological influence on the triggering of the slide. For instance, these pipes could have been the conduit for large excess pore pressures to the base of the peat mass from an extreme rainfall event. The presence of

peat pipes at the level of the failure surface has also been noted at other peat slope failures (Long & Jennings, 2006, Dykes & Warburton, 2007). The locations where the slide material was sampled at the head of the source area and an undisturbed location are also indicated in Figure 7.

Figure 9(a) to (d) presents the results of characterisation tests conducted on peat from the slide location and the undisturbed location. The moisture content at the slide location is slightly higher ranging from 700% - 1200%, compared to 500% - 900% at the undisturbed location. As the bulk densities (ρ_b) are relatively constant between 1000 – 1060 kg/m³, the dry density (ρ_d) profiles again reflect the inverse of the moisture content trends. Decomposition assessed using the method of von Post and Granlund (1926) show the peat at the slide location to be more decomposed than the undisturbed location, while the fibrosity measurements show a similar trend with the peat at the slide location having lower fibrosity values. At the base of the peat, where the failure surface is thought to have occurred, the fibrosity is 2% at the slide location compared to 12% at the undisturbed location.

DISCUSSION

This study has looked at some of the geotechnical characteristics of peat at the locations of two peat slope failures in the Wicklow Mountains. At both of the failures examined in this paper, the failure surface is thought to have occurred close to the base of the peat or at the interface with the subsoil below. At both failures, water contents and density profiles are broadly similar at both the slide locations and undisturbed locations of similar slope and peat depth. Decomposition profiles were compared using the method of von Post and Granlund (1926) and by quantitative measurement of fibrosity. At the Silsean failure, both methods suggested different trends of decomposition in the upper peat (above 1.5m) while both methods showed the peat at the slide location to be more decomposed between 1.5m and

1.7m. At the Kilbride, both methods showed the peat at the slide location to be more decomposed than the undisturbed location. The discrepancies at the Silsean failure may be due to the subjective nature of the von Post and Granlund (1926) method.

Fibrosity measurements at both sites show the peat close to the failure surfaces to have between 3 – 6 times less fibres than the undisturbed locations. At present, little is known about the influence of decomposition and fibrosity on the shear strength of peat. However, Helenelund (1980) found on the basis of in-situ shear vane tests in peat, that there is a negative correlation between increasing water content and undrained shear strength (s_u), as well as a negative correlation between increasing decomposition and s_u . Therefore, on the basis of these trends, the peat at the base of both slide locations could have lower shear strengths than the undisturbed locations. Given the many uncertainties relating to the results of in-situ vane tests in peat (Landva, 1980, Helenelund, 1967), the trends suggested by Helenelund (1980) cannot be relied on heavily in practice. However, it can also be inferred from studies in other soils that increasing levels of fibres would increase the shear strength and the level of strain which a soil mass is able to sustain before failure (Norris & Greenwood, 2000).

CONCLUSIONS

This paper has described a case study to identify peat slope failures in the Wicklow Mountains, and study the basic geotechnical properties of the failures. A number of desk and remote sensing based sources as well as field studies were used to identify peat failures in the case study area. Side by side analysis of these sources allowed potential peat failures to be identified and stable locations with some similar characteristics discounted. Failures were found to be most easily identified from Black and White orthophotographs as the contrast between the scar and the surrounding intact ground was most pronounced.

Examination of the geotechnical characteristics of two of the identified slides showed the base of the peat where the failure surfaces occurred to be more decomposed (and thus weaker) than the undisturbed locations. Fibrosity measurements using a method developed to overcome difficulties with the standard method gave quantitative measurements of the fibrosity at these locations, showing failure surfaces to have significantly lower fibrosities than stable locations.

The increasing levels of developments taking place on upland peat deposits and the predicted changes in climate (Sweeney et al., 2002), particularly increases in extreme rainfall events may result in a great frequency of landslides in the future (Creighton, 2006). However, mitigation of the risk of peat slope failures for developments on peat and assessment of the possible effects of climate change on peat deposits requires a better understanding of the causal factors of these events and the strength properties of peat. Further research is required to understand the contribution of fibres to the measured shear strength using methods other than in-situ vane tests, and build reliable relations between the water content, fibrosity and shear strength. Devices such as the axial shear device (Molenkamp, 1998) and the direct simple shear recently developed at University College Dublin (UCDDSS) (Boylan & Long, 2009) will assist in unravelling the contribution of fibres to peat strength. Research into the relationship of peat sedimentology and the locations of peat failures may also assist in understanding the susceptibility of particular locations to failure.

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TABLES

Table 1 - Desk Study Sources

Resource	Year	Data Type	Scale/Resolution
LANDSAT ETM+	2001	Satellite Imagery	30m & 15m
Black and White National Stereophotography	1973	Photographic	1:30,000
Black and White Digital Orthophotography	1995	Photographic	1:40,000
Colour Digital Orthophotography	2000	Photographic	1:40,000
Bedrock Field Maps	-	Map	1 :100,000
Quaternary Field Maps	Various	Map	-

Table 2 – Peat slope failures identified in the Wicklow Mountains

Ref	Location	Irish Grid Reference	Latitude & Longitude	Year	Volume (m ³)	Run-out Length (m)	Source
A	Lough Bray	O 14294 14851	53°10'19" N 6°17'26" W	1938	4000	235	Delap and Mitchell (1939)
B	Silsean	O 02571 05035	53°5'10" N 6°28'8" W	1937	12,000	550	Mitchell (1938)
C	Kilbride	O 08582 19074	53°12'40" N 6°22'28" W	c. 1995	10,900	400	Remote Sensing
D	Garryknock	O 02024 03703	53°4'27" N 6°28'39" W	Pre 1995	9000	350	Remote Sensing

Table 3. Determination of degree of humification (Hobbs, 1986)

Degree of Humification	Decomposition	Plant Structure	Amorphous Material Content	Material Extruded on Squeezing	Nature of Residue
H1	None	Easily Identified	None	Clear, colourless water	
H2	Insignificant	Easily Identified	None	Yellowish water	
H3	Very Slight	Still Identifiable	Slight	Brown, muddy water; no peat	Not pasty
H4	Slight	Not easily Identifiable	Some	Dark brown, muddy water; no peat	Somewhat pasty
H5	Moderate	Recognisable but vague	Considerable	Muddy water and some peat	Strongly pasty
H6	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
H7	Strong	Faintly Recognisable	High	About one half of peat squeezed out; any water very dark brown	Fibres and roots more resistant to decay
H8	Very Strong	Very Indistinct	High	About two thirds of peat squeezed out; also some pasty water	Fibres and roots more resistant to decay
H9	Nearly Complete	Almost Unrecognisable	Nearly all	Nearly all peat squeezed out as fairly uniform paste	
H10	Complete	Not discernable	All	All peat passes between fingers; no free water visible	

FIGURES

Figure 1. Map of Wicklow Mountains showing extent of peat (data from Connolly et al. 2007)	24
Figure 2. Spectral Signatures from LANDSAT ETM+ Imagery	25
Figure 3. (a) LANDSAT FCC 542 (b) LANDSAT FCC 542 with convolution filtering	25
Figure 4. Comparison of peat slope failure (a) Colour orthophotograph 2000 (b) Black and white orthophotograph ©Ordnance Survey Ireland. All Rights Reserved. Licence No. EN00472. In collaboration with the Geological Survey of Ireland.	26
Figure 5. Illustration of Silsean failure	27
Figure 6. Basic geotechnical properties at Silsean failure (a) Water Content (b) Bulk and dry density (c) Von Post (d) Fibrosity	28
Figure 7. Illustration of Kilbride failure.....	29
Figure 8. Pipe at head of Kilbride failure.....	30
Figure 9. Basic geotechnical properties at Kilbride failure (a) Water Content (b) Bulk and dry density (c) Von Post (d) Fibrosity	31

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