Roinn Cumarsáide, Fuinnimh & Acmhainní Nádúrtha
Department of Communications, Energy & Natural Resources

Geoscience Research GSI
Suirbhéireacht Gheolaíochta Éireann
Geological Survey of Ireland

Geological Survey of Ireland Research Programme
- Short Call 2015, Final Report -

Name of Lead Investigator	Paul Doherty
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Organisation name	Gavin & Doherty Geosolutions Ltd.		
Organisation type:	☐HEI	☐Public Sector (other)	☒Private Sector
Department/section			

Project Title	Analysis and monitoring strategy of Irish landslides
Contract No.	2015-sc-005

INFOMAR
Integrated Mapping for the Sustainable Development of Ireland's Marine Resource

Tellus
Understanding Underground

Marine Institute
Foras na Mara

2. Project information:

Title of project	Analysis and monitoring strategy of Irish landslides
Did you make any formal amendment to the project workplan / budget?	☐ yes ☒ no If yes, please specify:

Project Report (*max 1500 words, excluding figures and headings*):

(i) Objectives and scientific/engineering targets beyond the state of the art

Significant advances were made in the area of landslide triggers and factors influencing landslide susceptibility. This was specifically focused on the Irish landscape. Furthermore, novel research was completed with respect to rainfall thresholds for landslide initiation, which is a significant advancement beyond the state of the art.

(ii) Implementation (including reference to timelines, milestones, management)

The implementation of the project was relatively straightforward. The scope of work creeped slightly and additional topics of interest were investigated, including using InSar data to track ground movements, etc. This had a knock-on impact on the programme and budget.

(iii) Outputs (please use bullet points)

- Final technical report.
- Publications in preparation (Irish Rainfall Thresholds – submission Q4 2016)
- Publications in preparation (Landslide Geomorphology – submission Q1 2017)
- Presentation at GSI Annual Conference

Impact/value of the project (M*ax 500 words*):

The project identified two critical impact areas and potential topics for future work, including (a) bias factors that may influence the accuracy of landslide susceptibility maps that are trained off existing inventory data and (b) the value of a pilot demonstration project for trialling landslide monitoring techniques and sensor technology / early warning systems.

See the technical report for further details.

Appendix 1 – Publications & Presentations:

- Final technical report (see Appendix 2)
- Publications in preparation (Irish Rainfall Thresholds – submission Q4 2016)
- Publications in preparation (Landslide Geomorphology – submission Q1 2017)
- Presentation at GSI Annual Conference

Appendix 2 – Any additional information not included above:

See below.

Department of Communications, Energy and Natural Resources
An Roinn Cumarsáide, Fuinnimh agus Acmhainní Nádúrtha

Analysis and monitoring strategy of Irish landslides

Geological Survey of Ireland

Document Number 15070-01

Revision	Purpose	Date	Authored	Checked
00	Final Draft for GSI Review	08/12/16	K. Martinovic A Musial C. Dimet	P. Curran P. Doherty

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1 Executive summary

This project, entitled "Analysis and monitoring strategy of Irish landslides" has been commissioned and funded through Geological Survey of Ireland's (GSI's) 2015 Short Call research programme. The project, proposed and carried out by Gavin and Doherty Geosolutions (GDG), aims to provide an overarching analysis of landslide occurrences throughout Ireland. The analysis is based on a large volume of landslide inventory data collated through recent projects and research. The report includes statistical interrogation of existing landslide database records, coupled with the analysis of failure mechanisms. The project also includes interrogation of meteorological data in order to define the weather warning level for landslides in the form of rainfall thresholds. Finally, an overview of the testing and monitoring techniques suitable for typical landslides in Ireland is given, and a pilot-project monitoring strategy based on this is defined and presented. The guidelines given in this study provides a framework for monitoring landslides that can be rapidly implemented for future landslide data capture. This report is also intended to aid any general slope monitoring activities being undertaken by GSI.

2 Introduction

Following a series of catastrophic landslides over the last two decades, such as Pollatomish and Derrybrien landslides in 2003 (Figure 1), landslide events have received significant attention from a number of parties including the Geological Survey of Ireland (GSI). The desire to better understand landslide occurrences culminated in the formation of the Irish Landslides Working Group (led by GSI), which released a number of publications, with the most comprehensive being the "Landslides in Ireland" report which was published in 2006.

Figure 1 Landslides in (a) Pollatomish, Co. Mayo (source: ucd.ie), and (b) Derrybrien, Co. Galway (source: monasset.com)

Since then, the GSI initiated a large work programme related to landslide hazards in Ireland. The National Landslide Inventory was made publicly available in the interactive web GIS viewer. The original inventory was increased by a factor of thirty following the extensive data collection projects undertaken by Mouchel (2011), Trinity College Dublin (2014) and GDG (2014; 2014b; 2014c; 2014d). Part of the landslide inventory was used to develop the Irish landslide susceptibility map. This map was developed for the Wicklow and Cork areas, and is planned to be continuously updated using new inventory inputs. Additional research on geotechnical behaviour of Irish soils and scrutiny of some major landslide events has also been carried out (Long & Menkiti, 2007; Dykes & Warburton, 2007; Bourke & Thorp, 2005; Long & Jennings, 2006; Dykes & Jennings, 2011; Long, et al., 2011). All of this provides a valuable source of information which allows some general conclusions about Irish landslides to be made.

New landslides that have recently been recorded (Figure 2) clearly show that there is a need for on-going research in this field. These examples demonstrate the negative impact that landslides can have on the surrounding infrastructure. This makes landslide research in Ireland a matter of priority for industry and governmental bodies and not only an academic research topic. The landslide that swept away the Leenaun Bridge in Co. Galway in 2007 caused huge indirect damage, including traffic detours of up to 100 km and the substantial direct capital cost of replacing the bridge. Casualties were avoided by pure coincidence.


SKYCAM IRELAND
aerial imagery

Figure 2 Examples of landslide in Ireland in the last decade: a) the remains of Leenaun bridge after it was destroyed by a debris flow in 2007 (source: rte.ie), b) one of many landslides damaging local road infrastructure during heavy storms in December 2013 (author's photo of Dog's Bay, Co. Galway), c) landslide and coastal erosion of a coastal cliff supporting rail infrastructure in Co. Wicklow in 2016 (source: Skycam Ireland), d) peat slide blocking a national road N59 in Co. Galway in 2016 (source: blogs.agu.org/landslideblog)

Landslide occurrences can be directly linked to physical mechanisms such as "soil moisture deficit" and therefore more extreme rainfall events can be correlated with more frequent landslides occurring. With the ongoing climate change, the frequency of such landslides can be expected to rise. The Intergovernmental Panel on Climate Change (IPCC) scenarios (Solomon, 2007) downscaled to Ireland (Sweeney, et al., 2008; McGrath, et al., 2008) show a significant increase in precipitation during the autumn and winter months (up to 25 %). These wet periods already see the majority of landslides, and with rainfall being by far the most common landslide trigger, it is likely that the number of landslides will increase in future. Furthermore, the amount of precipitation is expected to reduce from current levels in summer periods, further enabling the formation of shrinkage tension cracks in surface soil that act as water conduits during subsequent rainfall events. This mechanisms has previously been shown to be responsible for initiation of some Irish landslides (Long & Jennings, 2006). Finally, the rise in total precipitation in autumn and winter months will likely manifest through a series of irregular high intensity rainfall events rather than a monotonous increase in the strength of current rainfall patterns. This is especially unfavourable as it is the high-intensity rainfall that is commonly attributed as a trigger for shallow translational earth slides and peat slides (Aleotti, 2004), the two types of landslides found most frequently in Ireland. Given the continuous increase in transport and building infrastructure throughout Ireland and the increase in population, the vulnerability to landslide events is also clearly on the rise. With the expected increase in both landslide likelihood and landslide consequences, research into Irish landslides should become an increasingly important topic. This project provides steps towards better understandings of Irish landslides, their consequences, and potential steps in response strategy.

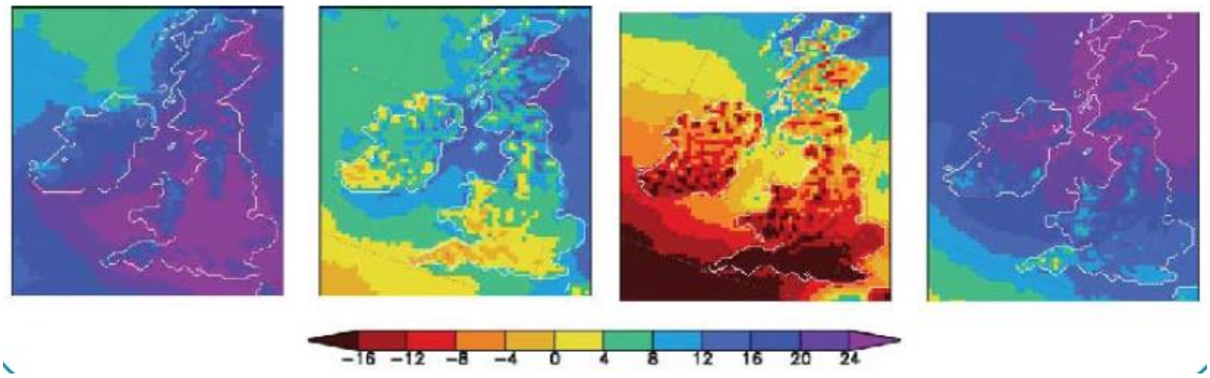


Figure 3 Modelled climate change for winter, spring, summer and autumn seasons. The figure shows percentage change in precipitation between the periods 2060-2099 and 1961-2000 (source: Ireland in a warmer world, Met Éireann and UCD)

3 Analysis of the landslide inventory database

The amount of data in the National landslide inventory has greatly increased in the last decade. The key publication, 'Landslide in Ireland' from 2006, mentions 117 recorded events, out of which 100 are in the Republic of Ireland. As of October 2016, there are over 3700 inputs in the National Landslide Inventory. The vast majority come from the inventory population projects carried on by the GSI (Pellicer & Verbruggen, 2006), Mouchel (2011), Trinity College Dublin (2014) and GDG (2014b; 2014; 2014c; 2014d). All projects used a two-step identification procedure: initial identification of candidate landslides using three sets of ortophotos originating from 2000 to 2010; followed by validation and further identification in the field. Not all of the candidate landslides were visited for validation due to inaccessibility or the lack of resources, so there is a possibility of additional landslides in the interrogated areas, notwithstanding the new failures that potentially occurred after the projects' end.

In brief, these projects covered the areas listed below and illustrated on Figure 4 and identified the following number of landslides:

- Mouchel (2011): two separate areas, Dublin & Wicklow and Southeast Cork (red squares). Total number of validated landslides: 396, out of which 391 in Dublin&Wicklow area.
- Trinity College Dublin (2014): two separate areas, County Mayo and County Kerry (green squares). Total number of landslides: 1810 (635 in Kerry and 1175 in Mayo). These numbers include the landslides that have not been validated on site (approximately 40% has been validated).
- GDG (2014b; 2014; 2014c; 2014d): four separate areas, Southwest Donegal, Slieve Bloom, South Tipperary and West Galway (blue squares). Total number of validated landslides: 353 (79 in SW Donegal, 64 in Slieve Bloom, 106 in South Tipperary, and 104 in Galway). It is worth noting that the majority of candidate landslides were not inspected due to the very short available validation timeframe therefore these numbers almost certainly underrepresent the actual number of failures.

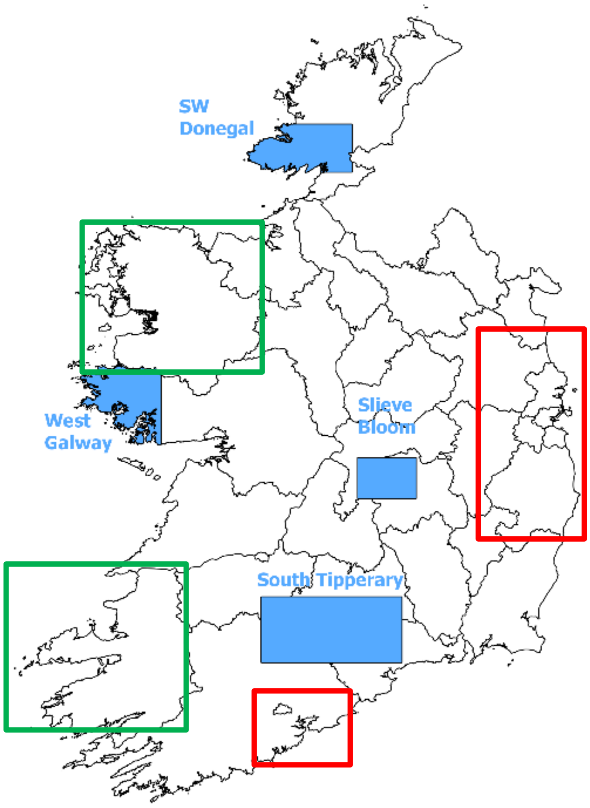


Figure 4 Areas covered by landslide inventory population projects

Locations of all recorded landslides (including landslides from the above mentioned database population projects) can be found in Irish landslides database, on the interactive web GIS viewer: http://spatial.dcenr.gov.ie/GeologicalSurvey/LandslidesViewer/index.html.

Most of the landslides are recorded with a point in the landslide source area, while there are also some rare examples of whole landslide area (source and deposit) being polygonised. The information field in the GIS database includes a wide range of options. For the vast majority of landslides, most of these input options lack the recorded data, including landslides for which the data was collated during the database population projects. This hampers the detailed interrogation of the inventory. Most of the populated input fields include the features that can be extracted from an underlying Digital Elevation Model for a known location, such as easting and northing, elevation, slope angle, slope aspect, quaternary deposit and bedrock. Features that are of most interest for this study, including source area dimensions, run-out length and failure mechanism are mostly missing. Dimensions and run-out length were seldom measured during the database population project due to small sizes of landslides (problem for ortophotos) and inaccessibility (problem for in-situ validation).

3.1 Analysis of failure mechanisms

Information on failure mechanisms differs between the reports produced for the various study areas. The landslide table included in Trinity College Dublin report (2014) includes the "Type of movement" field. However it is extremely sparsely populated, seemingly with only rockfalls being systematically highlighted. Original GIS data potentially possess more information but it has not been available to authors of this report at the time of writing.

The landslide table included in Appendix 2 of Mouchel's report (2011) contains the field 'Comment' with landslide mechanism descriptions for 182 validated landslides. The descriptions are somewhat unstandardized and inconsistent, making the summary of landslide types a non-trivial task, but nevertheless present a good source of information. GDG summarised, standardised and simplified the inputs, with the failure type distribution presented in Figure 5. 81, or 44 % of those failures were labelled as (large) peat slides, including several mentions of peat failures or bog bursts. Earth failures accounted for 42 % of all failures, including 56 (shallow) translational slides, 13 earth flows and 7 rotational slides. Rock falls and debris flows/slides accounted for the rest of the inputs.

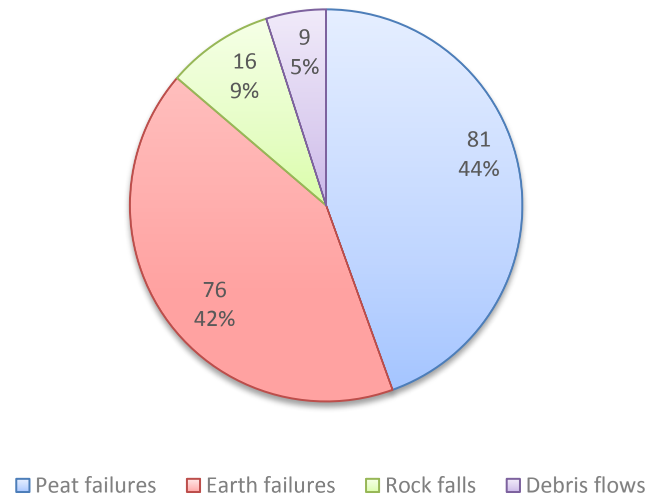


Figure 5 Distribution of main failure types in Mouchel report (2011)

In GDG's reports (2014b; 2014; 2014c; 2014d), failure type was assigned to each landslide validated in-situ. A landslide mechanism classification scheme based on Varnes (1978) and Cruden & Varnes (1996) was used to ensure the standardisation of inputs. This classification classifies landslides based on two major criteria, type of movement (falls, topples, slides spreads, flows) and type of material involved in the movement (rock, debris, earth). The landslide types used in this classification are illustrated in Figure 6.

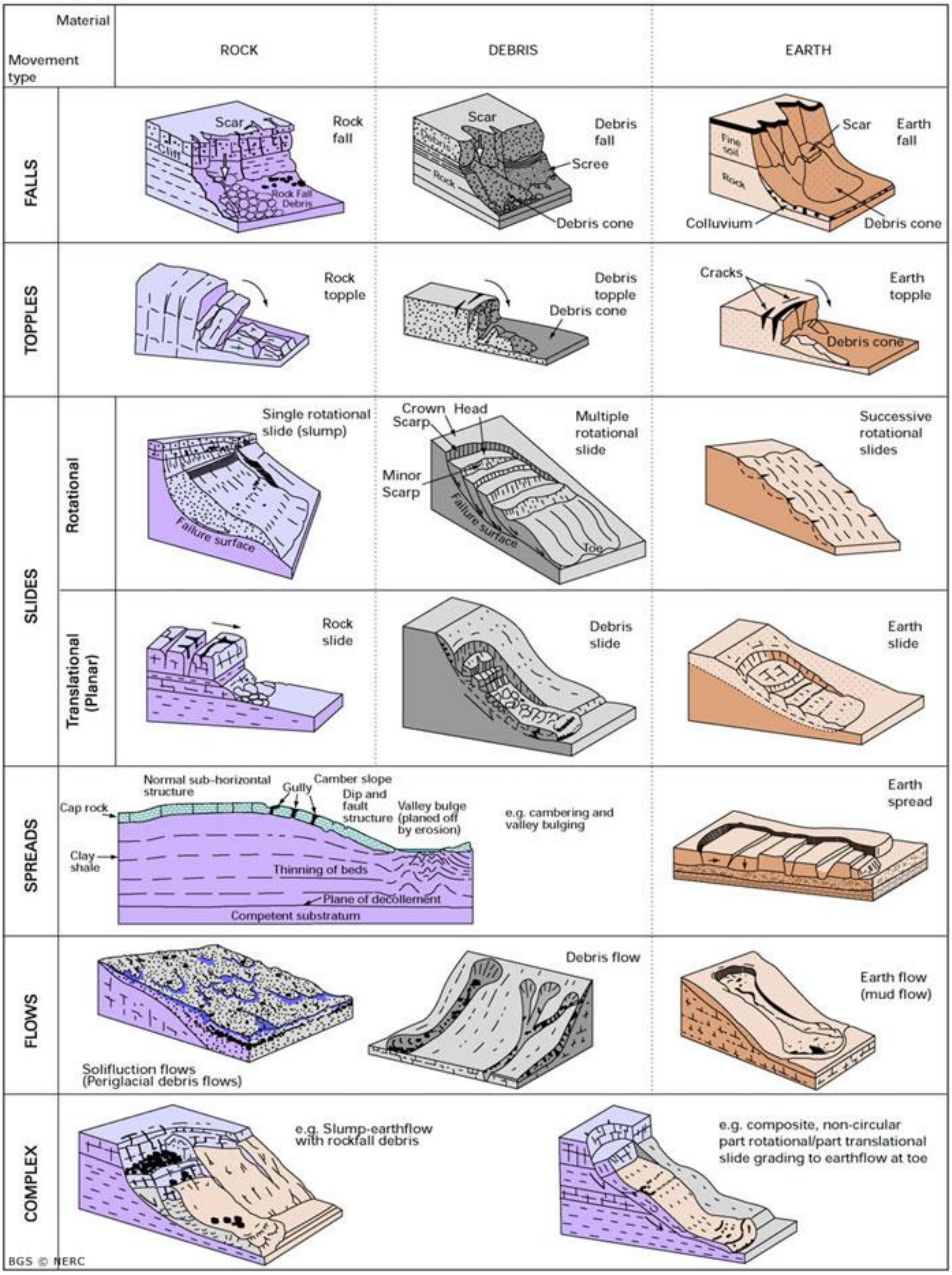


Figure 6 Landslide classification according to Varnes (1978) and Cruden & Varnes (1996)

Results of landslide classification of each of GDG's four study areas are presented in the tables below:

South Donegal:

Material Movement	Rocks	Debris	Earth	Peat
Falls	3	-	-	-
Topples	-	-	1	-
Rotational Slides	1	-	12	-
Translational Slides	-	1	22	13
Spreads	-	-	-	-
Flows	-	9	-	-

Slieve Bloom:

Material Movement	Rocks	Debris	Earth	Peat
Falls	-	-	1	-
Topples	-	-	1	-
Rotational Slides	-	-	13	-
Translational Slides	-	-	22	23
Spreads	-	-	1	-
Flows	-	1	8	8

South Tipperary

Material Movement	Rocks	Debris	Earth	Peat
Falls	12	14	-	-
Topples	3	-	1	-
Rotational Slides	-	-	-	-
Translational Slides	1	7	7	4
Spreads	-	-	-	-
Flows	-	20	4	4

West Galway

Material Movement	Rocks	Debris	Earth	Peat
Falls	11	3	-	-
Topples	-	-	2	-
Rotational Slides	-	-	14	-
Translational Slides	1	1	26	4
Spreads	-	-	-	-
Flows	-	12	2	-

These distributions reveal the specifics of each study area, for instance the abundance of peat failures attributed to vast and deep blanket bog in Slieve Bloom mountains, or frequent rockfalls on exposed cliffs of South Tipperary mountains.

The cumulative table, while admittedly hiding the specifics of each area, can help give the overall distribution of landslide mechanisms across Ireland:

Landslide Study Area's Review				
Material Movement	**Rocks**	**Debris**	**Earth**	**Peat**
Falls	26	17	1	0
Topples	3	0	5	0
Rotational Slides	1	0	39	0
Translational Slides	2	9	77	44
Spreads	0	0	1	0
Flows	0	42	14	12
Total	**32**	**68**	**137**	**56**

It is evident that translational slides and peat failures account for the majority of landslides, followed by debris flows (possibly created by channelling the original transational earth slides or rockfalls and entraining additional material) and rockfall. This distribution aligns very well with the one obtained by analysing Mouchel's data. As a conclusion, (shallow) translational slides and peat failures form the clear majority of Irish landslides. Anecdotal evidence and research studies furthermore show that these landslides are mostly triggered by rainfall.

3.2 Key conclusions

Analysis of the available data resulted in the identification and description of the most common landslide types/mechanisms in Ireland, presented in the previous section. The analysis also yielded some additional insights into landslide causes, behaviour and impacts. This section outlines the observed patterns that may improve the understanding of landslide behaviour and consequences; recording and analysis of future landslides; and those patterns that might affect future work on landslide susceptibility, hazard and risk mapping in Ireland.

3.2.1 Run-out analysis

The vast majority of recorded landslides is identified by a point located in the landslide source area. Similarly, the dimensions of landslides (both source area and deposition area) were extremely seldom recorded, with the exception of few major landslides studied in-depth in scientific publications (Long and Jennings 2006, Dykes and Jennings 2008, Long, et al., 2011). For the few landslides that are represented by a polygon vector in web viewer, there is no distinction between source and deposition areas. All of this hampers the exhaustive quantitative appraisal of landslide run-out. However, the few documented events, and GDG's first-hand experience in part of landslide inventory population process enables the completion of a general-level qualitative analysis.

Very long run-outs with significant deposit depth are characteristic for major peat failures, in particular bog bursts and peat flows where shear surface developed through the peat material itself rather than through basal contact or underlying layer of mineral soil. The combination of easily disturbed peat downstream of initial source area and lubricating action of the water contributes to landslides stretching for several hundreds of meters, with the largest of them stretching over several kilometers. Boylan et al. (2008) presented a correlation between the runout distance and the failure volume for the blanket bog and the raised bog (Figure 7). It shows that for peat failures of up to 50,000 m3 the observed run-outs were reaching 300-500 meters, with possibility of longer run-outs rapidly increasing with volumes larger than that. Run-out may not be the most correct term as these peat failures tend to disturb and entrain material during the course of the movement, effectively enlarging the initial source area. As a consequence of this, it is often difficult to diferentiate between source area and deposition area for these types of failures. The peat slide at Ballincollig Hill in Kerry in 2008 exhibited a total length of over 3 km after it joined the stream (Long, et al., 2011). Large run-outs tend to occur even on the very gentle slopes, in places less than 5˚. The run-out deposit depends on the depth of peat in-situ among other things, and was shown to exhibit significant depths of over 1.5 m for sustained lengths. All these features make peat slides/flows potentially dangerous even for those infrastructure and environmental features that are seemingly a safe distance from the hazard area. Examples of affected infrastructure include numerous local roads (Figure 8), private houses, and environmental property such as forestry or fish farms.

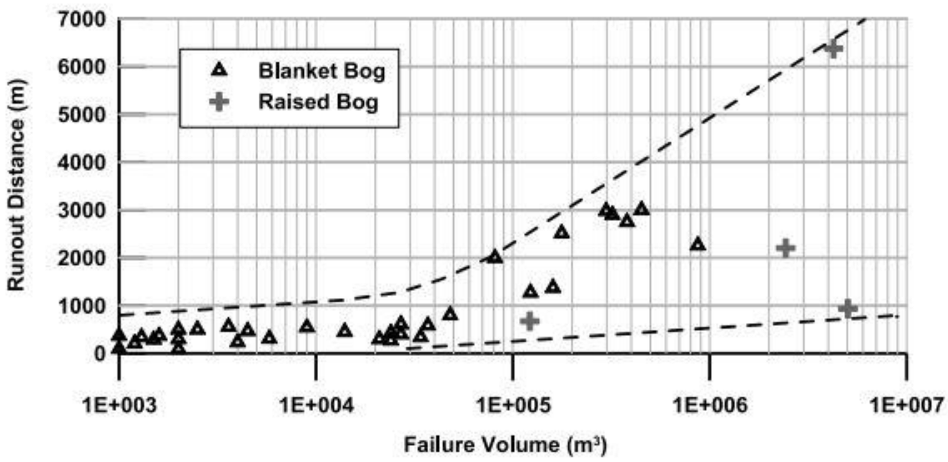


Figure 7 Run-out distance with failure volume (source: (Boylan, et al., 2008))

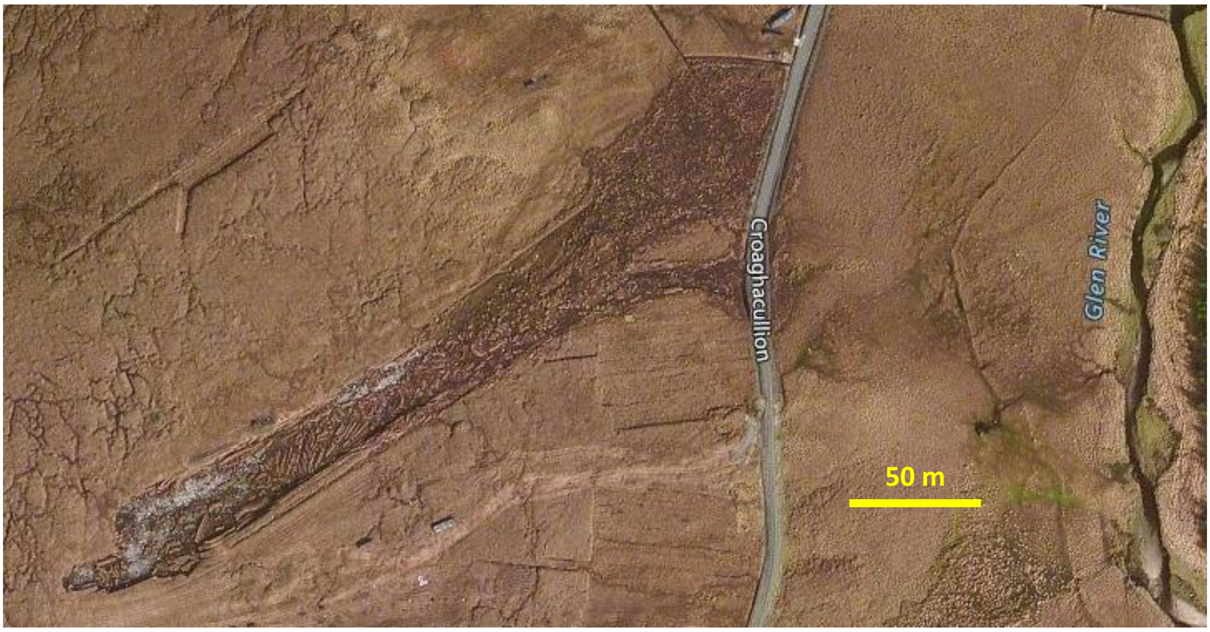


Figure 8: Aerial photo of a 2008 peat slide in Croaghcullion, Co. Donegal (source: Microsoft Bing Maps)

The other most frequent type of landslide, shallow translational earth slides, exhibit somewhat different behaviour. GDG's experience from the four study areas shows that the source area and deposition area can be clearly distinguished, both on aerial imagery and in-situ. This is especially visible for the landslides in shallow soil overyling the bedrock where the failure plane is located on the soil-rock contact. The vast majority of observed landslide scars (source areas) have an ellipsoidal, rounded shape with a pronounced semi-circular crown, which is usually the most clearly distinguishable feature in the field. The longer axis of the landslide scars, usually parallel to sliding direction, was observed to be up to 40 m long. While the exact measurements were seldom available due to reasons already outlined in this study, the source area of a typical large slide was in the range between 300 and 750 m^2, with failure depths between 0.75 and 2 m. The exceptional catastrophical events such as Pollatomish in 2003 and Croaghmoyle in 2009 involved volumes of material of up to 20,000 m^3 (Long 2006, Long et al. 2011).

The location of the shallow landslides adjacent to the near natural water channels/streams could be a contributing factor but does not seem to be the main driving factor, since a significant portion of the observed landslides appear to occur remote from such water features. Another interesting observation was that many landslides appeared on rectilinear or convex flanks rather than in hollows where the concentration of subsurface drainage and sediment depth is expected (Pierson 1980). Both remarks point to the possibility that surface and subsurface hydrology plays a less significant role than the depth to the bedrock or slope angle. This observation might be taken into account in subsequent landslide susceptibility analyses undertaken by GSI.

The size of average shallow slide provides limited volume of deposit for run-out. However, these run-out can in places also reach the length of several hundred meters. This typically occurs on steep and uniform slopes with little or no vegetation (frequently with a thin surficial blanket peat layer) or other kind of obstacles. Slopes like these are characteristic to sides of glacial valleys. The deposit is spread very thinly over a long and laterally confined area (Figure 9). As such it is very exposed to being gradually washed out by successive rainfall, more details on this topic will be presented later in this report. Many shallow failures actually exhibit very short run-outs, due to a combination of small size of source area (and subsequent small deposit volume) and characteristics of terrain such as concave slope form (at the base of hillslopes), hollows, vegetation, etc. This significantly decreases their potential impact to infrastructure and society if source area is not located directly next to the element at risk which is, for example, the case at steep road cuttings. However, evidence from several historical failures shows that the length of run-out and potential impact can be multiplied if the source area is located next to the existing stream. Water in the stream enables rapid transport, and hard and dense till particles (especially embedded boulders) easily erode stream sides, leading to entrainment of additional material on the way downward. The combination of high velocity and significant total mass of the debris material being transported by water creates high impact forces which can have devastating effects. A prime example of this is the collapse of Lennaun Bridge in July 2007, caused by a debris impact of landslide of a typical large but by no mean exceptional size. The landslide's source area and flow path are shown on Figure 10.

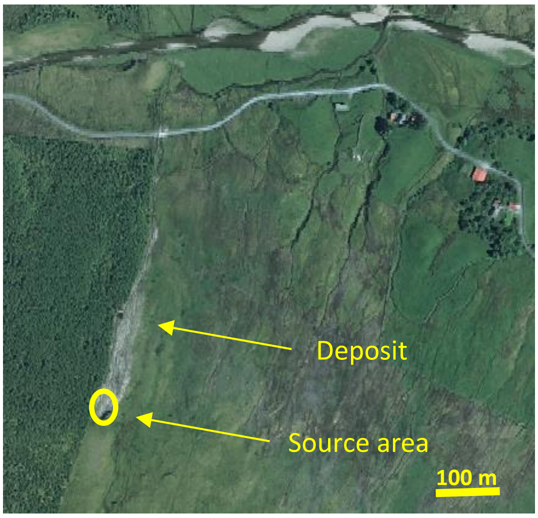


Figure 9 Typical deposit path from shallow translational slide in till (source: Google Maps)

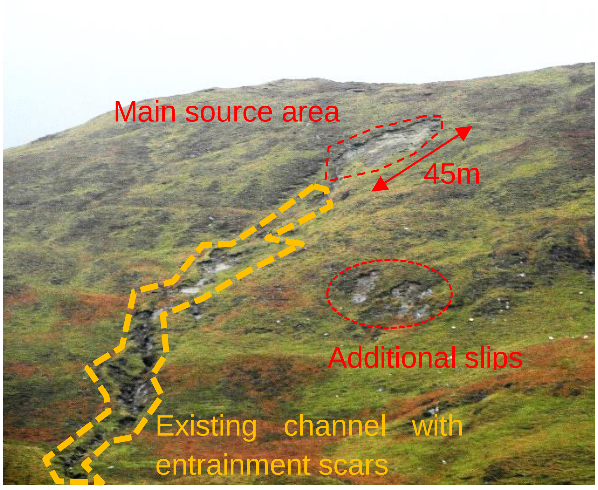


Figure 10 Source area and upper part of stream of the July 2007 Leenaun shallow landslide

3.2.2 Issues with inferring the landslide material from the existing maps

Quaternary deposit (subsoil) maps developed by GSI give excellent information on Irish soil cover, particularly the dominant type in the top 1 m below ground level. This is of clear significance for the understanding of Irish landslides, as the vast majority of them are shallow and controlled by surficial features. Provision of maps in shapefile format enables easy automatic identification of surficial soil type on the landslide location using GIS. Indeed, soil type is one of the rare categories available for almost all landslides in the national landslide inventory.

Knowing the soil type can give an indication of the type of failure likely to occurring within the soil mass. For example, in peat terrain, peat slides should be expected, while on areas designated as 'Rock on surface' (or 'Bedrock outcrop') only rock failures (rock falls/slides/topples) should be expected due to the absence of overburden. However, GDG's experience from on-site validation exercises have shown a significant discrepancy between the failure type expected based on soil maps and what was observed onsite. It was manifested in landslide types occurring on the locations where they should technically not be possible. This observation was usually discovered at the final stage of project, when the confirmed landslides have been placed in the GIS shapefile layer that was then interrogated for the summary of the discovered landslides characteristics. This discrepancy has also been noted in previous rounds of inventory population project. In this project it was checked in more detail and described.

One of the most easily identifiable issues was the presence of shallow landslides and debris flows on the terrain that was mapped as 'Bedrock outcrop'/'Rock on surface'. An example is shown in Figure 11. These landslides developed in thin surficial colluvium layers, with the failure plane developing either on the bedrock/soil interface or (less often) through the soil. The landslides have most probably been caused by rainfall infiltrating through the thin soil layer to the much less permeable bedrock and subsequent build-up of the soil water pressure from the rock/soil interface upwards. In cases this was aided by the exiting streams. The soil cover in these areas is extremely thin (less than

1.0 m), prompting the map to describe the area as bedrock at surface, owing to the definition of quaternary deposit map as showing the *dominant* type in the uppermost 1 m. In these cases, the rockfall would be expected, so a presence of shallow soil slides with vastly different trigger, size and run-out may pose serious repercussions in accuracy of future landslide, hazard and risk maps in such areas.

The frequency of this issue can be inferred from the summary statistics from West Galway study area covered by GDG in 2014. The simplified statistics in Figure 12 show the breakdown of landslides by landslide mechanism type, and the breakdown by soil type extracted from GSI subsoil map. The breakdown shows that while over 51% of failures occurred on the area mapped as 'Bedrock outcrop', only 15.8% of reported failures were actual rock failures (rock falls/slides/topples). The rest is attributed to earth slides and debris flows, which are also largely present at 'Scree' soil type. The difference clearly shows the scale of this issue and calls for potential further examination of soil maps used as factors in landslide susceptibility analyses. It should also be noted that landslide mechanism breakdown was made using the population of 76 positively validated landslide, while soil type was made using the population of 104 landslides (positively validated plus new) so minor discrepancies arising from this are possible.

Figure 11 Shallow soil slide on soil mapped as 'Bedrock outcrop' (source: GSI)

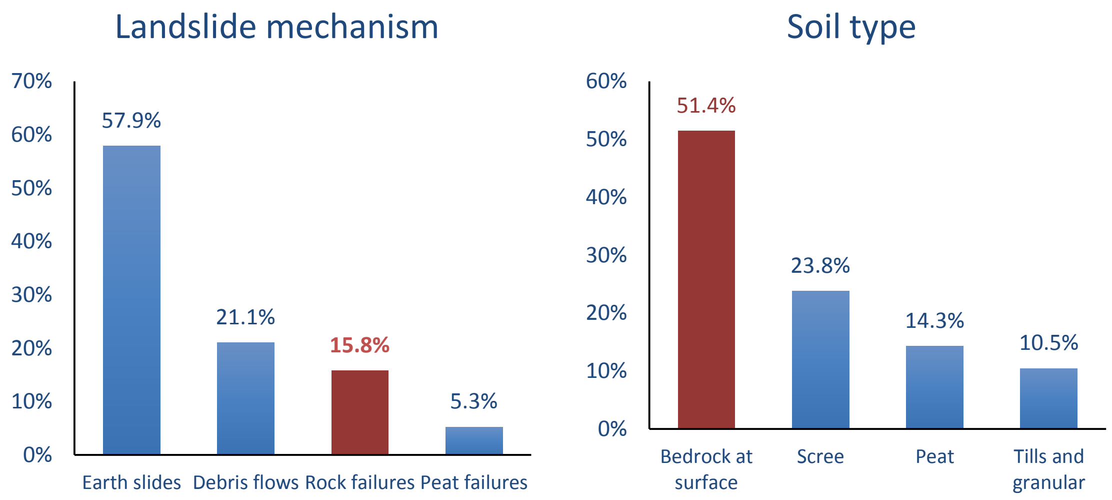


Figure 12 Breakdown of landslide mechanism and soil type for landslides recorded in West Galway study area

Similarly, landslides occurring on areas designated as having peat cover do not always manifest as typical peat slides/flows with flow like behaviour, large areas involved and very long run-out even on gentle slopes, as was observed at Derrybrien in 2003 and Croaghcullion in 2008. The majority of the slides occurring on the thin blanket bog covering the upper, steeper parts of hills actually exhibit the characteristics of minor shallow earth slides, see examples in Figure 13. An in-depth analysis of some of these slides (Long 2006, (Dykes & Warburton, 2007) showed that in this case the failure plane is actually developed i) through mineral soil (typically till) and/or weathered rock existing between top peat layer and bedrock, or ii) directly on the mineral soil / bedrock interface. This implies that the peat layer and its geotechnical shear strength characteristics do not actually play a major role in these cases, which explains the translational earth slide –like behaviour of these events. This particular type of peat-related failure has indeed been observed and classified by Dykes and Warburton (2007)as a separate peat failure type in their classification scheme of peat failures, where they were named ‘peaty-debris slides’. These slides are described as “shallow translational failure of a hillslope with a mantle of blanket peat in which failure occurs by shearing wholly within the mineral substrate and at a depth below the interface with the base of the peat such that the peat is only a secondary influence on the failure”. Due to these reasons, slides are often recorded as translational earth/debris slides in literature (Long 2006, 2011) and in the inventory population projects. These type of failures appear to be especially abundant in mountainous regions of Ireland due to the geomorphology of glaciated valleys and very thin peat cover at places, which is nevertheless mapped as ‘Blanket peat’ soil cover on subsoil maps. As peat slides and translational earth slides have very different behaviours and consequences, as described earlier in this report, it might be beneficial to increase the level of detail when dealing with expected landslides in these areas, i.e. in preparation of future susceptibility, hazard and risk maps. Some suggested ways forward might be to introduce peat depth as an additional factor, or to reclassify the recorded peat failures according to detailed peat failure classifications such as Dykes and Warburton (2007).

Figure 13 Examples of shallow earth slides on the terrain with "Blanket peat" soil cover mapped

It should also be mentioned that the slide surface at most peat failures is most probably complex and not just composed of one type, especially for bigger slides, which makes classification difficult.

Part of the problem in assigning the correct soil type to each landslide is that borders between soil types are approximate due to the scale of the soil mapping exercise, but this is out of the scope of landslide inventory and hazard/risk mapping issues.

In summary, as the current (and all other potential) landslide susceptibility analyses include soil cover as one of the most important conditioning factors, the results might be influenced by these observations. Furthermore, if in future there will be separate susceptibility analyses for each mechanism (peat failures, earths slides, debris flows, rockfalls), as is recommended in scientific literature, then actual landslide types might not be correctly observed for specific areas. More detailed investigation on this thematic is recommended.

3.2.3 Temporal fading of landslide features on aerial imagery

During aerial image processing (first step of landslide inventory population) and validation through subsequent fieldwork (second step), different types of landslides were found to exhibit very different levels of visual clarity when viewing aerial images and as a result there was a significant difference in the recognisability of some landslides. This is particularly noticeable when viewing older sets of aerial images, suggesting that the temporal processes that obscure landslide features over time can have a dramatic impact on identifying older failures and subsequently on the number of discovered landslides. This was particularly visible when comparing peat slides/flows and shallow earth slides in GDG's four study areas.

Peat slides in Ireland, although mostly having relatively similar failure depths as shallow earth slides, tend to be easily identified during aerial imagery processing due to clear features. Apart from their usually large size, some of the main characteristics they exhibit are clearly outlined boundaries, presence of multiple rafts of peat floating on the landslide area and clearly defined tension cracks on or behind the crown. Figure 14 shows a representative example of two large peat flows situated in Slieve Bloom mountains study area.

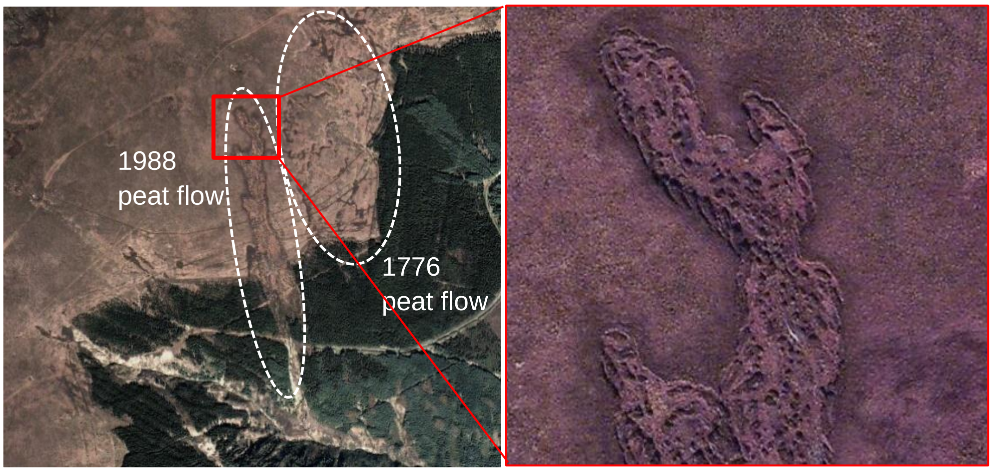


Figure 14 a) Aerial image of two bogflows in Slieve Bloom study area, b) close up of 1988 bogflow crown (source: Google Maps and Bing Maps)

Another defining feature of peat slope failures is the longevity of these characteristics. A common lack of diverse vegetation in blanket bogs that could obscure the landslide features, and a very slow rate of peat regrowth (Keddy , 2010; Lamb , 1977) ensure that peat failures are easily identified in aerial imagery in the decades and even centuries after they happened (Figure 14).

During the aerial imagery processing, shallow translational slides were largely recognized thanks to extensive deposit areas downslope from the failure scars. During the subsequent fieldwork (November 2014), it became clear that many of the sediment deposits that were clearly seen on aerial imagery dating from 2010 had been completely washed out by surface runoff and subsequently revegetated. The source areas of these landslides were much more difficult to recognise without adjoining deposits due to (i) their relatively small size (100 – 500 m^2), (ii) earth colour that matched those of surrounding low grass and moss vegetation, and (iii) a widespread lack of taller vegetation in the general area which, when swept out by the slide, usually serves as a first indicator of the slide. Considering that these historic landslides that were once clearly identifiable are now difficult to confirm even when standing in the known location of the slip, suggests that identifying older shallow translational failures from aerial imagery is an even more challenging task. This suggests that shallow landslides that are not identified quickly after the event are likely to be missed in subsequent inventory development due to the rapid obscuring of the landslide features in the immediate years after the failure.

In general, failure to identify all possible shallow landslides through aerial imagery processing might result in slightly skewed results of subsequent landslide susceptibility analysis. This is not considered a major problem because there is a large number of identified shallow landslides used for the creation of the existing susceptibility map. However, hazard assessment might be subject to larger errors, due to possible miscalculation of return periods and following probabilities of failure. That is especially applicable to areas with perceived relatively low density of landslides such as the study areas covered so far.

To avoid this issue in cases where multiple aerial imagery sets in close temporal succession are not available, time intervals between photo sets should be determined to be at least shorter than the 'deposit fading' period typical for the study area. This time frame will depend on the average landslide soil area and depth (and thus deposit size), terrain characteristics and rainfall characteristics of the study area. For Western Ireland, the deposit fading period is loosely determined to be less than four years, as evidenced by total disappearance of deposit layers exceeding 100 m length within that period. This rapid deposit receding rate can be attributed to several factors which include the shallow nature of the deposit layer (<0.3 m) caused by small average size and depth of landslides in the area, frequent rainfall, presence of many surface drainage lines, uniformity of terrain and a lack of major obstacles (surficial hollows, resistant vegetation).

A detailed example of analysis of reduction of a visible landslide deposit area is given in Figure 15. The deposit area of landslide (landslide ID 1805 in Irish Landslides Database) has been examined through several aerial imagery sources from different dates, including sets provided by Ordnance Survey Ireland and open sources such as Google Earth or Bing Maps. The landslide occurred in the townland of Poundcartron in Maumturk mountains in Connemara, and was characterised as a large shallow rotational slide in glacial till, although the soil map indicates bedrock at surface. The outline of the deposit area observed for each period clearly illustrates the receding trend. Possible explanations on why the lowest part of deposition area was erased first include very small deposit thickness at this location due to the distance from the source, and its position on a low lying river terrace susceptible to seasonal flooding from Bealnabrack River. Likewise, the still visible patch of deposit directly below the landslide scar might be caused by more significant initial sediment depth and continuing erosion of the exposed backscarp.

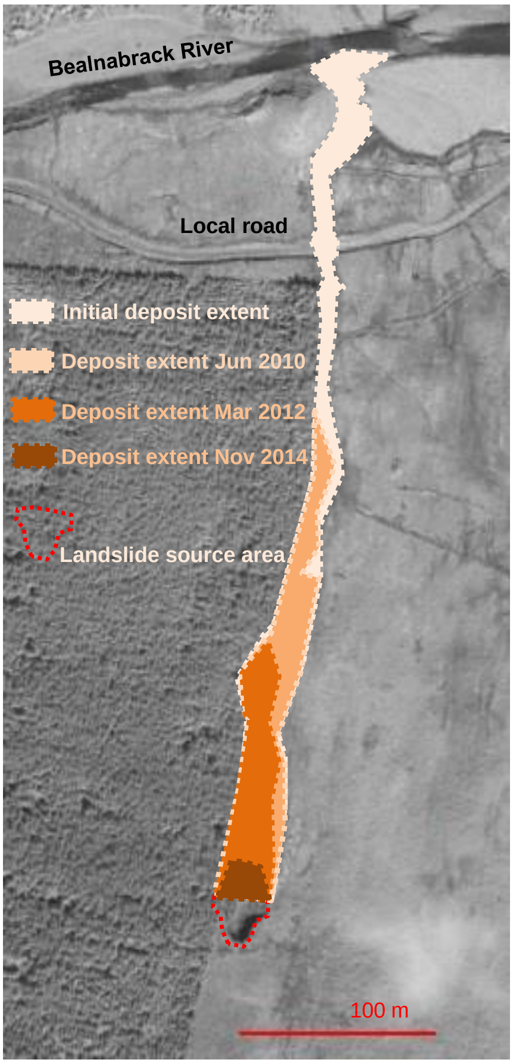


Figure 15 Deposit area of landslide 1805 through time (background image source: Google Earth)

One reason for the prevalence of shallow transitional earth slides among the landslides that rapidly loose identifiable features is the very shallow position of bedrock and often abrupt change from competent bedrock to soil, with little or no weathered rock layers in between. This in turn makes deep and large landslides that could be easily identified on aerial imagery extremely rare.

3.2.4 Additional analyses

Some additional analyses were carried out to interrogate the effect of landslide location. Three different study areas were examined and compared: i) SW Donegal, characterised by varied terrain including a combination of steep glacial valleys and gentle hills; and extensive peat cover in combination with till coverage and exposed bedrock; ii) Slieve Bloom, low lying rounded hills characterised by deep peat cover; and iii) South Tipperary, characterised by numerous very steep hills with exposed bedrock.

Figure 16 presents the scatter plot of elevation and slope angle for each recorded landslide point in the area. The absolute value of elevation itself does not offer the full picture as it depends on the general elevations of the study area. However, combined with the knowledge of the study area morphology, some interesting observations can be concluded. For example, the majority of landslides in Slieve Bloom are initiated in a tight range around 450 m of altitude and with slope angles between 5^{o} and 12^{o}. Observing the study area, this corresponds with the locations where relatively flat tops of the hills (with elevation between 450 and 500 m) with deeper peat cover make a convex break into the steeper hillside. These particular locations are therefore extremely susceptible to peat slides.

High peaks of Galtee, Knockmealdown and Comeragh mountains are responsible for the distribution of landslides in South Tipperary study area that sees landslides predominantly initiated on elevations between 500 and 800 meters. However, unlike at Slieve Bloom, majority of landslides are initiated on relatively high angles of over 30^{o}. Given the prevalence of rock falls/slides/topples and the associated debris flows documented in the area, it can be concluded that steep (occasionally sub-vertical) rock outcrops and cliffs at the higher reaches of the ranges are the most susceptible to failures. It should be noted that the actual slope angles at source points are most probably higher than reported in Figure 16, as 20mx20m DEM used for extracting data averages the values found across the pixel, thus often underreporting sub-vertical areas.

The distribution for the SW Donegal study area with its varied terrain was used to check and validate the conclusions from the previous two areas. Indeed, the distribution is quite evenly spread, which translates well to multiple different terrain features and landslide mechanisms recorded in the area.

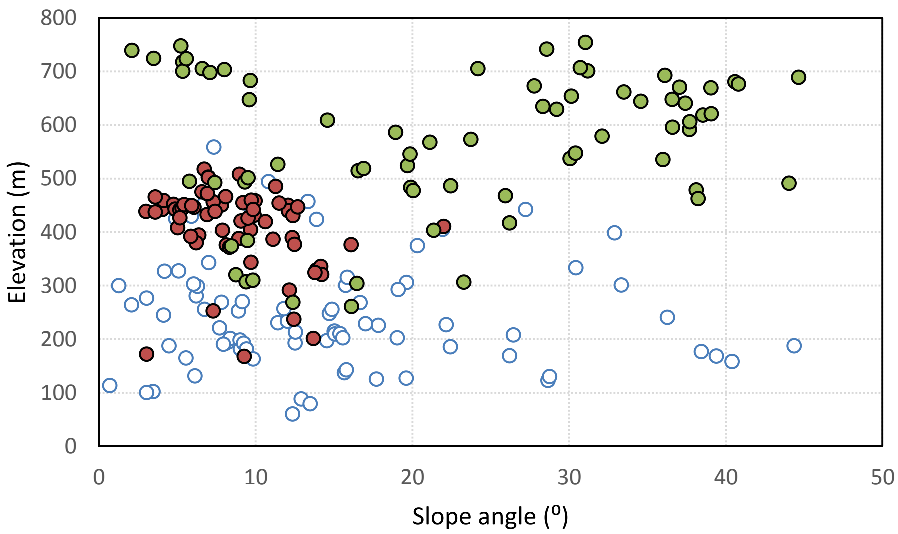


Figure 16 Summary of distribution of elevation and slope angles for the landslides in three study areas: SW Donegal (empty), Slieve Bloom (red) and South Tipperary (green)

3.2.5 Landslides affecting local road infrastructure

Transport infrastructure is the type of infrastructure most susceptible to landslides in Ireland due to its extents and reach in various areas including hilly terrains. Another reason is the existence of numerous man-made cuttings and embankments, often aged and installed using poor design and/or construction techniques, making them susceptible to failure. Media reports of blocked transport infrastructure, particularly local roads, are ubiquitous, especially following strong winter storms. While these events seldom cause serious physical damage to the infrastructure, the blockage of roads until the debris is cleaned or remediation actions carried out causes significant delays and indirect costs to local community. Furthermore, these events have the potential to cause direct damage and fatalities if the soil mass strikes a vehicle or vice versa.

While major peat and earth slides with long runouts that affect the road infrastructure can usually be easily identified through aerial imagery, the vast majority of slides that caused temporary road blockages are small failures occurring directly adjacent to roads. Analysis of landslides identified by GDG has shown that these slides were very seldom identified during aerial imagery phase of landslide inventory population. The reasons for this were mainly the very small size of these failures, and the complete clean-up of the deposit by local authority immediately after the failure. Some recent and well-defined slides were incidentally identified during the on-site validation phase, however it is assumed that the number of these slides is much bigger than reported. Underreporting these slides might lead to significant errors in the susceptibility analysis. As these slides on near-road areas yield serious consequences, it might lead to unacceptable underestimation of risks.

A good example of these slides was observed in the northernmost 3 km section of regional road R336 just south of Leenaun, Co. Galway, where slopes adjacent to road were composed of glacial tills and glaciofluvial sands and gravels. The west side of the road is cut into the base of a relatively steep till ridge with average slope angle varying between 30° and 45°. This natural slope is in places steepened by artificial sub-vertical cuttings (maximum height of 1.5 m) positioned directly next to the road. The natural slope face in this section exhibits many very shallow translational earth slides in sizes ranging from 5x5m to 20x20m with the spacing between two neighbouring landslides sometimes as little as 20 m. The landslide toes were observed to be always on or near the road level, suggesting that the road construction is an important factor in initiation for these landslides. The sliding distance seems to be limited to the range of a few decimetres. That might be attributed to two things: first, the hard layers of road surface prevent further slip of the solid landslide body. Second, very low height of the ridge (up to maximum 25 meters) mean that there is no upstream water-contributing area which can cause full saturation of downslope soil and subsequently transform soil slips into mobile debris flows. No deposit on the road was noticed at the time of inspection. This suggests that the landslide occurrences are old and/or that the local authority responsible for road maintenance is familiar with the issue. However, the sliding is very likely to repeat, especially during and immediately after heavy rainfall, which when coupled with the limited clearance between the slope and the traffic lane, can cause some material to be spread directly in the line of traffic, posing a serious threat to oncoming drivers. The road is unlikely to be damaged due to the small magnitude of the event, but the consequences for road users, and thus the indirect risk, are deemed very high.

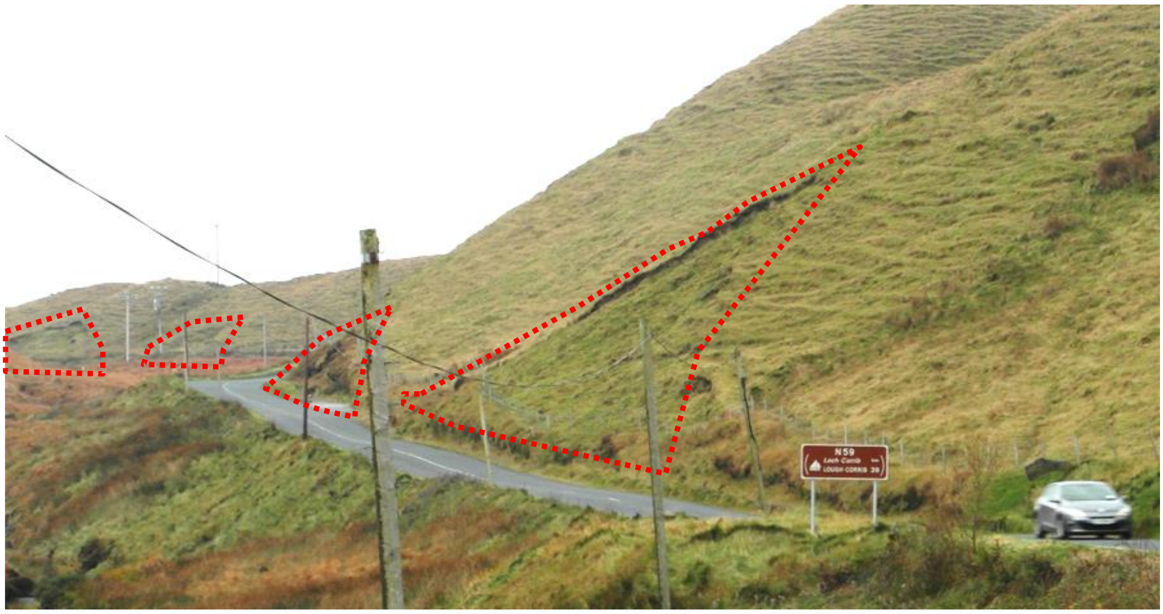


Figure 17 Shallow landslides along the regional road R336 in Co. Galway

The fact that these small landslides without visible run-out could not be identified during aerial imagery processing suggests a need for in-depth fieldwork analysis in the areas immediately adjacent to at risk infrastructure elements. It is recommended that a thorough review of local news reports is carried out as part of this process as some old slides might not be easy to identify. Another proposition for accounting for these slides is to introduce the additional factor 'distance to roads' in the future susceptibility, hazard and risk analyses.

4 Analysis of soil behaviour

This section gives a short overview of soil behaviour studies relevant for landslide assessment in Ireland. It is focused on shear strength and permeability characteristics of soils as these are the two of the most important geotechnical parameters contributing to the behaviour of soil masses. As peat and glacial till are identified as the two soil types most associated with landslides in Ireland, this section is focused on these soils. This section provides an overview of findings of previous research into these soils in Ireland.

The literature overview resulted in identification of knowledge gaps, or the soil behaviour topics that should be studied in more detail in order to gain more insight into landslide initiation processes in Ireland. The gaps identified here also form a suggestion for further investigation of soils and landslides in Ireland.

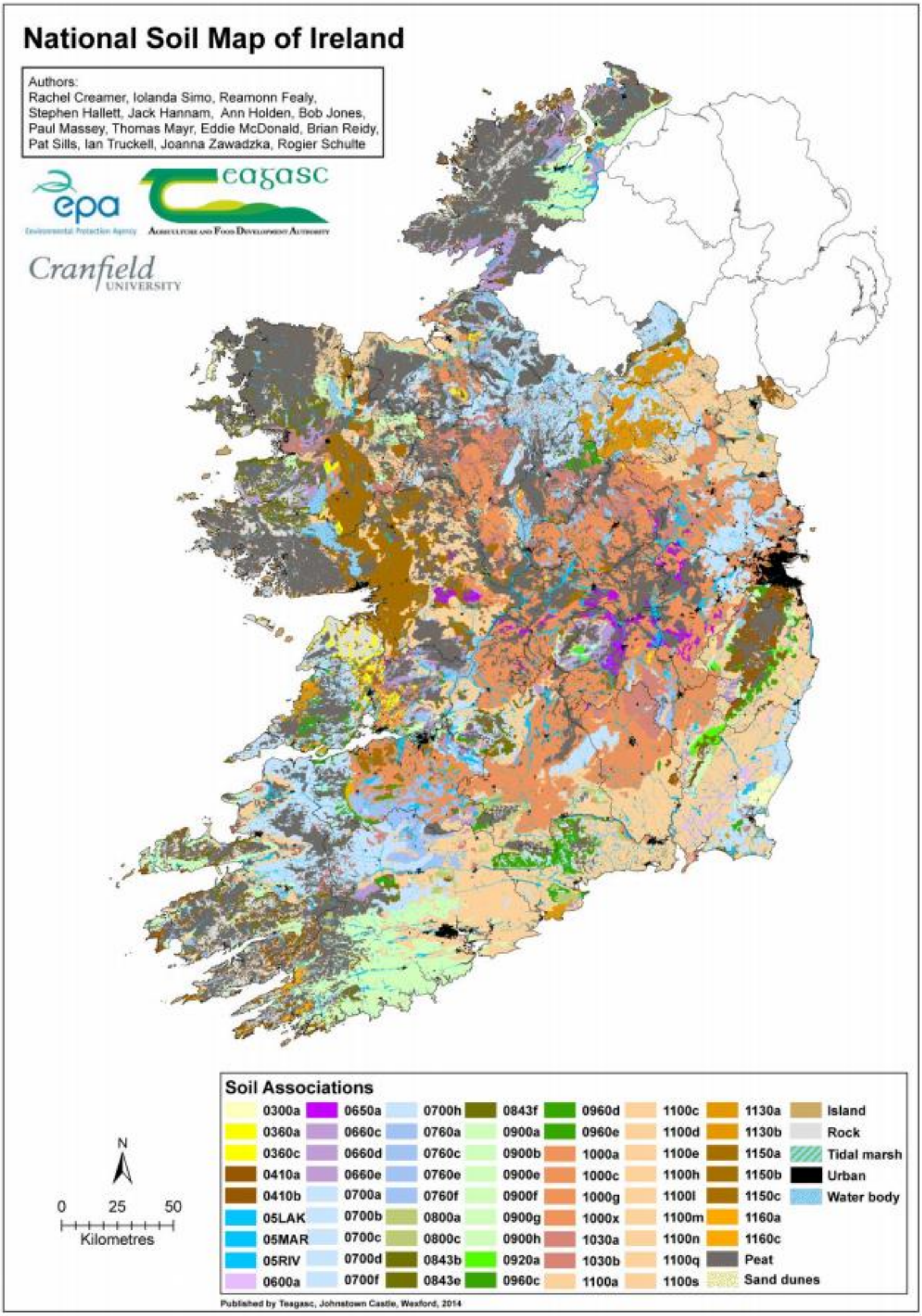


Figure 18 National Soil Map of Ireland (Simo, et al., 2014).

4.1 Properties of the soil

4.1.1 Peat

It can be seen in Figure 18 that Peat is widespread across Ireland. A large percentage of observed landslides occurred within peat deposits (for example 44% presented in Mouchel report (2011), which is similar to other studies). Given the portion of landslides that occur in peat, it is important to understand the soil parameters of this material in order to predict and control potential landslides. Precise identification of the peat parameters, such as shear strength is extremely difficult due to it`s organic origin (Long, 2005), as well as it`s fibrous structure (Long, 2005; Hebib, 2001). In addition to that, the applicability of site and laboratory investigation methods usually used for mineral soils is dubious (Long, 2005).

Peat is a highly organic soil type formed from decaying of plants and vegetation rich in carbohydrates to humus, a process known as humification (Timoney, Quigley, McCabe 2012). Peats can be classified into three simple categories in terms of their degree of humification (Hártlen, 1996):

(a) Fibrous peat which has a low degree of humification. This form will have a distinct plant structure and will produce a brown to colourless cloudy to clear water when squeezed.

(b) Pseudo-fibrous peat has a mid to high degree of humification. The plant structure is now less identifiable and a mushy mass will be extruded when squeezed.

(c) Amorphous is the classification used for the most highly humified peat. Very little, if any, of the plant structure remains and on squeezing no free water is released.

Mangan (1994) presented a simplified method of classifying peat, introducing fibrous, semi – fibrous and amorphous peat (Long, 2005).

Peat has a high-water content, is highly compressibility, non–homogeneous, has very low in situ stress and a low bulk density (typically 10-12 kN/m^3) (Boylan & Long, 2013). These properties make the behaviour of Peat very difficult to predict.

Organic content of Peat is very high, typically ranging from 80 to 99%. Moisture content is also typically very high and can often be many hundreds, even thousands of percent (Timoney, Quigley, McCabe 2012). The moisture content tends to reduce with increasing degree of humification of Peat.

Shear strength of peat is typically very low (generally 2kaA to 15kPa). This is a particularly important parameter in the assessment and modelling of Peat stability. A trend between moisture content, degree of humification and shear strength (both drained and undrained) of Peat was discussed by Long (2005) and is illustrated in Figure 19.

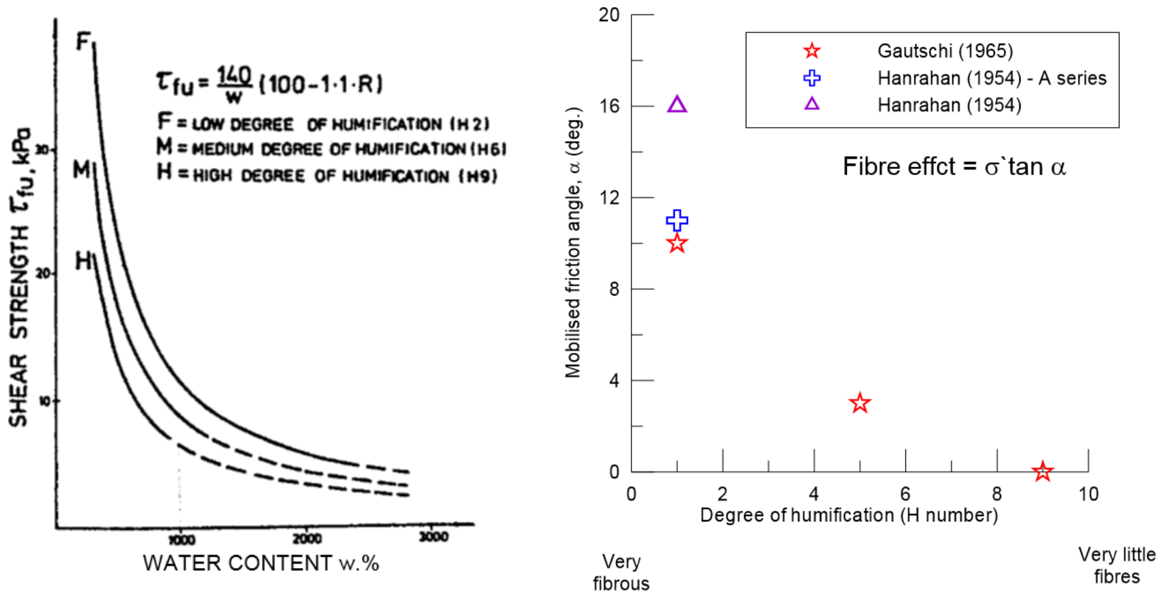


Figure 19 Trend between Shear Strength, water content and degree of humification (Long, 2005)

It was observed by various researchers, that there is an inconsistency in peat shear strength, depending on the test that was performed (Hebib, 2001; Farrell & Hebib, 1998). This is summarised in the below table.

Parameter/test	Description of test variables/ Findings
Friction angle, ϕ'	Friction angle obtained from triaxial test has the greatest value, whereas values obtained from Direct Shear, Direct Simple Shear and ring shear are decreasing.
Triaxial test	Results were overestimated because of the fact that peat is composed out of fibres, which may act as a reinforcement
Direct Simple Shear	Results are underestimated (but may represent the peat matrix in the most reliable way). This is caused by the orientation of the peat fibres – in the DSS test fibres are parallel to the shearing direction (Hebib, 2001)
$\frac{s_u}{\sigma'_{v0}}$	Relationship is non- linear and higher that in case of mineral soils Relationship of the laboratory test results are lower than field vane test

Long (2005) further illustrated this point by comparing shear strengths from various in-situ and laboratory tests on a blanket bog in the west of Ireland. This is shown in Figure 20.

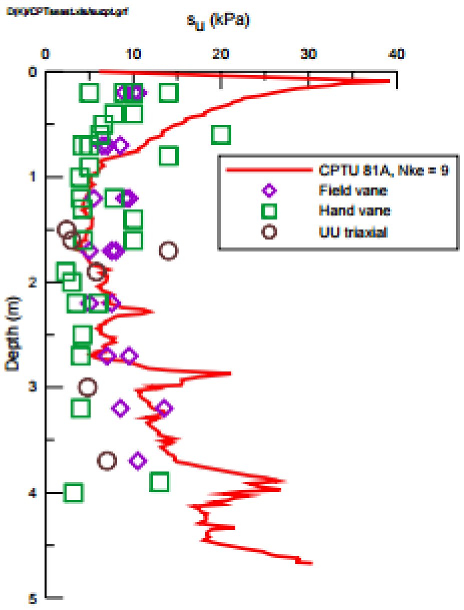


Figure 20 CPTU in blanket bog site in Western Ireland (Long, 2005).

4.1.2 Irish Glacial Tills

Failures within Glacial Tills are the second most common reason for landslides in Ireland according to Mouchel report (2011). Unlike peat, Irish tills are mineral soils, therefore their behaviour is easier to model and test.

Irish Tills deposited on land by The Irish Sea Glacier (McCabe, 2008) can be found in the soils across the country (Skipp, 1994). Glacial deposits usually are characterised as medium dense to dense with high content of gravels, cobbles and boulders (Long, et al., 2013 ; Skipp, 1994). Weak lenses of silt and sand can be found within this soils (Skipp, 1994).

The natural moisture content of tills is much lower than Peat. The moisture contents recorded in the below table range from 11 to 24 %. The bulk density of tills is much higher than Peat, typically in the range (18 to 22 kN/m^3).

Tills have higher shear strengths and stiffness than Peat. It can be seen from Figure 22 below that the shear strength can range from 20kPa to over 400kPa depending on depth, location and test method. Figure 21 illustrates that a wide variety of field stiffness have also been recorded depending on the location, and hence depositional environment, of the till.

Site Location	<63 µm (%)	LL (%)	PI (%)	Nat. Moist (%)	Till T (m)	SPT N	Load/ Fill Ht (kPa*/ m)	Settle ment (mm)	Field		
									E_v (MPa)	t_{95} (wks)	c_v (m^2/yr)
Tallaght, Dublin	39	24	10	10	3(1)	55	1015*	12.8	84	16	30
Dublin Port Tunnel	40	28	13	10	31	55	100-170*	6.3	553	6	
M9 Kilcullen SP1	33	23	9	12	5.3	6	6m	49	10.8	5	16
M9 Kilcullen SP5&6	32	25	6	11	5.2	8	8.5m	95	7.7	4	20
M7/M8 20+090	42	25	9	17	3.7	30	7.3m	32	14.1	26	8
M7/M8 22+800 to 22+950	46	28	6	16	3.5	4	6m	27	13.3	12	15
M7/M8 23+200 to 23+600	45	24	9	15	10.8	22	5.9m	37	30.7	26	66
M7/M8 27+200 to 27+300	29	22	9	14	9.5	25	3.7m	35	16.6	33	40
M7/M8 27+770 to 27+870	29	20	8	14	10	20	8.9m	26	56	21	70
A2 Shore Rd S		45	24	21	4.8	29	8.9m +1.2m	55	14.7	42	8
A2 Shore Rd N	44	43	22	24	5.5	34	6.4m +2.9m	65	13.1	36	12
M6 Athlone WB Roundabout		36	14	22	2.2	12(2)	10.5m	65	5.9	14	5
M6 Athlone Link Rd	95	31	14	18	3.2	8	5.7m +1.0m	55	6.6	14	11
M6 Athlone WBD	21	25	8	14	3.5	19	7.4m	60	7.1	22	8
Limerick Tunnel Clonmacken	36	34	14	18	6.2	13	3.0m +2.0m	78	6.9	39	14

Figure 21 Summary of Glacial Till Classification and Field Test / Monitoring Results (Buggy & Kissane, 2016).

Buggy and Kissane (2016) present an overview of properties of till derived from in – situ site investigations on various Irish development projects. It can be seen from Figure 21 that the geotechnical properties of a glacial till are variable properties and highly dependent of their deposited area.

Saturated permeability coefficient K_s is typically reported to be in the region of $1x10^{-11}$ to $1x10^{-8}$ in case where there is no permeable sand layers present in the soil. However Hughes et al. (2016) reported the saturated permeability of $1x10^{-6}$.

Figure 20 below presents the properties of the Dublin Boulder Clay. This soil is an example of a stiff to very stiff Irish till (Skipp, 1994) and over the years it has been well described and tested.

Peaks and dips visible on the CPT test result presented in Figure 22 are caused by the high stone content as well as various lenses containing sand and gravel (O'Kelly, 2014). Figure 23 presents typical parameters for this Till (Lehane & Simpson, 2000).

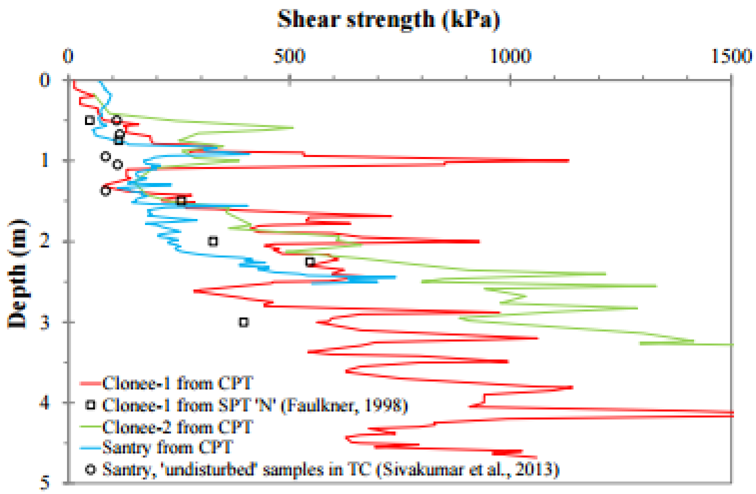


Figure 22 Strength profiles measure in triaxial compression (TC) and inferred from CPTu (N_{kt} = 15) and SPT data (O'Kelly, 2014).

Bulk density (kN/m^3)	21.5±0.5
Global water content (%)	11±3
Liquid limit (%)	25±4
Plastic limit (%)	14±2
Plasticity index (%)	11±2
Liquidity index	–0.2±0.03
Clay fraction (%)	15±5
Gravel fraction (%)	30±5
Permeability (m/s)	1×10^{-11} to 1×10^{-8}
Coefficient of consolidation, c_v (m^2/year)	40±20
Preconsolidation stress, σ'_{vy} (MPa)	1.3±0.3
In situ OCR	8–30
λ (reconstituted, intact)	0.04, 0.030±0.005
κ (reconstituted, intact)	0.008, 0.004±0.001

Figure 23 Typical properties of Dublin Boulder Clay (Lehane & Simpson, 2000).

4.2 Knowledge gaps

Conclusions from the section above show that Irish peats and glacial tills have been tested and described in various studies, with relatively well-determined classification and saturated shear strength behaviour. However, previous sections have drawn the conclusion that the majority of landslides identified across Ireland are related to surficial rainfall infiltration characteristics. Glacial tills in particular rely on the near-surface negative pore water pressures (suctions) in maintaining the stability. The role of unsaturated seepage characteristics is thus very important. However, there is a lack of information on unsaturated parameters in literature when it comes to Irish soils. The parameters that would be particularly beneficial for Irish geological and geotechnical community in modelling rainfall infiltration and sliding processes are outlined below.

1) Saturated permeability of surface layers.

Coefficients of saturated permeability reported for glacial tills usually come from testing of undisturbed samples taken from different depths. In general sampling too close to surface is avoided in order to avoid the 'disturbing' characteristics of tension cracks, vegetation roots, soil structure weathering, etc. These features can increase the 'normal' saturated permeability by several orders of magnitude. However, for rainfall induced shallow landslides which form the vast majority in Ireland, the surficial permeability that takes account of all these features is of much importance as the failure plane is frequently positioned in this 'disturbed' zone. Furthermore, the downward path of the wetting front created by rainfall infiltration goes from surface through this zone and is likely influenced by tension cracks that can act as a bypass to deeper layers. This also means that the concept of uniform saturated permeability might not be applicable. However as a start, the reliable range of saturated permeabilities for the surface should be determined and used when modelling shallow failures.

Looking specifically at Irish glacial tills, saturated permeability coefficient K_s is typically reported to be in the region of $1x10^{-11}$ to $1x10^{-8}$ in case where there is no permeable sand layers present in the soil. However Hughes et al. (2016) reported the saturated permeability of $1x10^{-6}$ for a surface layer of a road cutting in Northern Ireland. While this gives an indication of the preliminary values, more investigation is needed to give additional data on this characteristic.

2) Unsaturated parameters

Negative pore water pressures, or suctions, depend on the levels of water content relative to the maximum water content in the soil. The lower the water content in the soil is, the larger the suctions are. These suctions give an additional component to soil's shear strength, as described in Fredlund et al. (1978). However as these suctions fluctuate depending on water content which is influenced by infiltrated rainwater, slope stability depends directly on rainfall infiltration speed and capacity. These two features are an intrinsic characteristic of every soil and depend on soil particle size, void size distribution, soil skeleton composition and other parameters. In general, soils composed of small particles can generate larger suctions thanks to capillary forces.

The relationship between water content and suction is defined by a soil-water characteristic curve (SWCC). An example of different SWCCs are presented in Figure 24, and a typical SWCC for a glacial till site in Canada is given in Figure 25. SWCC can be determined in the laboratory on a sample cleaned of larger particles such as cobbles (which then gives more precise measurements but does not present the actual state of the soil in-situ), or on site using moisture sensors and tensiometers, which tend to give more coarse results. Once the SWCC is known, the unsaturated permeability curve can be derived from it (permeability decreases with the increase of suction).

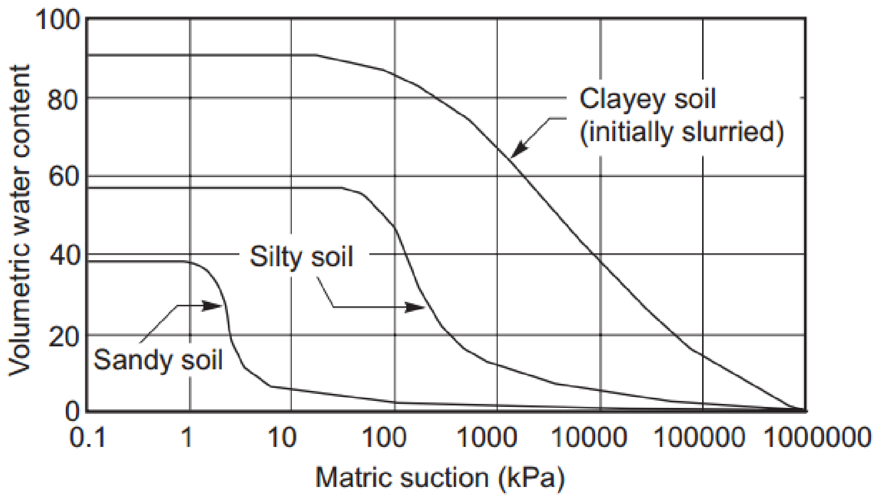


Figure 24 SWCC for three different soil types (source: (Fredlund & Xing, 1994))

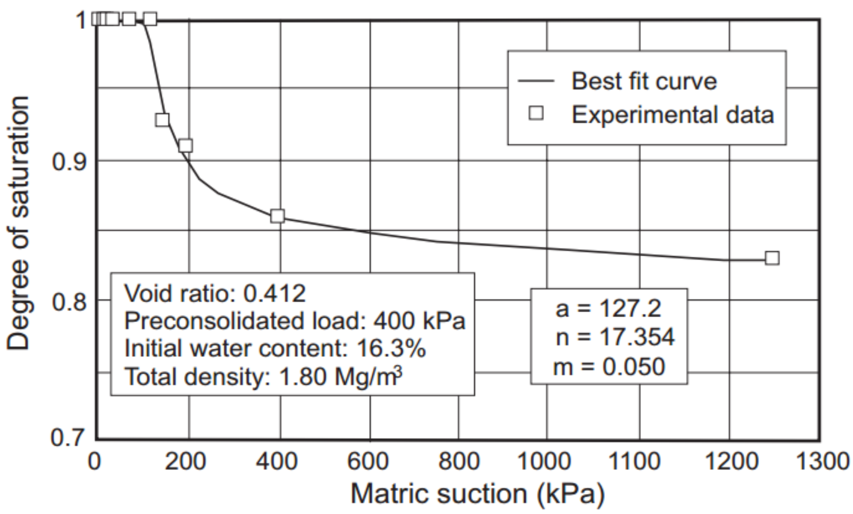


Figure 25 SWCC for a glacial till site in Canada (source: (Fredlund & Xing, 1994))

While SWCCs are well established for some glacial tills in Canada (Fredlund 1978, (Fredlund & Xing, 1994), Vanapalli et al. 1999) and there are examples available for glacial tills in UK (Toll et al. 2015), no research on SWCCs for Irish glacial tills have been carried out to date. This information would significantly improve the modelling and assessing of shallow landslides in Ireland.

5 Analysis of rainfall trigger thresholds

For rainfall induced landslides, the frequency of the triggering rainfall events may be used to indirectly describe the temporal aspect of landslide hazard (Corominas, et al., 2014). Critical triggering rainfall events can be described using rainfall thresholds. For rainfall induced landslides, the threshold is usually expressed as a minimum level of a combination of rainfall parameters that needs to be reached in order for a landslide to occur (Reichenbach, et al., 1998). Rainfall thresholds can be developed i) physically, based on numerical models (Iverson, 2000; Salciarini, et al., 2006) or ii) empirically (statistically), based on analysis of historical landslide events and accompanying rainfall. In relation to natural slope failures, empirically derived thresholds are particularly prevalent, with many examples found throughout the literature (Guzzetti, et al., 2007; Caine, 1980; Dahal & Hasegawa, 2008; Dahal & Hasegawa, 2008; Brunetti, el al., 2010, Guzzetti, 2008.)

While there is abundance of local, regional and national rainfall threshold available for different parts of the world, no thresholds have yet been developed for Ireland. In this section, preliminary rainfall thresholds for landslides on natural hillslopes in Ireland are developed based on the available data of landslide failures and accompanying rainfall data obtained from The Irish Meteorological Service.

5.1 Background

Various types of rainfall thresholds exist depending on measured rainfall characteristics/parameters used. Guzzetti et al. (2007) grouped the empirical thresholds into thresholds that use precipitation data describing a critical rainfall event, thresholds that include the antecedent conditions, and others. In the first group, the most common types of rainfall thresholds are identified as intensity-duration (ID) thresholds, thresholds based on the total event rainfall, rainfall event-duration (ED) thresholds and rainfall event-intensity (EI) thresholds. These are also often further normalised using mean annual precipitation (MAP) or rainy day normal (RDN) to disregard the effect of local climate and enable the comparison between thresholds from different study areas. A common feature to all of the minimum thresholds types is that they represent the lowest boundary in coordinate space of a pair of observed rainfall characteristics below which landslides do not occur. The thresholds are most commonly drawn graphically after the rainfall characteristics pairs of values have been plotted. However, for large datasets computer aided statistical techniques can be used ((Guzzetti, et al., 2007), Vennari et al. 2014).

Intensity-duration thresholds are the most common type of thresholds found in the literature. They are generally expressed by a power law:

$$I = c + \alpha \times D^{\beta} \qquad \textit{Equation 1}$$

Where I is rainfall intensity, D is rainfall duration, and c, α and β are fitting parameters. Negative β value sets a descending trend, simulating the decrease of mean intensity at longer durations. Each developed threshold is valid for a limited range of durations, usually provided along with the threshold.

Rainfall event – duration (E-D) thresholds generally exhibit an ascending trend as they present a cumulative measurement of precipitation during an event. Thresholds using antecedent rainfall aim to take into account not only the critical event rainfall but also the cumulative precipitation in a period preceding it; as antecedent precipitation sets the preparatory conditions for slope instability due to the increased soil moisture and groundwater levels. Existing antecedent rainfall thresholds (Glade, et al., 2000; Chleborad, 2000; Jaiswal & van Westen, 2009; Huang, et al., 2015) show that with an increased amount of the antecedent precipitation, the critical event precipitation required to trigger a landslide decreases. Different durations of antecedent rainfall are used, with most periods spanning between 3 and 30 days. A common practice is to test the influence of a set of different antecedent periods.

When constructing thresholds, some studies plot not only rainfall events that triggered landslides, but also a number of rainfall episodes that didn't trigger any landslides (Zezere et al. 2015, Gariano et al. 2015, Guo et al. 2016, Giannechini et al. 2016). The threshold is then constructed in a way to maximise the number of triggering events and minimise the number of non-triggering events above the threshold. In this study, the authors opted not to apply this approach because of data uncertainty with a large number of recorded landslides not being linked to a specific rainfall event, which would compromise the certainty of rainfall episode being a non-triggering one.

5.2 Data and methodology

The major sources of information available for natural landslides include the Geological Survey of Ireland's National Landslide Database (GSI 2016), research papers (Bourke and Thorp 2005, Long and Jennings 2006, Boylan, et al., 2008; Long, et al., 2011) and newspaper reports. While the National Landslide Database contains a reasonably large dataset of landslides with excellent spatial accuracy, the vast majority of landslides have no date recorded. This is understandable as the majority of landslides occurred in remote mountainous areas and were usually not reported unless they caused material damage or road blockage. This greatly reduced the number of appropriate landslide inputs available for developing rainfall thresholds. Following detailed interrogation of the available data, a database of 37 landslides with reliable time stamps was established.

Rainfall data was obtained from The Irish Meteorological Service (Met Éireann). The rain gauge network in Ireland is composed of 25 synoptic stations with hourly precipitation measurements and 423 rain stations with daily precipitation measurements. Hourly data from synoptic stations is available for the last 10 years, while the entire daily precipitation dataset from rain stations since their activation was obtained. The total number of rain gauges in Ireland corresponds to an average density of one rain gauge station every 157 km^2.

Hourly measurements from synoptic stations were obtained for 25 landslides that occurred between 2006 and 2015 along with the daily precipitation measurements from the rain station most relevant in terms of proximity, altitude, orientation and general setting. For 12 landslides that occurred before 2006 only daily rainfall measurements were available. For the 25 landslides with hourly readings a modified intensity was calculated using Equation 2. Only these landslide events have been used to construct I-D threshold, while the entire database was used to construct the critical –

antecedent rainfall thresholds. This equation is often used when assessing landslides on the rail network in Ireland, however, it should be noted that the breakdown of landslide types in this study differ somewhat from those on the rail network in Ireland. Approximately half of landslides are classified as peat failures, with the rest of them composed of shallow translational soil slides and debris flows. More accurate classification is hampered by the fact that some failures reported in National Landslide Database and newspapers lack detailed descriptions. Furthermore, some of the peat failure mechanisms involved shearing through the underlying mineral soil, making them essentially translational soil slides, often referred in literature as peaty-debris slides (Dykes & Warburton, 2007).

In developing any form of rainfall threshold, identifying the critical triggering rainfall from a continuous series of precipitation data is a crucial process. Critical rainfall represents the rainfall event during or immediately after which the landslide occurred. The start of critical rainfall is marked by a steep increase in cumulative precipitation plot immediately prior to the landslide event. In practice however it can sometimes be difficult to precisely identify the point of this increase. To do this process objectively and uniformly, definitions for determining the start of critical rainfall event are set in each study, with limits varying significantly depending on the study area's climate conditions. In this study, the start of the critical rainfall event was defined when hourly rainfall intensity exceeds 1 mm/h. To separate the critical rainfall from the antecedent rainfall, an additional requirement of 12 hours with hourly intensity <1 mm/h before the start of critical event also had to be met. Following this process, duration D and average hourly intensity I_{ss} for each of 25 landslides were collated using the precipitation data from the nearest synoptic station.

While the network of 25 national synoptic stations with hourly readings can provide useful data to assist with the initial analysis, the authors deemed it to be insufficiently dense for the detailed analysis intended in this study. For that reason, mean intensity values I_{ss} obtained from synoptic stations were modified using daily rainfall readings from the rain stations that were the closest to each failure location, thereby greatly reducing spatial uncertainty in the rainfall values. This was carried out by adjusting the I_{ss} with the ratio of cumulative daily rainfall on rain station (R_{rs}) and synoptic station (R_{ss}):

$$I = I_{ss} \times \frac{R_{rs}}{R_{ss}} \qquad \textit{Equation 2}$$

Due to the uniformity of the terrain over which the rail network operates and the relatively small catchment area of each synoptic station, the durations of a rainfall event spatially vary to a much lesser degree. This allowed the same value of critical rainfall durations to be adopted as those read in the synoptic station data.

5.3 Results

Asymptotic intensity-duration thresholds were then graphically fitted to the plot of 25 events with hourly measurements, disregarding two outliers (Figure 26). The threshold is defined with the equation:

$$I = 0.95 + 50 \times D^{-1.65}, (3 \leq D \leq 100)$$ *Equation 3*

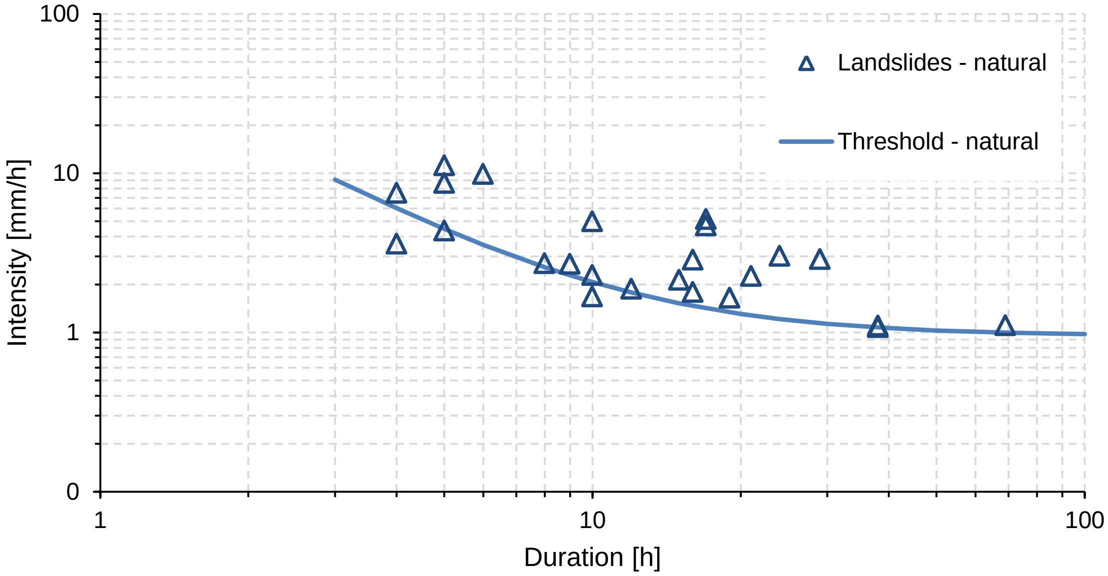
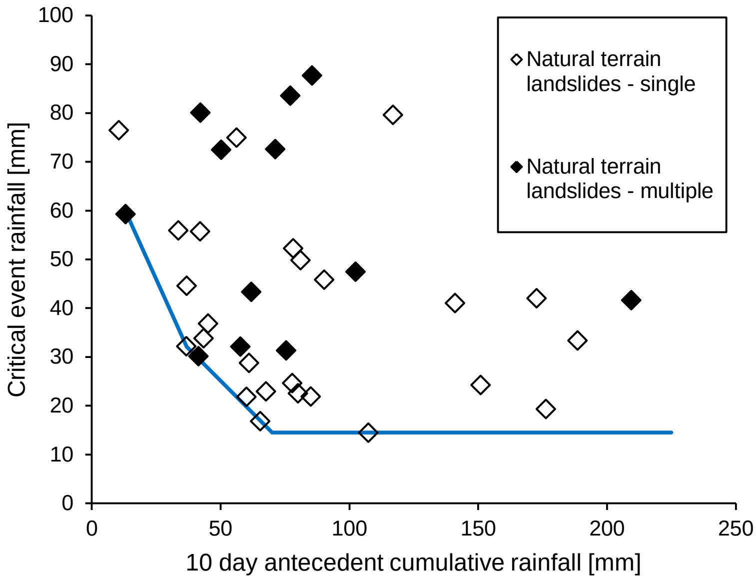


Figure 26 I-D rainfall threshold landslides on natural terrain in Ireland

The threshold was set with two outliers in order to capture the most probable landslide conditions. If the two outliers have been accounted for, the threshold would go “too low”, generating a lot of false alarms or ‘false positives’. It should be noted that not every rainfall that exceeds the threshold will automatically cause a landslide. This naturally depends on the terrain and slope features at the rainfall location. More interrogation is needed to estimate the probability of a landslide occurrence considering all of these variables. This threshold thus serves as a minimum requirement needed for landslide to happen. With more landslide data in the future, the threshold can be updated. The threshold is valid for the rainfall durations between 3 and 100 hours. More data on landslides caused by rainfall events with durations outside of this scope are needed to determine the threshold for these durations.

Figure 27 shows pairs of critical event – antecedent rainfall values and thresholds for 10 day and 30 day antecedent precipitation periods on two separate graphs. Both graphs show that for lower amounts of antecedent rainfall (up to 70 mm in 10 days and up to 220 mm in 30 days), a significant amount of critical rainfall is required to trigger the landslide on natural hillsides. Comparing the graphs for 10 day and 30 day antecedent rainfall, it can be seen that values on 10 day graph exhibit less scatter and that threshold is clearly discernible without outlier values. Furthermore, plotted natural landslides are grouped very densely in the area just above the threshold. This draws the conclusion that antecedent rainfall type of thresholds in Ireland are more appropriate for landslides on natural terrain and that mid-term antecedent period of 10 days can serve as a very useful indicator of rainfall triggering conditions.

One of the reasons for wide variation between existing thresholds worldwide lies in the selection of landslide events. Thresholds where all landslide events were included, including single and minor ones (as in this study), were shown to be lower than when only events with multiple or abundant landslides were collated in the database (Guzzetti et al. 2008, Brunetti, et al., 2010). To interrogate the effect of this, rainfall events causing landslides on natural terrain were classified into events that caused a single landslide (25 empty diamonds in Figure 27) and multiple or widespread landslides (12 full diamonds in Figure 27). Unsurprisingly, widespread landslides show strong connection with high amounts of critical rainfall. Critical rainfall of at least 30 mm is needed to trigger multiple landslides, and six out of nine events with cumulative rainfall of over 60 mm resulted in widespread landsliding. Further interrogation of these events shows high mean intensities and peak intensities attributed to these rainfall events. Widespread landsliding thus seems to be associated with strong intense rainfall events. This is especially important in light of more intense rainfall episodes being predicted in all scenarios for future climate in the 21st century (Sweeney, et al., 2008). Another thing in common to these events is that all but one recorded event occurred in conditions with relatively low antecedent rainfall. That is also evident in the fact that eight out of twelve occurred in, what Figure 2 suggests to be, a drier period countrywide (February – September). This can be partly explained by the drying and shrinkage of the material, causing cracking and opening preferential infiltration channels to critical depths (Long and Jennings 2006).



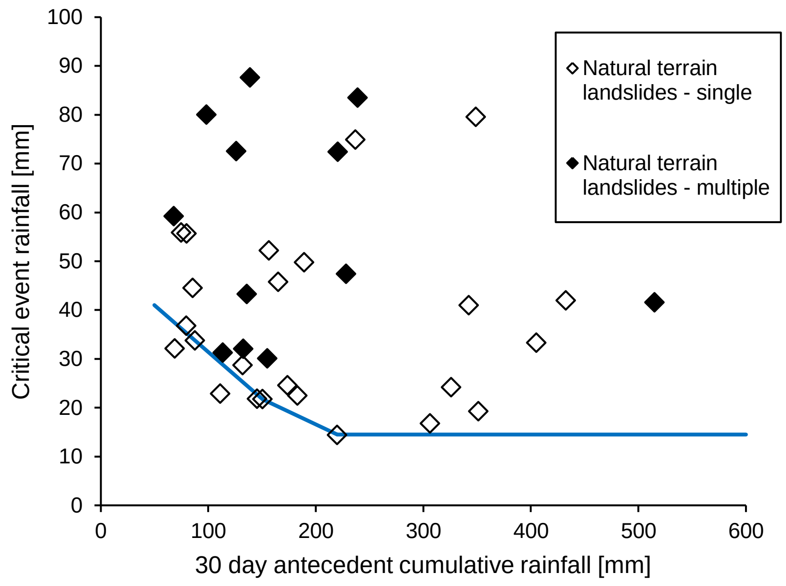


Figure 27 Cumulative – antecedent rainfall thresholds for landslides on natural terrain (straight blue line): a) 10 day antecedent period and b) 30 day antecedent period. Empty diamond – single landslide event, full diamond – multiple (widespread) landslide event.

5.4 Comparison with existing rainfall thresholds

The rainfall threshold for landslides on natural slopes developed in this study is representative of a national threshold as it is based on events that were recorded over the entire island of Ireland. In topographical terms they can also be considered as regional thresholds, given the size of the study area and the similarity of climatic and physiographic characteristics within it. This allows them to be compared to I-D thresholds proposed elsewhere in Europe and world. Figure 28 superimposes Irish I-D threshold with the range of 52 I-D thresholds collated by Guzzetti et al. (2007). These thresholds include global, regional and local thresholds from all over the world. Thresholds representing CADSES area (Central European Adriatic Danubian South-Eastern Space, essentially covering entire Central and South-Eastern Europe) were further singled out from the entire dataset. The Asymptotic nature of the Irish threshold makes it less straightforward for comparison with most of the thresholds, especially for very short (<5 hours) and very long (>50) durations. However, as 24 out of 25 interrogated landslide events (96%) have durations between 5 and 40 hours, this segment can be successfully compared to the collated thresholds. The Irish threshold is shown to be at the very bottom of both ranges, indicating that landslides in Ireland can be triggered by rainfall intensities lower than most other parts of Europe and world. The placement of Irish threshold among the lower group of collated thresholds also shows good agreement to the observed fact that global and regional thresholds are usually lower than local ones (Guzzetti, et al., 2007). Furthermore, the threshold for landslides on natural slopes in Ireland corresponds well to its counterpart developed by Guzzetti et al. (2007) for CADSES area and its subpart developed for severe mid-altitude climate.

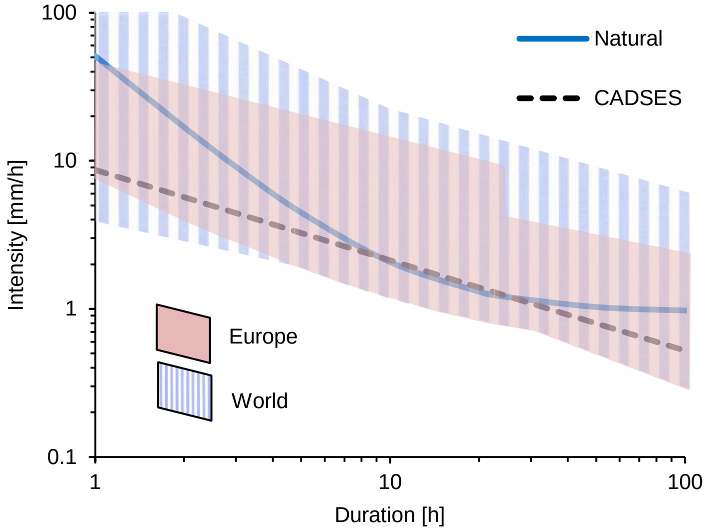


Figure 28 Range of thresholds collated by Guzzetti et al. (2007) in a) CADSES area (red) and b) world (striped blue). Threshold for natural slopes in Ireland (blue line); threshold for CADSES area (Guzzetti et al. (2007), dashed black line) superimposed.

6 Identifying the most appropriate monitoring methodology

The selection of the most appropriate monitoring methodology requires the consideration and understanding of the causes, trigger conditions, mechanism, stratigraphy, soil types, soil mechanical properties and ground water conditions associated with landslides. Each landslide is caused by a unique combination of these variables, therefore a monitoring strategy should only be designed once a sufficient understanding of these variables has been gained through desk studies, site walk overs, ground investigation and laboratory testing.

This chapter of the report reviews the available ground investigation, laboratory testing, monitoring techniques and equipment. The advantages, disadvantages and applicability of each method to the most vulnerable Irish soils (Peat and Glacial Till) are discussed. This is not an exhaustive list of techniques, it is simply a brief overview of those which are readily available and most commonly used in practice.

A discussion on how to combine these techniques to design an appropriate monitoring methodology and implement an early warning system is also given in this chapter.

6.1 In – situ testing

The main reason for performing site investigation is to identify the stratigraphy, soil types, soil mechanical properties and ground water conditions of the area under investigation. Soil properties typically investigated include particle size distribution, water content, density, Atterberg limits, permeability, shear strength and in organic soils, such as peat – state of decay. All of the information gained during this process are aiming to maximise the amount of data regarding ground conditions and use it to assess the susceptibility of the area to landslides, predict the likely failure mechanism and design an appropriate monitoring strategy.

Prior to site investigation, a desk study and site walkover should be completed in order to choose an investigation method best suited to the site. This process can also help to maximise the quality of the data obtained and do so in a cost-effective way.

The number of laboratory tests performed will directly depend on the number of samples obtained as well as project requirements and limitations. If possible, the following soil properties shall be identified: moisture content, bulk density, plastic limit, liquid limit, specific gravity, particle size distribution, triaxial test, shear box test, organic content (loss of ignition).

Methods of obtaining the information discussed above are discussed in the following sections.

6.1.1 Trial pits

Trial pits are a simple and cost effective intrusive means of obtaining a ground profile over a relatively shallow depth range (typically 1 to 5m). They are typically excavated using excavation plant but can be excavated using hand tools where access for plant is an issue. Disturbed soil samples can be taken for classification and environmental laboratory testing. In situ testing, such as hand shear vane, plate load and dynamic probe testing can be carried out within trial pits. Trial pits can be excavated in most soil types however the stability of the excavation can be compromised by groundwater ingress.

Trial pits are suitable for use in Peat and Glacial tills.

Figure 29 Trial Pit (http://www.wilson-bailey.co.uk/).

Advantages	Disadvantages
•Cost effective •Many tests can be carried out in a relatively short time period •Gives a wider view of the ground profile in comparison to boreholes •Allows for collection of disturbed samples for geotechnical and classification testing •In situ strength tests can be carried out within a trial hole •Suitable for a wide variety of soils •No sophisticated equipment or calibration required, just standard excavation plant	•Shallow depth range due to limited reach of excavation plant •Pits can become unstable in soft ground or when high groundwater •Only heavily disturbed samples can be collected •Only a limited number of in-situ tests can be carried out

Soil Type	Applicable
Glacial Till	Yes (but could refuse on large boulders or very stiff clays)
Peat	Yes (but trial hole can become unstable depending on the nature of the peat)

6.1.2 Cone Penetration Test (CPT)

Cone penetration testing is an intrusive investigation technique that involves pushing an instrumented cone through the ground and analysing the cone and skin resistance to determine the nature of the material through which it passes. A large amount of information can be gathered using a CPT including stratigraphy of layers, depth to firm layers, soil identification and mechanical soil characteristics. Additional sensors can be placed on the cone including pore pressure, environmental and seismic sensors. Although a large amount of data can be collected quickly using a CPT, a number of disadvantages include lack of a visual sample, limited penetration capacity of the cone, expense of specialist equipment and requirement for calibration. It is recommended that CPTs are carried out as part of a wider ground investigation which includes conventional boreholes, geophysics and laboratory testing so information gained form the CPT can be verified.

CPT equipment is generally mounted on specially constructed trucks (see below photograph). The test can also be carried out on smaller equipment such as tracked machines or trailers but these are not as widely available as the more conventional truck shown in the photograph below.

Advantages	Disadvantages
•A large amount of data can be gained relatively quickly •Can be used to identify stratigraphy of layers, depth to firm layers, soil type and mechanical soil characteristics •Additional sensors can be used to gain information on pore pressure, environmental and seismic sensors •Useful in soils where testing using conventional boreholes is difficult •Useful for contaminated sites as no soil is extracted from the ground during testing, eliminating any potential waste disposal issues	•No sample is obtained for visual description or lab testing •Specialist equipment and calibration is required •Test depths are limited by the capacity of the cone. Tends to refuse on cobbles, boulders, stiff clays or bedrock •Can be expensive to mobilise rigs •Significant post processing and interpretation of information required

Soil Type	Applicable
Glacial Till	Yes (but could refuse on large boulders or very stiff clays)
Peat	Yes (but choice of equipment on which the test equipment is mounted is important due to the soft nature of Peat)

Figure 30 CPT testing (http://www.insitusi.com/research/).

6.1.3 Boreholes

Boreholes are a site investigation method that involve drilling a relatively small hole (typically 75mm to 150mm in diameter) through the ground to extract samples for identification of stratigraphy, ground water level and extraction of soil samples for laboratory testing. There are many techniques available for drilling boreholes but the two most widely used are rotary coring and cable percussive (shell and auger). Boreholes can be drilled to significant depths to provide a deep ground profile. In-situ tests such as the Standard Penetration Test (SPT), pressure meter and double packer testing can be carried out in boreholes. The holes can also be instrumented to obtain information on groundwater and ground movement. Some of these tests are discussed in later sections of this report.

This study has shown that the boundary between strata is often the location where the failure zone within a landslide is found. Boreholes are a very useful site investigation technique for landslides as they allow for clear identification of strata boundaries. High quality testing for laboratory sampling can be obtained for classification, strength and stiffness testing in the laboratory. This combined with instrumentation to identify ground water level and ground movement make boreholes extremely useful for obtaining an abundance of information on numerous factors that contribute to landslides.

Boreholes are suitable for use in all soil types including glacial tills and peat.

Advantages	Disadvantages
•Many techniques available to suit all soil types, terrains and depth requirements •Allows collection of quality samples for detailed logging and lab testing •Allows for various in-situ testing techniques •Boreholes can be instrumented for ground water and ground movement assessment	•Can be relatively expensive •Gives information on a specific point therefore doesn't provide information variation across the site without multiple holes or use in conjunction with other methods •Bores can be time consuming to drill depending on ground conditions, depth and

	rig used

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

Figure 31 Rotary coring rig (left) and cable percussive rig (right) (photos from http://www.geotronuk.co.uk/wp-content/uploads/2010/12/com205-2a.jpg and http://www.dando.co.uk/photos/cable-percussion-drilling-rigs accessed 03/12/2016)

6.1.4 Geophysics – MASW and GPR

Multichannel Analysis of Surface Waves (MASW) and Ground Penetrating Radar (GPR) are non – intrusive methods that can provide information on stratigraphy, soil density and stiffness of the ground.

During MASW testing, surface waves are generated by introducing an impact load (and hence body waves) into the ground at various locations. Shear Wave velocity (Vs) is then measured using a series of Geophones. Tests performed on Irish glacial till (Long, et al., 2013) have proven a strong correlation between V_s and Undrained Shear Strength (S_u), therefore the application of this method may be a reliable supplement to an intrusive ground investigation, or in some cases a cost-effective substitute.

GPR works by sending a tiny pulse of energy into a material and recording the strength and the time required for the return of any reflected signal.

Geophysical methods are usually used as a supplement to an intrusive site investigation. It is generally best to preform geophysics prior to intrusive investigation as it can help to inform a more targeted, cost effective ground investigation.

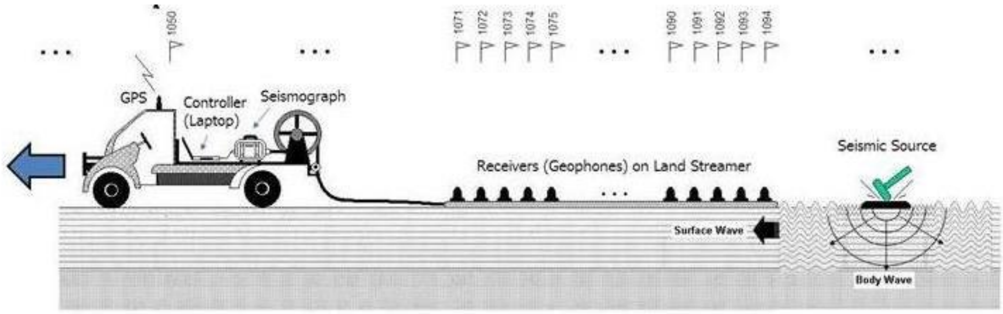


Figure 32 Multichannel Analysis of Surface Waves (MASW) (http://www.masw.com/WhatisMASW.html).

Figure 33 Ground Penetrating Radar (GPR) (http://www.perth-businessdirectory.com/wp-content/uploads/2016/05/Ground-penetrating-radars.jpg)

Advantages	Disadvantages
• Large areas can be covered • Information on numerous properties of the ground including stratigraphy, soil type, shear strength and stiffness can be gained • Cost effective if used as part of a wider ground investigation	• Results need to be verified by other means (eg boreholes and trial pits) • Specialist sophisticated equipment required • Geophysical expertise needed to interpret results.

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (for GPR, MASW not recommended)

6.1.5 Soakaway or Percolation testing

Soakaway or percolation testing is performed to estimate the in-situ permeability of a soil mass. The test involves excavating of a trial pit of a known size, filling the pit with clean water and measuring the change in water level over time. The permeability of the soil encountered in the trial pit can then be estimated from these measurements.

The location for a soakaway test needs to be relatively easy to access as excavation plant, a large water tank and a vehicle to tow them are required. This makes this test unfeasible for potential landslide locations on steep slopes, in remote locations, or where very soft ground (eg Peat) is present.

This test introduces a relatively large amount of water into a mass of soil. As water is known to be a trigger for landslides, the impact of using this test on potentially unstable slopes needs to be carefully considered prior to specifying it.

Advantages	Disadvantages
•Simple test with no requirement for sophisticated equipment and calibration •Measures permeability of a relatively large soil mass	•Introduction of large amounts of water to a slope can have a destabilising effect •Difficult to carry out test on steep slopes Difficult to carry out test on areas of very soft ground due to size of equipment needed •Difficult to carry out test in remote locations Permeability can be underestimated due to smearing of the sides of base of the pit during excavation •Ground needs to be sufficiently stable to stay open for the duration of the test

Soil Type	Applicable
Glacial Till	Yes
Peat	No

Figure 34 Percolation test (http://www.percolationtests.ie/).

6.1.6 Shear Vane Test

The Shear Vane Test is an in-situ test used to measure the undrained shear strength of cohesive soils. This test is unsuitable for granular soils. The equipment required to carry out this test is hand operated, easy to use, compact and light. This makes it suitable for use in locations where heavy plant and equipment cannot gain access. This is particularly useful for many potential landslide locations in Ireland. The test is very quick which allows a large number of readings to be obtained in a short period of time. It also gives a direct reading of shear strength without any interpretation of results. It is generally performed from the surface or within trial pits. It should be noted that this technique is most applicable to soft to medium strength clays and generally not applicable for materials with an undrained shear strength in excess of 100 kPa. Furthermore, due to the presence of fibres within a peat matrix, the shear vane can provide an artificially high strength value in peats due to the torsional stress path and added resistance provided as the fibres rotate around the vane.

Shear strength results from this test can vary greatly depending on the user. Results should be used as part of a wider investigation into the strength of the soil and not a standalone investigation technique.

This test is suitable for use in Peat and cohesive Glacial Tills.

Advantages	Disadvantages
• Simple test that gives a direct reading of shear strength • Light hand operated equipment which can be used in difficult to access locations • Quick test allowing a large amount of readings to be obtained in a short period of time	• Results can vary significantly depending on user • Limited depth range

Soil Type	Applicable
Glacial Till	Yes (Cohesive only)
Peat	Yes

Figure 35 An example of vane (http://www.controls-group.com/eng/soil-testing-equipment/shear-hand-vane-tester.php).

6.1.7 Hand Augering / Hand Coring

Hand Augers can be used to obtain shallow cores sufficient to prepare logs of a ground profile less than 5m in depth where the sides are expected to be stable. It is a hand-held tool that can be used in locations difficult to access with the heavy plant and drilling rigs. The method is suitable for both granular and cohesive soils. The hand auger can be difficult to advance through stiff clays and dense sands/gravels. It is also likely to refuse on cobbles and boulders typically found within glacial tills in Ireland. The effectiveness of this method within peat is heavily dependent on the nature of the peat.

Figure 36 Hand Auger (https://www.spaldings.co.uk/livestock/spear-jackson-hand-post-hole-auger)

Advantages	Disadvantages
•Simple method of obtaining a ground profile •Light hand operated equipment which can be used in difficult to access locations	•Limited depth range •Likely to refuse on stiff clays, cobbles and boulders

Soil Type	Applicable
Glacial Till	Yes (but likely to refuse on stiff clays, cobbles and boulders)
Peat	Yes (but it's effectiveness is dependent on the nature of the peat)

6.2 Laboratory Testing

6.2.1 Shear box test

Shear box tests can be used to estimate the drained or undrained strength of granular or cohesive material. In shear – box tests a soil sample is placed between the two frames, subjected to a vertical load to mimic the effect of overburden, then a bottom frame is pulled in the horizontal direction to provide a shear force through the soil block. Observations are focusing on the load applied, as well as the displacement (Schneider-Muntau, et al., 2006).

Figure 37 Digital shear testing machine (http://www.controls-group.com/eng/soil-mechanics-testing-equipment/digital-shear-testing-machine.php).

6.2.2 Triaxial test

During a triaxial test a sample is subjected to the three dimensional stress, but loading is subjected vertically. This method is representing the conditions similar to the one occurring in the soil mass. Test is suitable for all soil types (Schneider-Muntau, et al., 2006; Barnes, 2000).

Figure 38 Triaxial test (http://www.matest.com/en/Products/soil/Triaxial-testing-equipment/traxial-tests/triaxial-automated-testing-system).

6.2.3 Constant Head Permeability Test

A constant head Permeability test can be performed on soils within a range of permeability of 10^{-2} and 10^{-5} m/s, such as sands, as well as sandy gravels. In addition to that test is suitable to use in disturbed or remoulded samples. Through the test a flow and a hydraulic head loss are observed until they reach a study state. Coefficient of permeability is calculated using values measured during the test – flow rate and head loss (Barnes, 2000).

Figure 39 Combined Constant Head and Falling Head Permeameter (http://www.controls-group.com/eng/soil-testing-equipment/combined-constant-or-falling-head-apparatus.php).

6.2.4 Falling Head Permeability Test

The Falling Head Permeability test is suitable for soils characterised by low or intermediate permeability. During the test water flows down a standpipe and through the sample. Hydraulic head is then a difference between a meniscus level in a standpipe and the overflow level. Figure XXX, above, Presents the permeameter that could be used for the aforementioned test (Barnes, 2000).

6.2.5 Moisture Content

Moisture content is an indicator of the state of soil and its behaviour. The value of a moisture content is calculated as a ratio of the mass of water to the mass of the solid particles, presented in percentage. A test is compiled of initial weighting sample, drying it in controlled temperature environment and weighting the dried sample (Barnes, 2000).

6.2.6 Atterberg Limits

Atterberg limit is describing the properties of plasticity and cohesiveness of fine soils, such as clays and silts. It describe a liability of soil to change or remould without changes in volume or breaking up (Barnes, 2000).

Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
A definitive cone penetrometer method is believed to be the most reliable. During the test a cone is falling onto a very moist soil. A cone penetration, as well as moisture content are measured, however the value of Liquid Limit is the value of moisture content observed at 20mm penetration.	Plastic Limit is defined by measuring the moisture content of the dried sample. Sample is dried until it crumbles or shears at 3mm diameter. The test result is highly dependent on the operator, as it requires to use a manual force.	Plasticity Index can be calculated by subtracting a value of Plastic Limit from Liquid Limit.

Figure 40 An exaple of Liquid Limit cone penetration method (http://www.sisc.com.vn/en/detail.php?module=product&iCat=2097&iData=221&#page=page-3).

6.2.7 Particle Size Distribution

Particle size distribution is performed by Sieving and Sedimentation. Soil is placed on the top sieve and during the process of shaking smaller particles are falling onto the bottom sieves, where each of the underlying allows smaller and smaller particles to pass. Particles which passed through all sieves can be subjected to an additional test – Sedimentation. During this test soil particles are suspended in fluid and are falling at different velocity. At 4 minutes a sample is taken and particles >20µm are expected not to be in a suspension (Barnes, 2000).

Figure 41 An example of an Electromagnetic Sieve Shaker (http://an.geotechnical-equipment.com/Pages/Search.aspx?s=Electromagnetic%20Sieve%20Shaker).

6.3 In – situ monitoring methods

The selection of monitoring methods presented below contains various intrusive and non-intrusive techniques. Selection of the most appropriate monitoring technique is dependent on a number of factors including nature of the site, access, ground conditions, slope angle, available budget etc. The selection of appropriate combinations of techniques is discussed further in Chapter 7 of this report.

6.3.1 Rain Gauge

A rain gauge is an instrument used in meteorology which measures the amount of precipitation fallen in a particular location during a certain period of time. It is not a direct landslide monitoring method, but allows observation of a how changes in precipitation influence slope stability. There are variable types of devices available on the market, some of which are automatic and some require direct measurements.

When installing a rain gauge, a precipitation collector shall be placed approximately one meter above the ground and no object or structure should influence the inflow. MetÉirann monitor rainfall in various locations across Ireland. Where MetÉirann rain gauges are not in close proximity to the landslide being monitored, one should be installed specifically for the site.

Figure 42 Optical gauge (automated system) and standard type rain gaugee (required direct readings) (http://www.nwclimate.org/guides/how-to-use-rain-gauge/).

Advantages	Disadvantages
•Popular and easy to imply monitoring method •Low cost •Reliable •Existing data can be requested from MetÉirann	•To high rainfall can introduce errors in readings •Readings can be influenced by evaporation or strong winds •As debris (leaves) can block the collector entrance, therefore instrument require maintenance

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

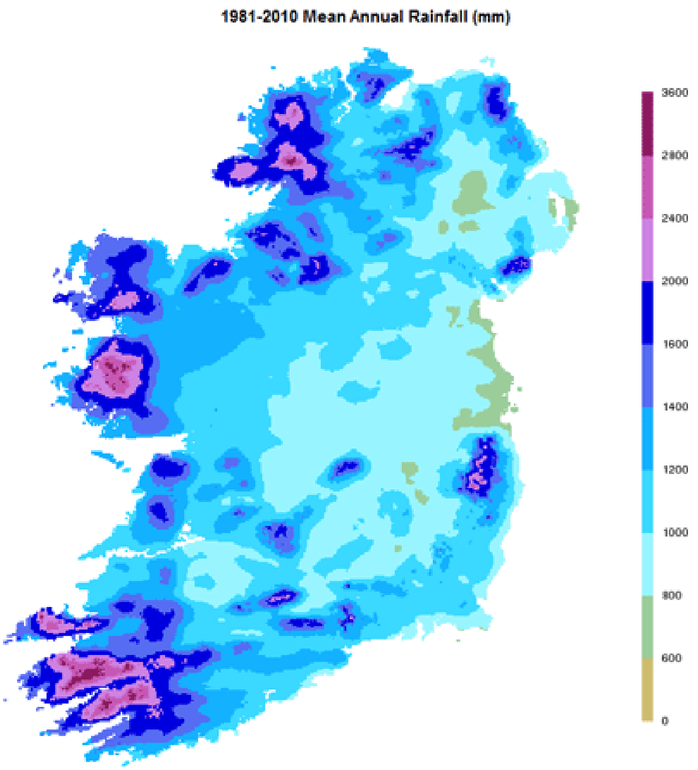


Figure 43 Mean Annual Rainfall (mm) in Ireland (http://www.met.ie/climate-ireland/rainfall.asp).

6.3.2 Weather Stations

In addition to local rain gauges, a full weather station can be installed to measure additional components of weather. Relevant parameters include the barometric pressure, the solar flux, the temperature, wind speed, wind direction and humidity. These values can be used to determine relevant parameters such as the local Soil Moisture Deficit (SMD), which is calculated as a derived parameter based on the weather patterns and soil type. A weather station should ideally be installed with a robust housing capable of resisting the weather. The housing should also be secure against theft and human interference. A local datalogger complete with telemetry system should also be installed to facilitate remote transmission of the data without the need for manual visits to the site. In addition, the power supply should contain a solar panel and a battery pack for full redundancy. The site location should be carefully selected to ensure adequate reception for the GPRS modem.

6.3.3 Extensometers

Extensometers are devices used to measure the amount and rate of movement in either the horizontal or vertical direction. Many types of extensometer are available, most of which are installed inside the borehole. One of the most popular extensometer is the Magnet Extensometer. Along the length of an extensometer, several magnets are coupled to the surrounding soil. Base readings are taken of the position of the magnets on installation. As soil movement occurs the magnets move relative to their initial position. The readings are made by drawing the probe through the access pipe. This probe beeps as it passes through the magnetic field of the magnets in the borehole and the location/depth can be read from a graduated cable. This process can be repeated over time to gain an understanding of both the magnitude and rate of movement of the soil mass.

Figure 44 Magnet Extensometer (http://www.slopeindicator.com/instruments/ext-magnet.php).

Advantages	Disadvantages
•Easy to use	•Requires manual readings

•Quick data collection process •High level of accuracy •Does not require post processing	•The process of installation can damage surroundings •Monitoring is carries out only in specific localisation •Vertical or horizontal movement can be observed but device cannot detect both at the same time

Soil Type	Applicable
Glacial Till	Yes
Peat	No (Access to peat areas can be difficult)

6.3.4 Inclinometers

An Inclinometer is an instrument used to monitor lateral movements of the ground. The inclinometer device itself consists of an instrumented torpedo shaped probe. The Inclinometer`s probe is suspended on a cable and is lowered into a plastic grooved casing which is encased within grout within a borehole. The grooved casing has a cruciform set of grooves in which the torpedo wheels run. Usually, one set of grooves are aligned with the direction of greatest expected movement. The torpedo is lowered and raised four times with the instrument being rotated through 90 degrees between each reading. This allows the plastic casing shape to be defined in two orthogonal directions with an error check for each set of readings. The movement of the ground can then be deduced form changes in shape of the plastic casing over time.

Figure 45 Example of digital inclinometer system (http://www.geokon.com/GK-604D).

Advantages	Disadvantages
•Easy to use	•Requires manual readouts

•Quick data collection process •Accurate •Can identify depth of failure plane of landslide	•Care must be taken in the selection of the grout to use within the borehole as the stiffness of this material can affect readings

Soil Type	Applicable
Glacial Till	Yes
Peat	No (Peat likely to flow around grout and inclinometer installation)

6.3.5 Crackmeters

Crackmeter is a device which measures the ground movement across an existing crack. Either side of the crack a gauge is anchored to the ground. When movement occurs, a slider changes its position and an applied voltage measures the slider and an end point.

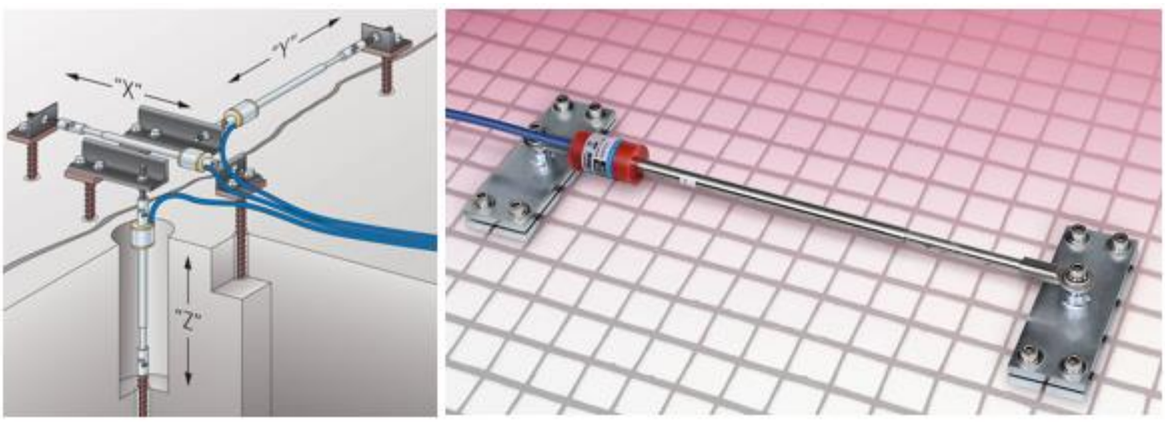


Figure 46 Example of Crackmeter (right) and an example of usage (left) (http://www.geokon.com/4420).

Advantages	Disadvantages
•Easy to use •Quick data collection process •Accurate •Can be connected with a datalogger	•Installation may be difficult •More suitable to stiff soils/rocks as well defined cracks tend to appear in these landslides.

Soil Type	Applicable
Glacial Till	Yes (only for very stiff tills where a defined crack can be seen)
Peat	No (Peat slides tend to be sudden and it is not likely that a well-defined crack will be visible for a long period prior to failure)

6.3.6 Standpipe Piezometers

A standpipe piezometer is an instrument that measures ground water level. A standpipe needs to be installed within a borehole. It consists of a plastic pipe with a perforated zone which allows ground water to flow into the pipe. The piezometer device is located inside the pipe in the zone subjected to observation and the piezometers filter is attached to a riser pipe which comes to the surface. The observations of water level are conducted using a sounder or a water level meter (http://www.geokon.com/4590). A water level meter is often used to measure the water level within a standpipe.

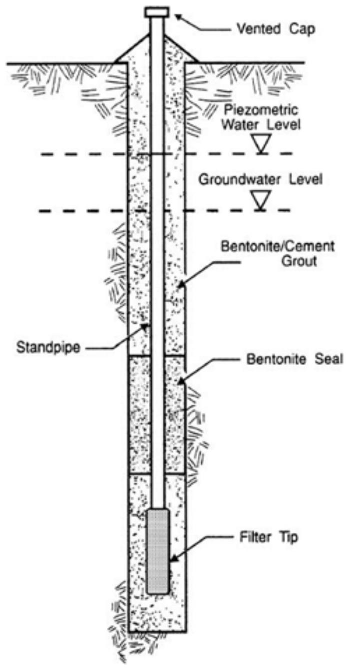


Figure 47 Standpipe Piezometer (http://www.risknat.org/projets/riskydrogeo/docs/guide_pratique/Acivite1_Ateliers/Presentations%20Atelier1/A1P13-Coastal%20changes/programs/instability.html).

Advantages	Disadvantages
•Easy to use •Reliable •Accurate •Allow to take samples of ground water •Cost effective •No electronic components	•Easily damaged during construction •Require to prevention of rainwater run off to the Standpipes •Monitoring is carried out only in specific localisations. •Manual readings •Response time is directly dependant on the soil`s permeability

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.7 Vibrating Wire Piezometers

This device is installed in order to monitor pore water pressure. There is a wide range of Vibrating Wire Piezometers available. These devices are commonly used, widely applicable, and can be installed inside a borehole, embedded in fill or suspended in a standpipe. Readings of the water pressure is transmitted as a frequency and can be taken using readout or a datalogger (http://www.geokon.com/4500-Series).

Figure 48 VW Piezometers (http://www.geokon.com/4500-Series).

Advantages	Disadvantages
•Reliable •The frequency signal can be transmitted through a very long cable, up to several kilometres •Filter stone ahead of the diaphragm allows water to pass but protects ingress of soil particles •High Accuracy •Easy to operate •Inbuilt temperature sensor monitors temperature	•Require calibration •Water sample cannot be collected Relatively expensive •Require maintenance

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.8 Tensiometer

Tensiometer is an instrument that measures the potential or tension of water held in soil. It consists of porous ceramic cup closing the Tensiometer, inside which is a vacuum. The water from the soil moves inside the tensiometer in order to equilibrate and a vacuum causes the readings. The reading from the Tensiometer gauge increases, when soil dries, and as water potential decreases – tension increases (http://www.earthsystemssolutions.com/). During an installation operator must assure that sensor is in the direct contact with soil.

Figure 49 Dial - Gauge Tensiometer (http://www.earthsystemssolutions.com/).

Advantages	Disadvantages
•Simple •Reliable	•Cannot be used in a freezing soil conditions •An ingress of air with water or during dry conditions is possible and can distort results

Soil Type	Applicable
Glacial Till	Yes
Peat	No

6.3.9 Water Content Reflectometers

This device was designed to measure the volumetric content of water in the soil. Installed probe generates an electromagnetic pulse and measuring the time needed for the impulse to return. The Water Content Reflectometer can carry out various functions depending on the angle of insertion, for instance probe placed vertically is measuring the water content in upper 30 cm of the ground, horizontal orientation measures passing or wetting points, whereas 30° inclination detects the water content in top 15 cm of the soil (https://www.campbellsci.com/cs616-reflectomer).

Figure 50 An Example of Water Content Reflectometer (http://www.iarc.uaf.edu/research/highlights/2008/northern-alaska-2).

Advantages	Disadvantages
•Can be connected with a datalogger •Does not require periodic maintenance • Highly accurate •Fast response time •Suitable for a long-term monitoring	•Probe installation may affect the results •Temperature dependant

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (note, organic soil can attenuate a signal)

6.3.1 Theta probe

Theta probe is a moisture content sensor. The device is buried in the ground and connected to a datalogger. Connecting the sensor to a source of power induces an electromagnetic wave transmission from the steel rods to surrounding soil. Depending on the water content, soil's permittivity changes and is detected and measured by the device.

Figure 51 ThetaProbe (http://www.delta-t.co.uk/product/ml3/).

Advantages	Disadvantages
•Can be connected to a datalogger •Can be calibrated to specific types of soil	•If used in hard soils, device shall be installed into pre – formed holes •Not suitable for temperature measurements •Readings may be affected by roots, animal's burrows, stones, and subsoil drainage

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (note, organic soil can attenuate a signal)

6.3.2 Tiltmeters

Tiltmeter is a device designed to measure tilt in structures. It is installed permanently attached to the structure in order to perform a long term monitoring. The device is very precise and can measure very small movements. The device can be connected to a data logger.

Figure 52 Tiltmeter (http://www.geokon.com).

Advantages	Disadvantages
• Combine a high range with a sensitivity and very high calibration accuracy • The output produced, a frequency, can be transmitted over long cables • Sensors are less likely to be influenced by the effects of the moisture intrusion • Easy to obtain biaxial measurements by installing two devices together one at 90° to the other • In build shock absorbers protect sensors from shock loadings	• Shock sensitive – shocks can cause several offsets • May require a damping fluid if the output is unstable

Soil Type	Applicable
Glacial Till	Yes (if a sensitive structure is being affected by a nearby landslide, or potential landslide in Till)
Peat	Yes (note, sensitive structures are rarely constructed on Peat therefore the situations in which this tiltmeter could be used is limited)

6.3.3 Time Domain Reflectometry (TDR)

Time Domain Reflectometry is a method of detecting, as well as interpreting, rock and soil mass movements. TDR requires the installation of a cable inside a borehole, which is then encased in grouted. A voltage pulse is sent through the cable and can be reflected if the change in the characteristic impedance of the cable has changed. Changes can be caused by the crimps, kinks, presence of water, as well as by the broken cable (Kane, W.F., 2000).

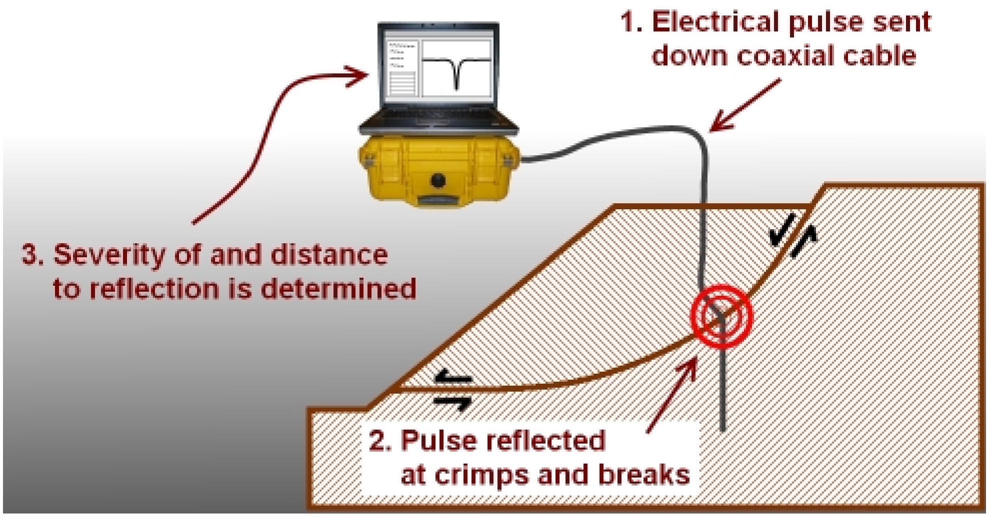


Figure 53 Principles of TDR (http://www.kanegeotech.com/instrumentation/).

Advantages	Disadvantages
• Easy to use • Quick data collection process • Remote access • Does not require excessive funds • Collected data indicates the depth of slip surface	• Cannot be used for monitoring tilt as TDR can be damaged by shearing only • To achieve the best results should be installed in the back of a structure, eg: retaining wall • Requires the installation of long probes • Magnitude of movement as well as the direction are not measured

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.4 Laser scanning

Laser Scanning is a widely applicable method which can be used to survey discontinuities as well as surface deformation and displacements. The scanner captures the 3D data imaging of the area, which are extremely precise (6 mm in position and 4mm in distance for every 50m). Recorded scans are saved on the instrument and need post processing. A map or 3D model can be produced using the scanner results. For the purpose of use of this system on landslides, numerous scans should be taken as a baseline reading with repeat readings at regular intervals to detect movement of the landslide over time.

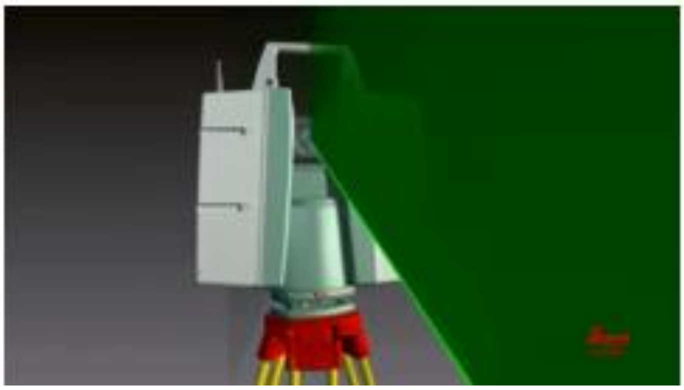


Figure 54 Example of Laser Scanner Equipment (http://leica-geosystems.com).

Advantages	Disadvantages
• Easy to use • Quick data collection process • Accurate positioning and precise measurements • Does not require excessive funds • Non-intrusive method	• Post processing requires specialised software • Changes can be observed only when comparing with previously acquired data • Not suitable for permanent installation • Require the usage of highly specification software • Require geodetic monitoring points to be set up

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.5 Radar Interferometry InSar (Synthetic Aperture Radar Inferometry)

Radar Interferometry is a technique of mapping ground deformation using captured images made by orbiting satellites. Pictures are made in a time space from similar vantage points. Collating images with each other can provide a visual of the change in the topography (potential deformation) over time (USGS website). Soldata provides a service, during which up to 4 measurements per month can be made. Measurements can be as precise as 3mm in movement and 1mm a year in displacement rate.

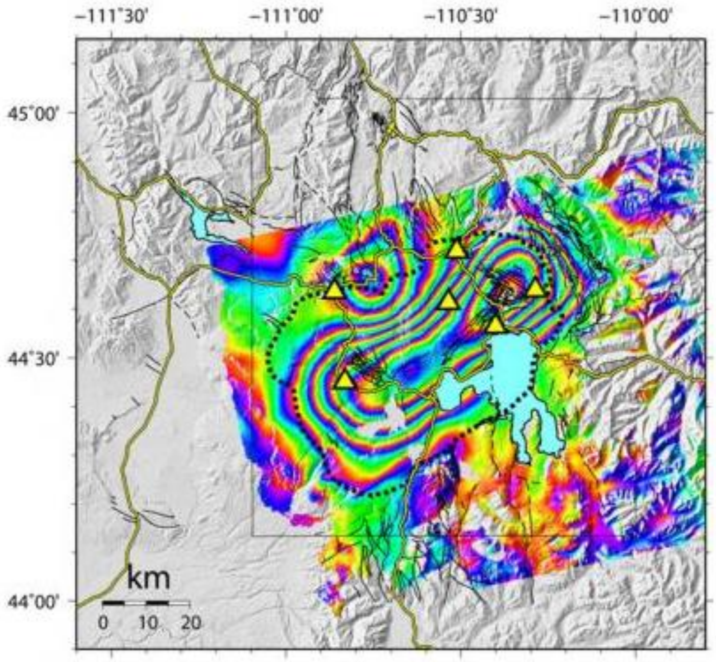


Figure 55 Example of ground movement map - observations of Yellowstone area Sept 2004 - Aug 2006) (https://volcanoes.usgs.gov/vhp/insar.html).

Advantages	Disadvantages
•Applicable regardless of weather conditions and day/ night light •Good application on a large-scale projects •Very high density of points (up to 10 000 points/km2) •Method can be applied in areas of difficult accessibility. •Easy comparison of slope mass movements with stable area •Non-intrusive •Data from the past may be acquired	•Changes can be observed only when comparing with previously aquired data •Only displacements along line of sight (LOS) in 2D between satellite and field can be measured. •The technique is not applicable in vegetation covered area. •Highly specific software. •Real time monitoring is not possible.

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.4 Suggested approach to proposing an appropriate monitoring strategy

The most appropriate monitoring methodology does not need to be expensive, but does require the landslides triggering factors to be fully understood, as well as to be tailored to the site conditions. A good monitoring methodology will be simple, robust and orientated to survey relevant parameters. An additional factor, which is worth noting is the seasonal dependencies of slope movement.

A monitoring strategy is a combination of the monitoring itself and the site and laboratory investigation and desk studies carried out to identify the pertinent parameters that require monitoring. A desk study should gather all existing available information regarding site and neighbourhood likely to be affected by a potential landslide. Basing on data coming from the historical sources, geological survey, heritage and environmental organisations as well as weather reports, the significance and likelihood of a landslide could be assessed. Based on the findings of this study, an appropriate site investigation could be designed to further develop the understanding of the site.

As a supplement to the information gathered during the desk study, prior to the site investigation a walk over is advisable. During the site visit, manifestations of an instability, such as displaced features, leaning posts and fences, scour should be noted (Bromhead, 2006).

A site investigation shall include a combination of the methods discussed in the previous sections of this report. The advantages and disadvantages of each method should be assessed against the nature of the specific site being investigated. Whichever combination of methods are used, the designer should ensure a thorough understanding of stratigraphy, soil types, soil mechanical properties and ground water conditions is gained.

In order to achieve the greatest benefit from a monitoring strategy, detailed modelling work should be carried out to assess the likely failure mechanisms and triggers based on the information from the site-specific investigation.

Once the above information has been obtained, then the monitoring regime itself can be designed. Depending on the strategic position of a potential landslide and the cost associated with predicted damage (property and infrastructure damage, heritage loss and environmental changes), the cost of chosen monitoring method should be appropriate. In the locations of low importance, for example isolated barren regions, simple solutions will be sufficient. In locations of high importance, for example densely populated urban areas or adjacent to critical infrastructure, a robust monitoring strategy combined with an early warning system is recommended.

Ideally, a monitoring strategy should involve monitoring of rainfall, ground water level and deformation of the ground. As the most common landslide triggering factor in Ireland is rain, available and relevant meteorological data should be gathered and monitored against trigger levels tailored to the nature of the area being monitored (Wieczorek & Snyder, 2009). If no monitoring station is available within an acceptable distance of the site, one should be installed at the site. As many landslides are triggered due to loss of matic suctions as the ground water table level rises, a suite of piezometers and tensiometers or Theta Probes should be installed to monitor these variables. Regular deformation observations using InSar or Laser scanner should be performed.

Surface and below ground movement should be taken monitored using strategically placed inclinometers and crackmeters.

6.5 Early Warning System

The key to the success of an Early Warning System is to apply a set of activities which help to manage risk. Early warning systems have been used in a number of countries including USA, Italy and Hong Kong. This section draws on the experience gained from these countries and looks at their potential applicability to Irish landslides.

In Hong Kong, a Slope Safety system has been put in place which applies the following points (Ho, et al., 2016):

- Create a landslide catalogue including risk assessment and repair order
- Inspect listed slopes and prepare safety recommendations
- Regular slope maintenance
- Mitigate the risk of the instability
- Introducing educational campaign (raising awareness)

This process allows information to be gained on the landslides in the area and a proactive approach to mitigation of instability to be implemented.

This approach has been further developed for a major landslide in Torgiovannetto in Central Italy. Here a well-known and studied landslide with potential to cause significant damage to both a provincial and region roadway has been heavily instrumented as part of an early warning system (Intrieri et al, 2011). The monitoring system on this landslide consists of 13 wire extensometers, 1 thermometer, 1 rain gauge and 3 cameras. Studies, site investigation and analysis has been carried out on this landslide to determine trigger levels for potential landslide movement. These trigger levels were based on kinematics of the landslide. If the velocity threshold set by this analysis is exceeded by two or more sensors, the attention level would be entered, causing improved monitoring and surveillance. Following this more detailed monitoring and surveillance, if the kinematics continue to exceed the threshold or worsens, an alarm is issued and the road is closed. The measures implemented here are ideal for situations where critical infrastructure could be majorly impacted.

In the USA, the United States Geological Survey (USGS) have introduced live monitoring systems to a number of landslides. The system used provide continuous, real-time monitoring to some sites and periodic monitoring to others. The most recent measurements are provided online for a number of the sites. Instruments monitored include rain gauges, geophones, pore pressure sensors and slope movement sensors. The live monitoring allows appropriate mitigation measures to be taken when pre-defined trigger levels are reached. Possible alarm measures include SMS, media, sirens and police door to door visits (http://landslides.usgs.gov/monitoring/ access 07/12/2016).

DiBiagio and Kjekstad (2007) discussed a general approach that should be taken to implementation of early warning systems. They identified that EWS should comprise the following activities

- Monitoring, including data acquisition, transmission and maintenance of the instruments;
- Analysis and forecasting, which can be done by using thresholds, expert judgment, forecasting methods and so on;
- Warning, i.e. the dissemination of understandable messages alerting for the impending threat;
- Response, concerning if people are able to understand and how they react to the warning.

They also summarised their suggested approach in a flow chart as shown below in Figure 56.

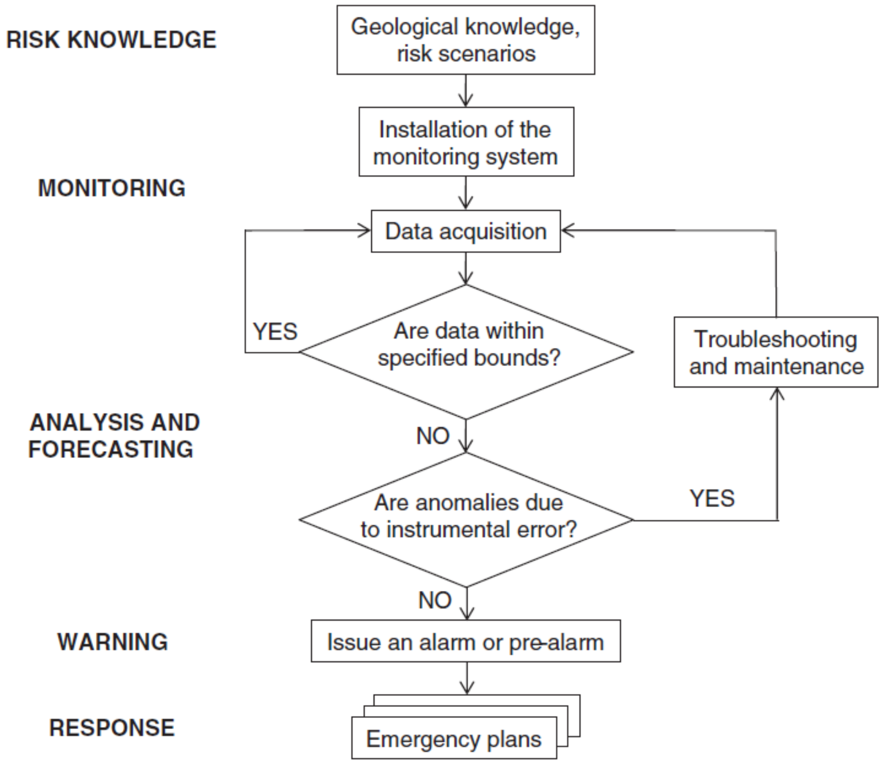


Figure 56 Example of an Early Warning System (DiBiagio and Kjekstad, 2007).

The above approach could be applied to Irish Landslides. Although the geology and triggers of Irish landslides differ from those discussed above, the general approach can still be applied. For example, rainfall levels have previously been identified as a key contributor to Irish landslides and hence this could be set as a trigger. Ideally, a series of triggers could be set of parameters including a combination of rainfall, soil moisture, pore pressure, water table level, displacement and any other parameters deemed critical to the stability of a particular landslide.

Monitored data is not only used to activate warnings and alarms, but also in order to adjust the thresholds, and to define the landslide model. An accurate analysis of a landslide should start from the analysis of its time histories and the correlation between different parameters. The use of innovative instruments, such as ones mentioned in the previous chapter, should ideally connect to a data loggers allow real-time monitoring, which reduces the intervention time. Measured data gained during the desktop study, ground investigation, laboratory tests as well as monitoring is logged, can be reviewed and used for better understanding of the landslides occurrences.

Office of Emergency Planning have prepared "A National Risk Assessment for Ireland" (Department of Defence, 2012), a response arrangement for major emergences, each of which has a five stage emergency management plan. A five-staged classification of likelihood, as well as five staged classifications of impact could be adopted by local bodies when assessing a risk of a landslide occurrence.

The below table presents Likelihood classification (Department of Defence, 2012).

Ranking	Classification	Likelihood
1	Extremely Unlikely	May occur only in exceptional circumstances; Once every 500 or more years.
2	Very Unlikely	Is not expected to occur; and/or no recorded incidents or anecdotal evidence; and/or very few incidents in associated organisations, facilities or communicates; and / or little opportunity, reason or means to occur; May occur once every 100-500 years.
3	Unlikely	May occur at some time; and /or few, infrequent, random recorded incidents or little anecdotal evidence; some incidents in associated or comparable organisations worldwide; some opportunity, reason or means to occur; may occur once per 10-100 years.
4	Likely	Likely to or may occur; regular recorded incidents and strong anecdotal evidence and will probably occur once per 1-10 years.
5	Very Likely	Very likely to occur; high level of recorded incidents and/or strong anecdotal evidence. Will probably occur more than once a year.

The below table presents impact classification (Department of Defence, 2012).

Ranking	Classification	Impact	Description
1	Very low impact	Life, Health, Welfare	Limited number of people affected; 0-4 fatalities and limited number of minor injuries requiring first aid treatment.
		Environment	Simple, localised contamination.
		Infrastructure	<4M Euros.
		Social	Localised disruption to community services or infrastructure (<48 hours).
2	Low impact	Life, Health, Welfare	4-8 fatalities; considerable number of people affected; serious injuries with hospitalisation and medical treatment required. Localised displacement of a considerable number of people for 2-8 days. Personal support satisfied through local arrangements.
		Environment	Simple, regional contamination, effects of short duration.
		Infrastructure	4-24M Euros.
		Social	Community functioning with considerable inconvenience.
3	Moderate impact	Life, Health, Welfare	Significant number of people in affected area impacted with multiple fatalities (8-20), multiple serious or extensive injuries (20), significant hospitalisation. Large number of people displaced for 2-8 days or possibly beyond; up to 4000 evacuated. Regional resources required for personal support.
		Environment	Heavy contamination localised effects or extended duration.
		Infrastructure	24-80M Euros.
		Social	Community only partially functioning, some services available.

4	High impact	Life, Health, Welfare	20 to 50 fatalities, up to 100 serious injuries, up to 16000 evacuated.
		Environment	Heavy contamination, widespread effects or extended duration.
		Infrastructure	80-200M Euros
		Social	Community functioning poorly, minimal services available.
5	Very high Impact	Life, Health, Welfare	Large numbers of people impacted with significant numbers of fatalities (>50), significant injuries in the hundreds, more than 16000 evacuated.
		Environment	Very heavy contamination, widespread effects of extended duration.
		Infrastructure	>200M Euros.
		Social	Serious damage to infrastructure causing significant disruption to, or loss of, key services for prolonged period. Community unable to function without significant support.

In general, further research is required into early warning systems in Ireland. A number of trial sites and monitoring systems need to be identified and a number of pilot projects carried out to inform future decisions on the implementation of landslide monitoring systems in Ireland.

7 Monitoring strategy and pilot project outline

7.1 Detailed monitoring example

Landslides are complicated events which are dependent on several different factors. Therefore one single monitoring solution will not be globally applicable to every scenario. However, considering the prevalence of shallow translational earth and peat slides in the previous chapters and the driving influence of rainfall in triggering such events, an example pilot strategy is outlined below which can be applied to the majority of landslide susceptible areas. It is proposed that a dedicated landslide area is selected which is highly pre-conditioned toward slope instability or has evidence of existing movement and this slope is used to demonstrate the effectiveness of various monitoring approaches, including physical sensor systems and remote monitoring including drone surveys.

Framework for Pilot Programme:

- Prepare shortlist of pilot programme objectives ;
- Develop technical constraints for the study area (eg. soil type, etc.) ;
- Develop practical constraints for the study area (eg. access, security, …) ;
- Short-list demonstrator sites based on specific prioritisation criteria ;
- Complete desk study of every possible site ;
- Select demonstrator site and validate using detailed site visit ;
- Complete Site Investigation (drilling and geophysical) ;
- Prepare accurate maps (topographical and geological) of the demonstrator site ;
- Develop detailed intrusive monitoring regime ;
- Develop non-intrusive monitoring regime ;
- Analyse results, interpret results and report to ensure the system is functioning ;
- Tweak system to enhance the “live” component toward an Early Warning System
- Establish IT systems (applications and web portals) for public data access in a filtered format for lay understanding.

Proposing Monitoring Regime:

- Weather station: Considering the strong correlation between rainfall, soil moisture and landslide occurrence, installation of a local weather station is critical to the success of a pilot project. This weather station should be installed in an appropriate location to ensure representative data in attained for the slope of interest. Therefore the aspect and microsite location is important.
- Direct measure of Soil Suctions: As the most common landslide trigger is due to decreasing soil suctions in the upper soil layers near ground surface as the soil moves from a partially saturated to a fully saturated state due to rainfall infiltration, this is a critical parameter to measure. Soil suctions can be measured directly using tensiometers. Tensiometers should be placed over at least three different depth ranges (0.5, 1 and 2m depth).
- Indirect measure of Soil Suctions: As soil suctions are difficult to measure directly due to the accuracy, reliability and robustness of tensiometers it is proposed that supplementary

measurements are taken for redundancy by using soil moisture measurements as a proxy for soil suctions. For example, tensiometers can be susceptible to very small interferences such as frost effects, whereas theta probes that measure the soil moisture are much more robust. During the early phases of the monitoring regime the theta probes can also be validated against the tensiometer measurements to confirm the accuracy of the proxy approach.

- Direct Movement Analysis: Establishing a direct measurement system that is capable of monitoring movements at a mm scale is not trivial and most systems do not have the accuracy needed to measure slow ground movements. Early stage Fibre Optic Systems have been used for infrastructure applications and could be deployed to measure local strains. In addition, survey markers/pegs should be used to determine movements at the pilot site.
- Remote Data (Drone): It would be very worthwhile establishing a fly over drone survey for both photographic records and x,y,z coordinates. A pre-programmed flight path would allow comparative surveys to be undertaken at 3-6 month intervals to determine whether there is any mass movement.
- Remote Data (InSAR): Satellite imagery should also be used as a comparator to the drone survey and site intrusive data. The relative accuracy and applicability of the various techniques should be compared following 12 months of data capture.

The main objectives of a pilot project are to establish an R&D demonstrator site for landslide research and for proving new technologies for sensors, remote data capture and early warning systems. A provisional monitoring regime was outlined above which aims to capture the landslide trigger mechanisms as well as the resulting movements.

The minimum type and number of intrusive sensors and monitoring devices used during this scheme are as presented in the Table below:

Monitoring Method	Minimum Number of devices	Reason
Tensiometer	3	To measure soil suction
Theta Probe	3	To measure soil moisture (proxy for suction)
Weather Station	1	To measure and record meteorological conditions
GP 2 Data Logger Controller	1	To measure and feed – back control
FBG Monitoring Gauges	2 strings with FBGs at 10m intervals over 100m	To measure movements

The overall cost range of monitoring ranges from €45,000 to €80,000 for a scheme outlined above.

8 Suggestions for Future Work

There are two main outcomes from this work, which we feel would benefit from further investigation. The first is around bias factors that we think are likely to affect future landslide susceptibility mapping and the second is around monitoring approaches for ground movements (i.e. a pilot monitoring study).

a) Landslide Susceptibility Bias Factors: In order to develop and calibrate the landslide susceptibility maps, it is necessary to train or validate the maps based on the density of landslides occurring at sites with specific characteristics. We have identified a few factors which may skew the results slightly, such as apparent peat slides (based on quaternary mapping) that are actually natural earth slides occurring 500mm below peat surface. We think the overlying peat may precondition the earth to failure by opening up preferential drainage pathways into the subsoil below. Also, there are areas of rock outcropping that suggests there is rock at ground surface (based on mapping) but the actual landslide is occurring on a veneer of peat.

To address these issues, we suggest that a Quality Assurance exercise is undertaken for the GSI susceptibility maps to see if these biases have any impact on the predictive capability for new landslide identification.

b) Pilot Slope Monitoring Programme: As outlined in section 7, we feel that there is merit to establishing a demonstration site and pilot monitoring regime. One of the things that we have been exploring is the possibility of deploying a system that could act as an early warning mechanism for slope instability and an alarm mechanism in advance of landslides occurring. There are two aspects to this, dealing with slow moving natural landforms (peat creep, etc) and rapid landslides such as bog bursts. One of the things we would be keen to do is to select a slope that is heavily preconditioned to movement and set it up as a trial monitoring site where we could test different instrument systems. In particular, what we would like to do is the following (i) install intrusive sensors in the slope to pick up physical measurements of pore pressure change, movement, etc. (ii) install an on-site weather station to get local rainfall measurements, humidity, baramoterics, etc. (iii) undertake regular drone flyovers including drone based lidar data for vector difference mapping and (iv) use regular satellite imagery (INSAR) to track movements remotely.

9 References

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Department of Communications, Energy and Natural Resources
An Roinn Cumarsáide, Fuinnimh agus Acmhainní Nádúrtha

Analysis and monitoring strategy of Irish landslides

Geological Survey of Ireland

Document Number 15070-01

Revision	Purpose	Date	Authored	Checked
00	Final Draft for GSI Review	08/12/16	K. Martinovic A Musial C. Dimet	P. Curran P. Doherty

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1 Executive summary

This project, entitled “Analysis and monitoring strategy of Irish landslides” has been commissioned and funded through Geological Survey of Ireland’s (GSI’s) 2015 Short Call research programme. The project, proposed and carried out by Gavin and Doherty Geosolutions (GDG), aims to provide an overarching analysis of landslide occurrences throughout Ireland. The analysis is based on a large volume of landslide inventory data collated through recent projects and research. The report includes statistical interrogation of existing landslide database records, coupled with the analysis of failure mechanisms. The project also includes interrogation of meteorological data in order to define the weather warning level for landslides in the form of rainfall thresholds. Finally, an overview of the testing and monitoring techniques suitable for typical landslides in Ireland is given, and a pilot-project monitoring strategy based on this is defined and presented. The guidelines given in this study provides a framework for monitoring landslides that can be rapidly implemented for future landslide data capture. This report is also intended to aid any general slope monitoring activities being undertaken by GSI.

2 Introduction

Following a series of catastrophic landslides over the last two decades, such as Pollatomish and Derrybrien landslides in 2003 (Figure 1), landslide events have received significant attention from a number of parties including the Geological Survey of Ireland (GSI). The desire to better understand landslide occurrences culminated in the formation of the Irish Landslides Working Group (led by GSI), which released a number of publications, with the most comprehensive being the "Landslides in Ireland" report which was published in 2006.

Figure 1 Landslides in (a) Pollatomish, Co. Mayo (source: ucd.ie), and (b) Derrybrien, Co. Galway (source: monasset.com)

Since then, the GSI initiated a large work programme related to landslide hazards in Ireland. The National Landslide Inventory was made publicly available in the interactive web GIS viewer. The original inventory was increased by a factor of thirty following the extensive data collection projects undertaken by Mouchel (2011), Trinity College Dublin (2014) and GDG (2014; 2014b; 2014c; 2014d). Part of the landslide inventory was used to develop the Irish landslide susceptibility map. This map was developed for the Wicklow and Cork areas, and is planned to be continuously updated using new inventory inputs. Additional research on geotechnical behaviour of Irish soils and scrutiny of some major landslide events has also been carried out (Long & Menkiti, 2007; Dykes & Warburton, 2007; Bourke & Thorp, 2005; Long & Jennings, 2006; Dykes & Jennings, 2011; Long, et al., 2011). All of this provides a valuable source of information which allows some general conclusions about Irish landslides to be made.

New landslides that have recently been recorded (Figure 2) clearly show that there is a need for on-going research in this field. These examples demonstrate the negative impact that landslides can have on the surrounding infrastructure. This makes landslide research in Ireland a matter of priority for industry and governmental bodies and not only an academic research topic. The landslide that swept away the Leenaun Bridge in Co. Galway in 2007 caused huge indirect damage, including traffic detours of up to 100 km and the substantial direct capital cost of replacing the bridge. Casualties were avoided by pure coincidence.


SKYCAM IRELAND
|aerial imagery

Figure 2 Examples of landslide in Ireland in the last decade: a) the remains of Leenaun bridge after it was destroyed by a debris flow in 2007 (source: rte.ie), b) one of many landslides damaging local road infrastructure during heavy storms in December 2013 (author's photo of Dog's Bay, Co. Galway), c) landslide and coastal erosion of a coastal cliff supporting rail infrastructure in Co. Wicklow in 2016 (source: Skycam Ireland), d) peat slide blocking a national road N59 in Co. Galway in 2016 (source: blogs.agu.org/landslideblog)

Landslide occurrences can be directly linked to physical mechanisms such as "soil moisture deficit" and therefore more extreme rainfall events can be correlated with more frequent landslides occurring. With the ongoing climate change, the frequency of such landslides can be expected to rise. The Intergovernmental Panel on Climate Change (IPCC) scenarios (Solomon, 2007) downscaled to Ireland (Sweeney, et al., 2008; McGrath, et al., 2008) show a significant increase in precipitation during the autumn and winter months (up to 25 %). These wet periods already see the majority of landslides, and with rainfall being by far the most common landslide trigger, it is likely that the number of landslides will increase in future. Furthermore, the amount of precipitation is expected to reduce from current levels in summer periods, further enabling the formation of shrinkage tension cracks in surface soil that act as water conduits during subsequent rainfall events. This mechanisms has previously been shown to be responsible for initiation of some Irish landslides (Long & Jennings, 2006). Finally, the rise in total precipitation in autumn and winter months will likely manifest through a series of irregular high intensity rainfall events rather than a monotonous increase in the strength of current rainfall patterns. This is especially unfavourable as it is the high-intensity rainfall that is commonly attributed as a trigger for shallow translational earth slides and peat slides (Aleotti, 2004), the two types of landslides found most frequently in Ireland. Given the continuous increase in transport and building infrastructure throughout Ireland and the increase in population, the vulnerability to landslide events is also clearly on the rise. With the expected increase in both landslide likelihood and landslide consequences, research into Irish landslides should become an increasingly important topic. This project provides steps towards better understandings of Irish landslides, their consequences, and potential steps in response strategy.

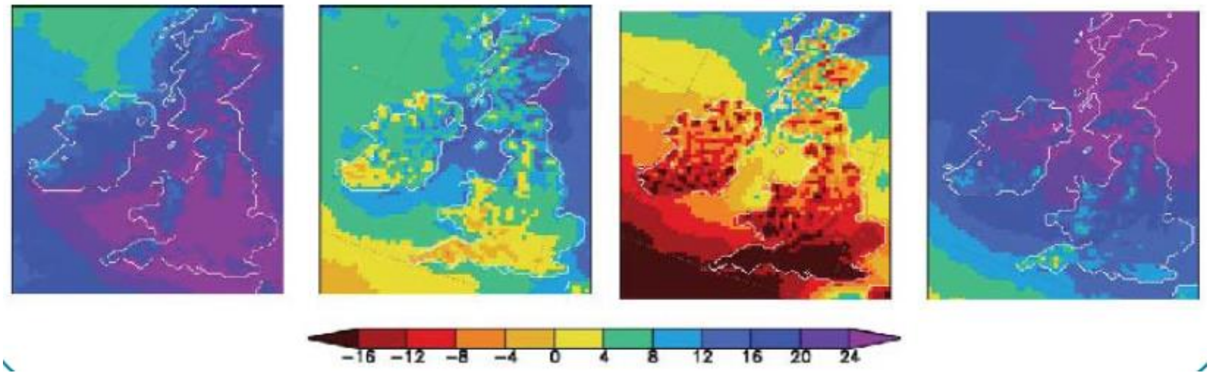


Figure 3 Modelled climate change for winter, spring, summer and autumn seasons. The figure shows percentage change in precipitation between the periods 2060-2099 and 1961-2000 (source: Ireland in a warmer world, Met Éireann and UCD)

3 Analysis of the landslide inventory database

The amount of data in the National landslide inventory has greatly increased in the last decade. The key publication, 'Landslide in Ireland' from 2006, mentions 117 recorded events, out of which 100 are in the Republic of Ireland. As of October 2016, there are over 3700 inputs in the National Landslide Inventory. The vast majority come from the inventory population projects carried on by the GSI (Pellicer & Verbruggen, 2006), Mouchel (2011), Trinity College Dublin (2014) and GDG (2014b; 2014; 2014c; 2014d). All projects used a two-step identification procedure: initial identification of candidate landslides using three sets of ortophotos originating from 2000 to 2010; followed by validation and further identification in the field. Not all of the candidate landslides were visited for validation due to inaccessibility or the lack of resources, so there is a possibility of additional landslides in the interrogated areas, notwithstanding the new failures that potentially occurred after the projects' end.

In brief, these projects covered the areas listed below and illustrated on Figure 4 and identified the following number of landslides:

- Mouchel (2011): two separate areas, Dublin & Wicklow and Southeast Cork (red squares). Total number of validated landslides: 396, out of which 391 in Dublin&Wicklow area.
- Trinity College Dublin (2014): two separate areas, County Mayo and County Kerry (green squares). Total number of landslides: 1810 (635 in Kerry and 1175 in Mayo). These numbers include the landslides that have not been validated on site (approximately 40% has been validated).
- GDG (2014b; 2014; 2014c; 2014d): four separate areas, Southwest Donegal, Slieve Bloom, South Tipperary and West Galway (blue squares). Total number of validated landslides: 353 (79 in SW Donegal, 64 in Slieve Bloom, 106 in South Tipperary, and 104 in Galway). It is worth noting that the majority of candidate landslides were not inspected due to the very short available validation timeframe therefore these numbers almost certainly underrepresent the actual number of failures.

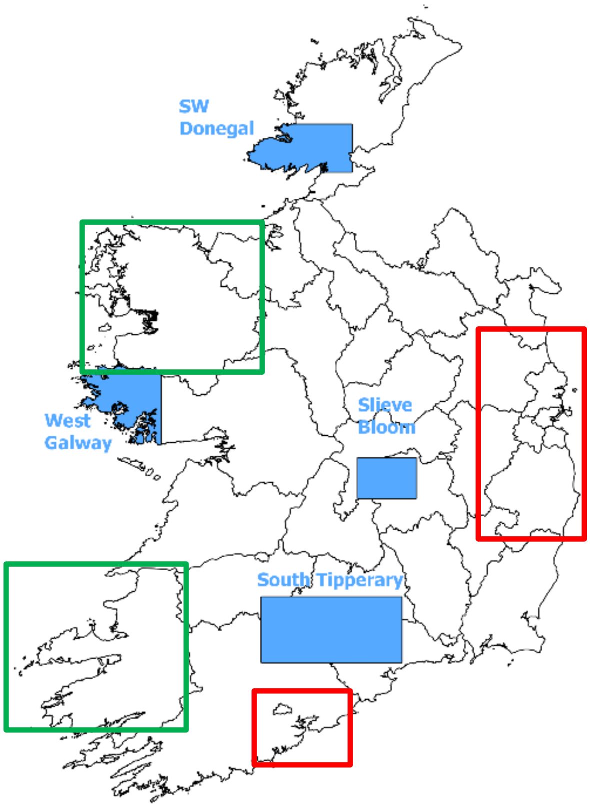


Figure 4 Areas covered by landslide inventory population projects

Locations of all recorded landslides (including landslides from the above mentioned database population projects) can be found in Irish landslides database, on the interactive web GIS viewer: http://spatial.dcenr.gov.ie/GeologicalSurvey/LandslidesViewer/index.html.

Most of the landslides are recorded with a point in the landslide source area, while there are also some rare examples of whole landslide area (source and deposit) being polygonised. The information field in the GIS database includes a wide range of options. For the vast majority of landslides, most of these input options lack the recorded data, including landslides for which the data was collated during the database population projects. This hampers the detailed interrogation of the inventory. Most of the populated input fields include the features that can be extracted from an underlying Digital Elevation Model for a known location, such as easting and northing, elevation, slope angle, slope aspect, quaternary deposit and bedrock. Features that are of most interest for this study, including source area dimensions, run-out length and failure mechanism are mostly missing. Dimensions and run-out length were seldom measured during the database population project due to small sizes of landslides (problem for ortophotos) and inaccessibility (problem for in-situ validation).

3.1 Analysis of failure mechanisms

Information on failure mechanisms differs between the reports produced for the various study areas. The landslide table included in Trinity College Dublin report (2014) includes the "Type of movement" field. However it is extremely sparsely populated, seemingly with only rockfalls being systematically highlighted. Original GIS data potentially possess more information but it has not been available to authors of this report at the time of writing.

The landslide table included in Appendix 2 of Mouchel's report (2011) contains the field 'Comment' with landslide mechanism descriptions for 182 validated landslides. The descriptions are somewhat unstandardized and inconsistent, making the summary of landslide types a non-trivial task, but nevertheless present a good source of information. GDG summarised, standardised and simplified the inputs, with the failure type distribution presented in Figure 5. 81, or 44 % of those failures were labelled as (large) peat slides, including several mentions of peat failures or bog bursts. Earth failures accounted for 42 % of all failures, including 56 (shallow) translational slides, 13 earth flows and 7 rotational slides. Rock falls and debris flows/slides accounted for the rest of the inputs.

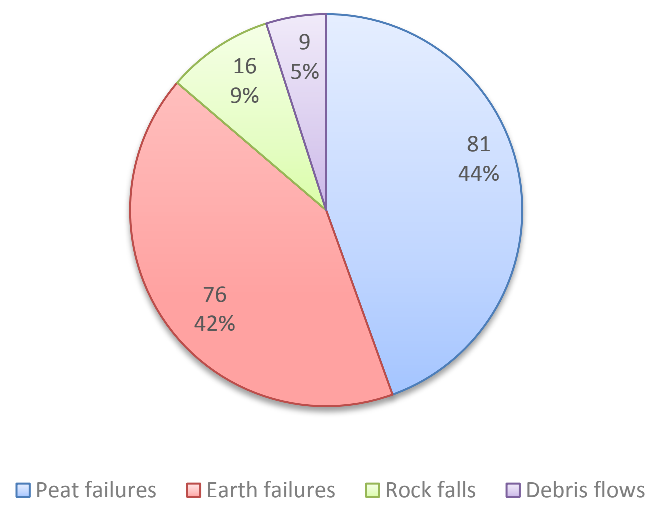


Figure 5 Distribution of main failure types in Mouchel report (2011)

In GDG's reports (2014b; 2014; 2014c; 2014d), failure type was assigned to each landslide validated in-situ. A landslide mechanism classification scheme based on Varnes (1978) and Cruden & Varnes (1996) was used to ensure the standardisation of inputs. This classification classifies landslides based on two major criteria, type of movement (falls, topples, slides spreads, flows) and type of material involved in the movement (rock, debris, earth). The landslide types used in this classification are illustrated in Figure 6.

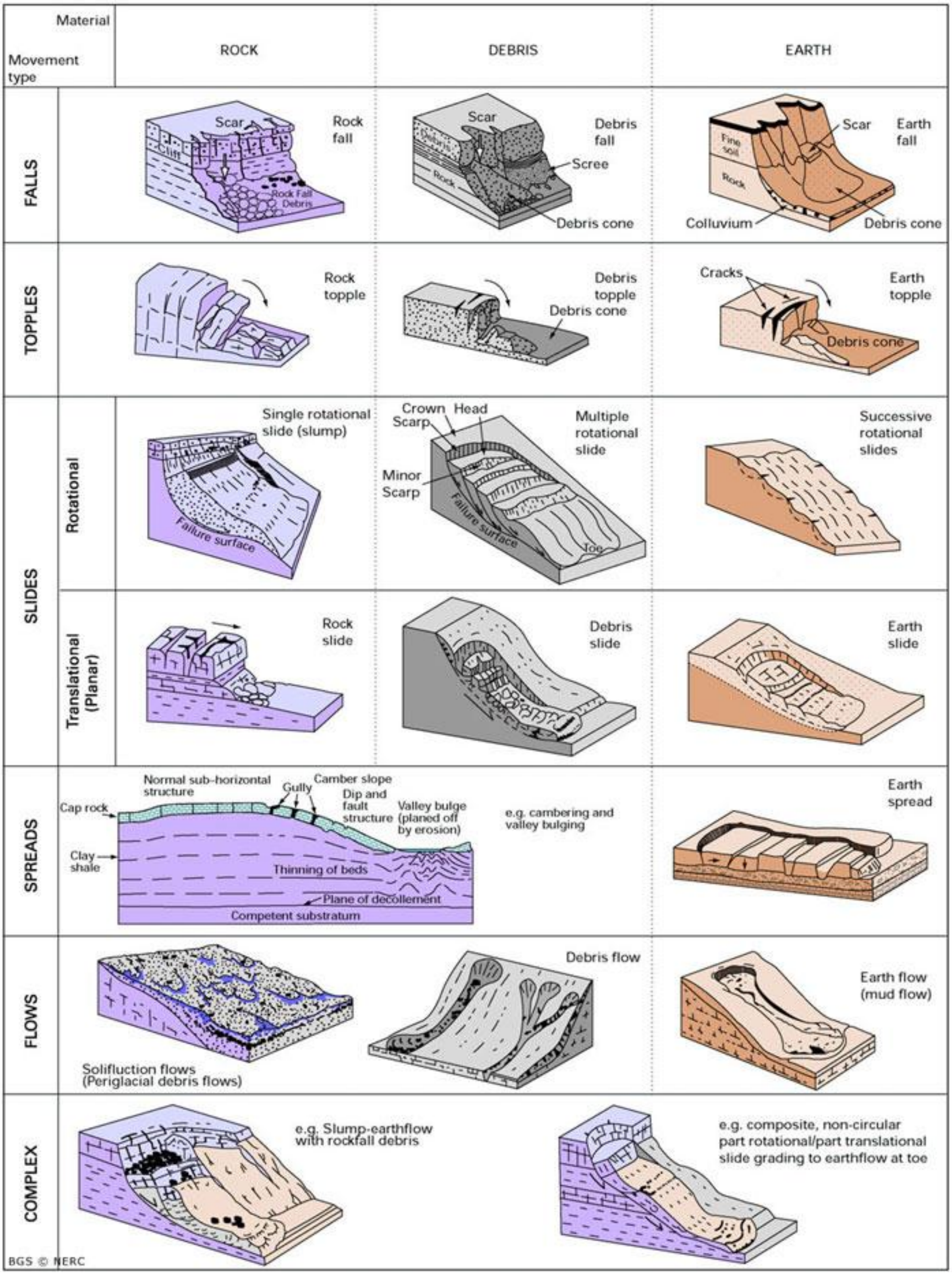


Figure 6 Landslide classification according to Varnes (1978) and Cruden & Varnes (1996)

Results of landslide classification of each of GDG's four study areas are presented in the tables below:

South Donegal:

Material Movement	Rocks	Debris	Earth	Peat
Falls	3	-	-	-
Topples	-	-	1	-
Rotational Slides	1	-	12	-
Translational Slides	-	1	22	13
Spreads	-	-	-	-
Flows	-	9	-	-

Slieve Bloom:

Material Movement	Rocks	Debris	Earth	Peat
Falls	-	-	1	-
Topples	-	-	1	-
Rotational Slides	-	-	13	-
Translational Slides	-	-	22	23
Spreads	-	-	1	-
Flows	-	1	8	8

South Tipperary

Material Movement	Rocks	Debris	Earth	Peat
Falls	12	14	-	-
Topples	3	-	1	-
Rotational Slides	-	-	-	-
Translational Slides	1	7	7	4
Spreads	-	-	-	-
Flows	-	20	4	4

West Galway

Material Movement	Rocks	Debris	Earth	Peat
Falls	11	3	-	-
Topples	-	-	2	-
Rotational Slides	-	-	14	-
Translational Slides	1	1	26	4
Spreads	-	-	-	-
Flows	-	12	2	-

These distributions reveal the specifics of each study area, for instance the abundance of peat failures attributed to vast and deep blanket bog in Slieve Bloom mountains, or frequent rockfalls on exposed cliffs of South Tipperary mountains.

The cumulative table, while admittedly hiding the specifics of each area, can help give the overall distribution of landslide mechanisms across Ireland:

Landslide Study Area's Review				
Material Movement	**Rocks**	**Debris**	**Earth**	**Peat**
Falls	26	17	1	0
Topples	3	0	5	0
Rotational Slides	1	0	39	0
Translational Slides	2	9	77	44
Spreads	0	0	1	0
Flows	0	42	14	12
Total	**32**	**68**	**137**	**56**

It is evident that translational slides and peat failures account for the majority of landslides, followed by debris flows (possibly created by channelling the original transational earth slides or rockfalls and entraining additional material) and rockfall. This distribution aligns very well with the one obtained by analysing Mouchel's data. As a conclusion, (shallow) translational slides and peat failures form the clear majority of Irish landslides. Anecdotal evidence and research studies furthermore show that these landslides are mostly triggered by rainfall.

3.2 Key conclusions

Analysis of the available data resulted in the identification and description of the most common landslide types/mechanisms in Ireland, presented in the previous section. The analysis also yielded some additional insights into landslide causes, behaviour and impacts. This section outlines the observed patterns that may improve the understanding of landslide behaviour and consequences; recording and analysis of future landslides; and those patterns that might affect future work on landslide susceptibility, hazard and risk mapping in Ireland.

3.2.1 Run-out analysis

The vast majority of recorded landslides is identified by a point located in the landslide source area. Similarly, the dimensions of landslides (both source area and deposition area) were extremely seldom recorded, with the exception of few major landslides studied in-depth in scientific publications (Long and Jennings 2006, Dykes and Jennings 2008, Long, et al., 2011). For the few landslides that are represented by a polygon vector in web viewer, there is no distinction between source and deposition areas. All of this hampers the exhaustive quantitative appraisal of landslide run-out. However, the few documented events, and GDG's first-hand experience in part of landslide inventory population process enables the completion of a general-level qualitative analysis.

Very long run-outs with significant deposit depth are characteristic for major peat failures, in particular bog bursts and peat flows where shear surface developed through the peat material itself rather than through basal contact or underlying layer of mineral soil. The combination of easily disturbed peat downstream of initial source area and lubricating action of the water contributes to landslides stretching for several hundreds of meters, with the largest of them stretching over several kilometers. Boylan et al. (2008) presented a correlation between the runout distance and the failure volume for the blanket bog and the raised bog (Figure 7). It shows that for peat failures of up to 50,000 m3 the observed run-outs were reaching 300-500 meters, with possibility of longer run-outs rapidly increasing with volumes larger than that. Run-out may not be the most correct term as these peat failures tend to disturb and entrain material during the course of the movement, effectively enlarging the initial source area. As a consequence of this, it is often difficult to diferentiate between source area and deposition area for these types of failures. The peat slide at Ballincollig Hill in Kerry in 2008 exhibited a total length of over 3 km after it joined the stream (Long, et al., 2011). Large run-outs tend to occur even on the very gentle slopes, in places less than 5˚. The run-out deposit depends on the depth of peat in-situ among other things, and was shown to exhibit significant depths of over 1.5 m for sustained lengths. All these features make peat slides/flows potentially dangerous even for those infrastructure and environmental features that are seemingly a safe distance from the hazard area. Examples of affected infrastructure include numerous local roads (Figure 8), private houses, and environmental property such as forestry or fish farms.

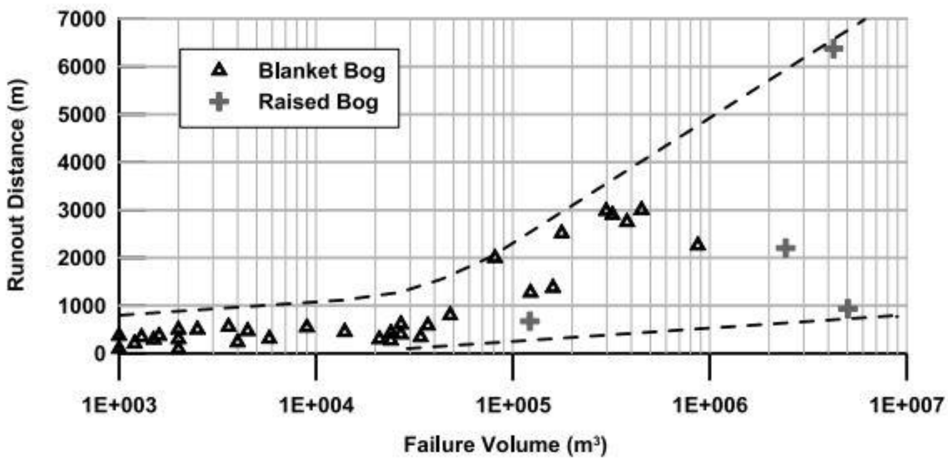


Figure 7 Run-out distance with failure volume (source: (Boylan, et al., 2008))

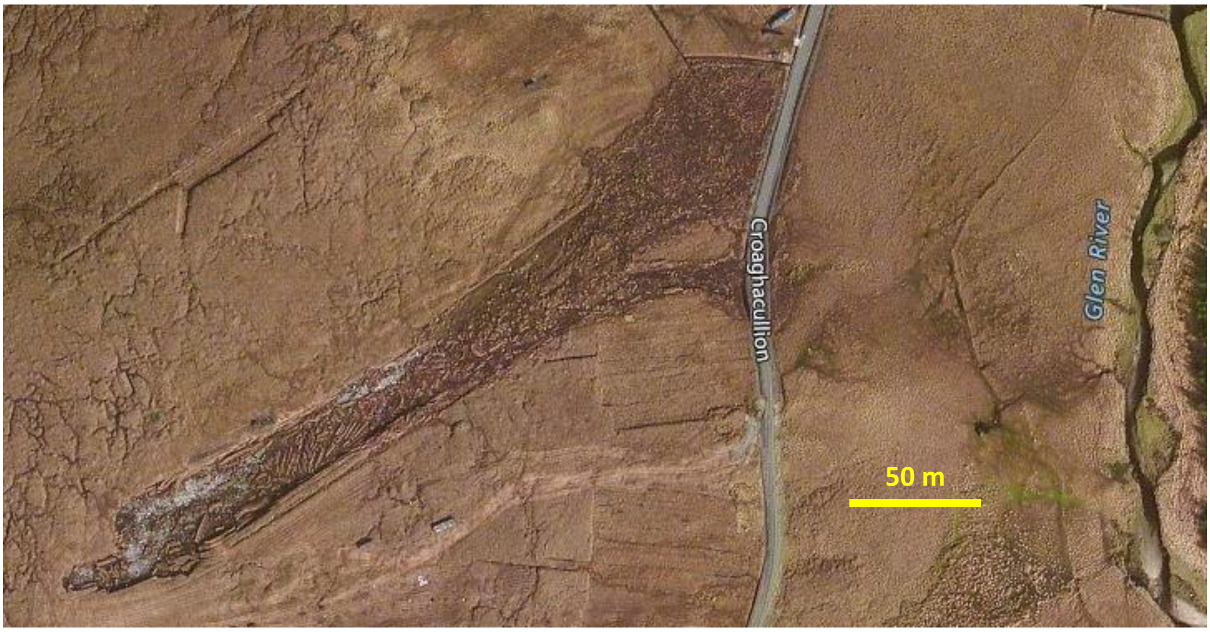


Figure 8: Aerial photo of a 2008 peat slide in Croaghcullion, Co. Donegal (source: Microsoft Bing Maps)

The other most frequent type of landslide, shallow translational earth slides, exhibit somewhat different behaviour. GDG's experience from the four study areas shows that the source area and deposition area can be clearly distinguished, both on aerial imagery and in-situ. This is especially visible for the landslides in shallow soil overyling the bedrock where the failure plane is located on the soil-rock contact. The vast majority of observed landslide scars (source areas) have an ellipsoidal, rounded shape with a pronounced semi-circular crown, which is usually the most clearly distinguishable feature in the field. The longer axis of the landslide scars, usually parallel to sliding direction, was observed to be up to 40 m long. While the exact measurements were seldom available due to reasons already outlined in this study, the source area of a typical large slide was in the range between 300 and 750 m^2, with failure depths between 0.75 and 2 m. The exceptional catastrophical events such as Pollatomish in 2003 and Croaghmoyle in 2009 involved volumes of material of up to 20,000 m^3 (Long 2006, Long et al. 2011).

The location of the shallow landslides adjacent to the near natural water channels/streams could be a contributing factor but does not seem to be the main driving factor, since a significant portion of the observed landslides appear to occur remote from such water features. Another interesting observation was that many landslides appeared on rectilinear or convex flanks rather than in hollows where the concentration of subsurface drainage and sediment depth is expected (Pierson 1980). Both remarks point to the possibility that surface and subsurface hydrology plays a less significant role than the depth to the bedrock or slope angle. This observation might be taken into account in subsequent landslide susceptibility analyses undertaken by GSI.

The size of average shallow slide provides limited volume of deposit for run-out. However, these run-out can in places also reach the length of several hundred meters. This typically occurs on steep and uniform slopes with little or no vegetation (frequently with a thin surficial blanket peat layer) or other kind of obstacles. Slopes like these are characteristic to sides of glacial valleys. The deposit is spread very thinly over a long and laterally confined area (Figure 9). As such it is very exposed to being gradually washed out by successive rainfall, more details on this topic will be presented later in this report. Many shallow failures actually exhibit very short run-outs, due to a combination of small size of source area (and subsequent small deposit volume) and characteristics of terrain such as concave slope form (at the base of hillslopes), hollows, vegetation, etc. This significantly decreases their potential impact to infrastructure and society if source area is not located directly next to the element at risk which is, for example, the case at steep road cuttings. However, evidence from several historical failures shows that the length of run-out and potential impact can be multiplied if the source area is located next to the existing stream. Water in the stream enables rapid transport, and hard and dense till particles (especially embedded boulders) easily erode stream sides, leading to entrainment of additional material on the way downward. The combination of high velocity and significant total mass of the debris material being transported by water creates high impact forces which can have devastating effects. A prime example of this is the collapse of Lennaun Bridge in July 2007, caused by a debris impact of landslide of a typical large but by no mean exceptional size. The landslide's source area and flow path are shown on Figure 10.

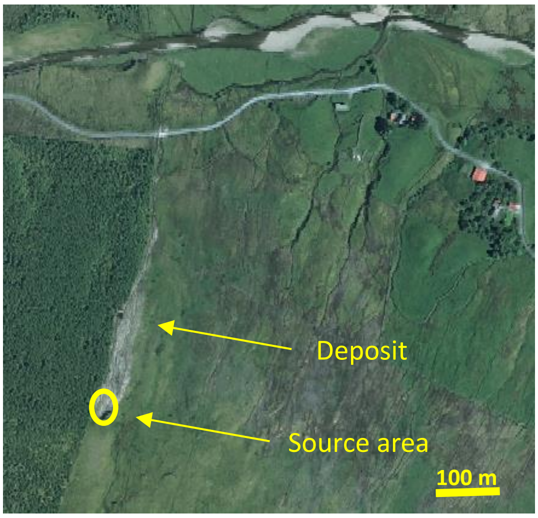


Figure 9 Typical deposit path from shallow translational slide in till (source: Google Maps)

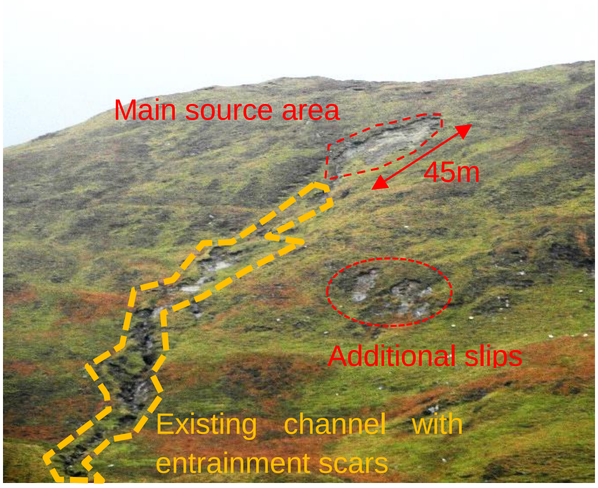


Figure 10 Source area and upper part of stream of the July 2007 Leenaun shallow landslide

3.2.2 Issues with inferring the landslide material from the existing maps

Quaternary deposit (subsoil) maps developed by GSI give excellent information on Irish soil cover, particularly the dominant type in the top 1 m below ground level. This is of clear significance for the understanding of Irish landslides, as the vast majority of them are shallow and controlled by surficial features. Provision of maps in shapefile format enables easy automatic identification of surficial soil type on the landslide location using GIS. Indeed, soil type is one of the rare categories available for almost all landslides in the national landslide inventory.

Knowing the soil type can give an indication of the type of failure likely to occurring within the soil mass. For example, in peat terrain, peat slides should be expected, while on areas designated as 'Rock on surface' (or 'Bedrock outcrop') only rock failures (rock falls/slides/topples) should be expected due to the absence of overburden. However, GDG's experience from on-site validation exercises have shown a significant discrepancy between the failure type expected based on soil maps and what was observed onsite. It was manifested in landslide types occurring on the locations where they should technically not be possible. This observation was usually discovered at the final stage of project, when the confirmed landslides have been placed in the GIS shapefile layer that was then interrogated for the summary of the discovered landslides characteristics. This discrepancy has also been noted in previous rounds of inventory population project. In this project it was checked in more detail and described.

One of the most easily identifiable issues was the presence of shallow landslides and debris flows on the terrain that was mapped as 'Bedrock outcrop'/'Rock on surface'. An example is shown in Figure 11. These landslides developed in thin surficial colluvium layers, with the failure plane developing either on the bedrock/soil interface or (less often) through the soil. The landslides have most probably been caused by rainfall infiltrating through the thin soil layer to the much less permeable bedrock and subsequent build-up of the soil water pressure from the rock/soil interface upwards. In cases this was aided by the exiting streams. The soil cover in these areas is extremely thin (less than

1.0 m), prompting the map to describe the area as bedrock at surface, owing to the definition of quaternary deposit map as showing the *dominant* type in the uppermost 1 m. In these cases, the rockfall would be expected, so a presence of shallow soil slides with vastly different trigger, size and run-out may pose serious repercussions in accuracy of future landslide, hazard and risk maps in such areas.

The frequency of this issue can be inferred from the summary statistics from West Galway study area covered by GDG in 2014. The simplified statistics in Figure 12 show the breakdown of landslides by landslide mechanism type, and the breakdown by soil type extracted from GSI subsoil map. The breakdown shows that while over 51% of failures occurred on the area mapped as 'Bedrock outcrop', only 15.8% of reported failures were actual rock failures (rock falls/slides/topples). The rest is attributed to earth slides and debris flows, which are also largely present at 'Scree' soil type. The difference clearly shows the scale of this issue and calls for potential further examination of soil maps used as factors in landslide susceptibility analyses. It should also be noted that landslide mechanism breakdown was made using the population of 76 positively validated landslide, while soil type was made using the population of 104 landslides (positively validated plus new) so minor discrepancies arising from this are possible.

Figure 11 Shallow soil slide on soil mapped as 'Bedrock outcrop' (source: GSI)

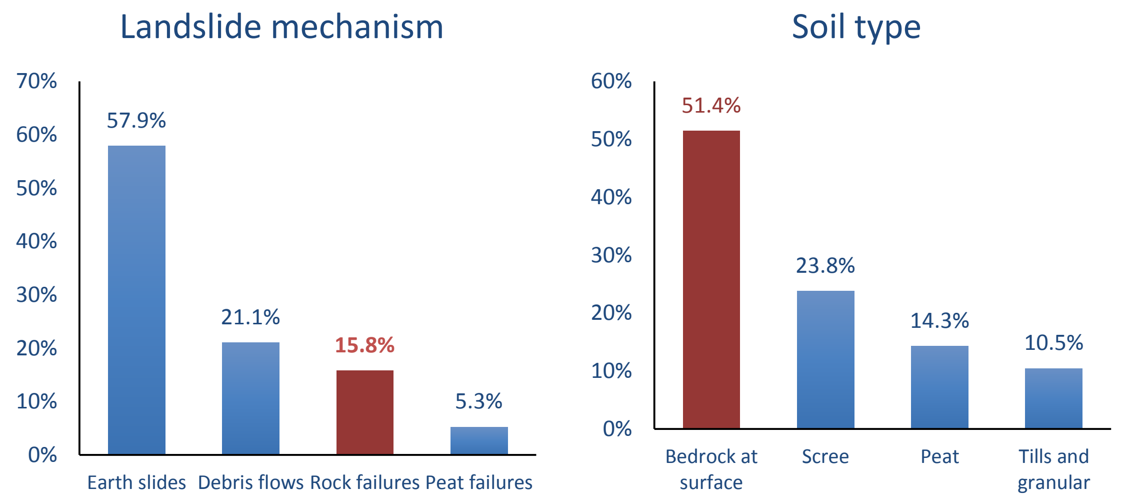


Figure 12 Breakdown of landslide mechanism and soil type for landslides recorded in West Galway study area

Similarly, landslides occurring on areas designated as having peat cover do not always manifest as typical peat slides/flows with flow like behaviour, large areas involved and very long run-out even on gentle slopes, as was observed at Derrybrien in 2003 and Croaghcullion in 2008. The majority of the slides occurring on the thin blanket bog covering the upper, steeper parts of hills actually exhibit the characteristics of minor shallow earth slides, see examples in Figure 13. An in-depth analysis of some of these slides (Long 2006, (Dykes & Warburton, 2007) showed that in this case the failure plane is actually developed i) through mineral soil (typically till) and/or weathered rock existing between top peat layer and bedrock, or ii) directly on the mineral soil / bedrock interface. This implies that the peat layer and its geotechnical shear strength characteristics do not actually play a major role in these cases, which explains the translational earth slide –like behaviour of these events. This particular type of peat-related failure has indeed been observed and classified by Dykes and Warburton (2007)as a separate peat failure type in their classification scheme of peat failures, where they were named 'peaty-debris slides'. These slides are described as "shallow translational failure of a hillslope with a mantle of blanket peat in which failure occurs by shearing wholly within the mineral substrate and at a depth below the interface with the base of the peat such that the peat is only a secondary influence on the failure". Due to these reasons, slides are often recorded as translational earth/debris slides in literature (Long 2006, 2011) and in the inventory population projects. These type of failures appear to be especially abundant in mountainous regions of Ireland due to the geomorphology of glaciated valleys and very thin peat cover at places, which is nevertheless mapped as 'Blanket peat' soil cover on subsoil maps. As peat slides and translational earth slides have very different behaviours and consequences, as described earlier in this report, it might be beneficial to increase the level of detail when dealing with expected landslides in these areas, i.e. in preparation of future susceptibility, hazard and risk maps. Some suggested ways forward might be to introduce peat depth as an additional factor, or to reclassify the recorded peat failures according to detailed peat failure classifications such as Dykes and Warburton (2007).

Figure 13 Examples of shallow earth slides on the terrain with "Blanket peat" soil cover mapped

It should also be mentioned that the slide surface at most peat failures is most probably complex and not just composed of one type, especially for bigger slides, which makes classification difficult.

Part of the problem in assigning the correct soil type to each landslide is that borders between soil types are approximate due to the scale of the soil mapping exercise, but this is out of the scope of landslide inventory and hazard/risk mapping issues.

In summary, as the current (and all other potential) landslide susceptibility analyses include soil cover as one of the most important conditioning factors, the results might be influenced by these observations. Furthermore, if in future there will be separate susceptibility analyses for each mechanism (peat failures, earths slides, debris flows, rockfalls), as is recommended in scientific literature, then actual landslide types might not be correctly observed for specific areas. More detailed investigation on this thematic is recommended.

3.2.3 Temporal fading of landslide features on aerial imagery

During aerial image processing (first step of landslide inventory population) and validation through subsequent fieldwork (second step), different types of landslides were found to exhibit very different levels of visual clarity when viewing aerial images and as a result there was a significant difference in the recognisability of some landslides. This is particularly noticeable when viewing older sets of aerial images, suggesting that the temporal processes that obscure landslide features over time can have a dramatic impact on identifying older failures and subsequently on the number of discovered landslides. This was particularly visible when comparing peat slides/flows and shallow earth slides in GDG's four study areas.

Peat slides in Ireland, although mostly having relatively similar failure depths as shallow earth slides, tend to be easily identified during aerial imagery processing due to clear features. Apart from their usually large size, some of the main characteristics they exhibit are clearly outlined boundaries, presence of multiple rafts of peat floating on the landslide area and clearly defined tension cracks on or behind the crown. Figure 14 shows a representative example of two large peat flows situated in Slieve Bloom mountains study area.

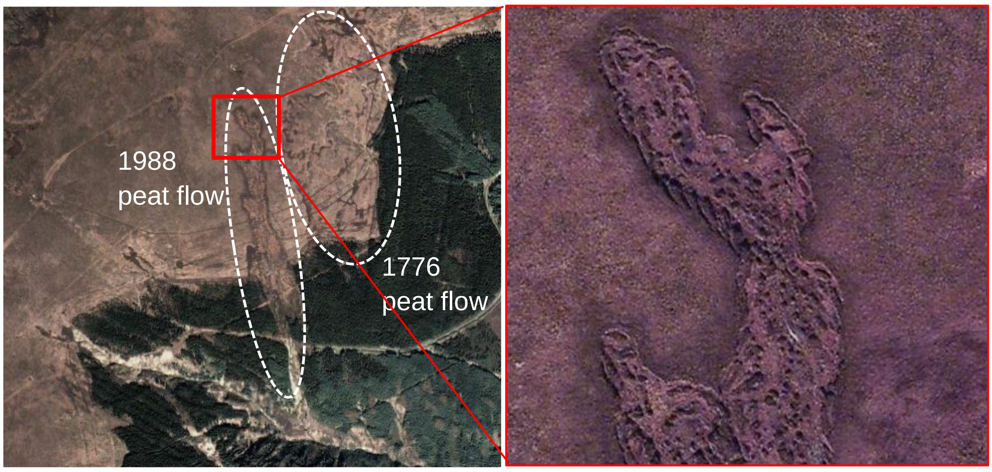


Figure 14 a) Aerial image of two bogflows in Slieve Bloom study area, b) close up of 1988 bogflow crown (source: Google Maps and Bing Maps)

Another defining feature of peat slope failures is the longevity of these characteristics. A common lack of diverse vegetation in blanket bogs that could obscure the landslide features, and a very slow rate of peat regrowth (Keddy , 2010; Lamb , 1977) ensure that peat failures are easily identified in aerial imagery in the decades and even centuries after they happened (Figure 14).

During the aerial imagery processing, shallow translational slides were largely recognized thanks to extensive deposit areas downslope from the failure scars. During the subsequent fieldwork (November 2014), it became clear that many of the sediment deposits that were clearly seen on aerial imagery dating from 2010 had been completely washed out by surface runoff and subsequently revegetated. The source areas of these landslides were much more difficult to recognise without adjoining deposits due to (i) their relatively small size (100 – 500 m^2), (ii) earth colour that matched those of surrounding low grass and moss vegetation, and (iii) a widespread lack of taller vegetation in the general area which, when swept out by the slide, usually serves as a first indicator of the slide. Considering that these historic landslides that were once clearly identifiable are now difficult to confirm even when standing in the known location of the slip, suggests that identifying older shallow translational failures from aerial imagery is an even more challenging task. This suggests that shallow landslides that are not identified quickly after the event are likely to be missed in subsequent inventory development due to the rapid obscuring of the landslide features in the immediate years after the failure.

In general, failure to identify all possible shallow landslides through aerial imagery processing might result in slightly skewed results of subsequent landslide susceptibility analysis. This is not considered a major problem because there is a large number of identified shallow landslides used for the creation of the existing susceptibility map. However, hazard assessment might be subject to larger errors, due to possible miscalculation of return periods and following probabilities of failure. That is especially applicable to areas with perceived relatively low density of landslides such as the study areas covered so far.

To avoid this issue in cases where multiple aerial imagery sets in close temporal succession are not available, time intervals between photo sets should be determined to be at least shorter than the 'deposit fading' period typical for the study area. This time frame will depend on the average landslide soil area and depth (and thus deposit size), terrain characteristics and rainfall characteristics of the study area. For Western Ireland, the deposit fading period is loosely determined to be less than four years, as evidenced by total disappearance of deposit layers exceeding 100 m length within that period. This rapid deposit receding rate can be attributed to several factors which include the shallow nature of the deposit layer (<0.3 m) caused by small average size and depth of landslides in the area, frequent rainfall, presence of many surface drainage lines, uniformity of terrain and a lack of major obstacles (surficial hollows, resistant vegetation).

A detailed example of analysis of reduction of a visible landslide deposit area is given in Figure 15. The deposit area of landslide (landslide ID 1805 in Irish Landslides Database) has been examined through several aerial imagery sources from different dates, including sets provided by Ordnance Survey Ireland and open sources such as Google Earth or Bing Maps. The landslide occurred in the townland of Poundcartron in Maumturk mountains in Connemara, and was characterised as a large shallow rotational slide in glacial till, although the soil map indicates bedrock at surface. The outline of the deposit area observed for each period clearly illustrates the receding trend. Possible explanations on why the lowest part of deposition area was erased first include very small deposit thickness at this location due to the distance from the source, and its position on a low lying river terrace susceptible to seasonal flooding from Bealnabrack River. Likewise, the still visible patch of deposit directly below the landslide scar might be caused by more significant initial sediment depth and continuing erosion of the exposed backscarp.

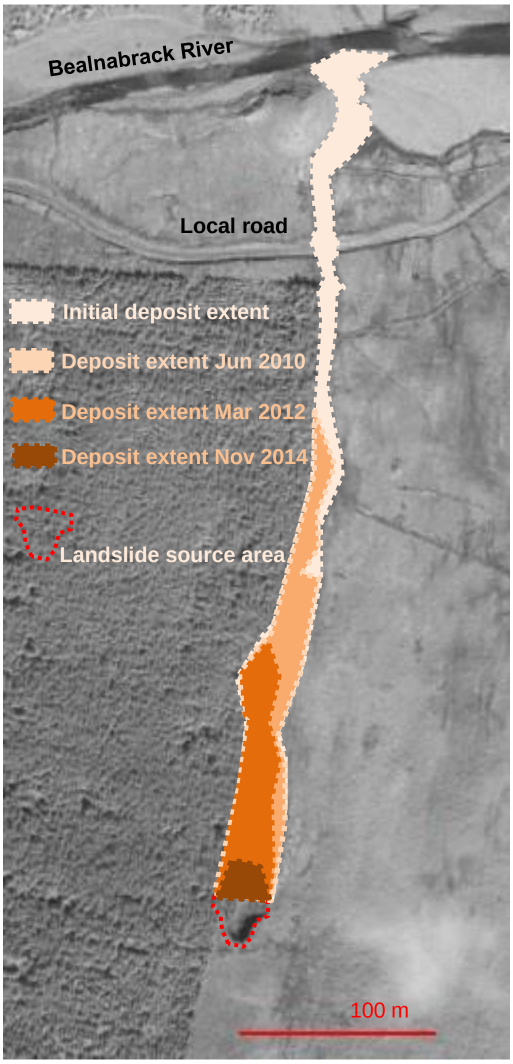


Figure 15 Deposit area of landslide 1805 through time (background image source: Google Earth)

One reason for the prevalence of shallow transitional earth slides among the landslides that rapidly loose identifiable features is the very shallow position of bedrock and often abrupt change from competent bedrock to soil, with little or no weathered rock layers in between. This in turn makes deep and large landslides that could be easily identified on aerial imagery extremely rare.

3.2.4 Additional analyses

Some additional analyses were carried out to interrogate the effect of landslide location. Three different study areas were examined and compared: i) SW Donegal, characterised by varied terrain including a combination of steep glacial valleys and gentle hills; and extensive peat cover in combination with till coverage and exposed bedrock; ii) Slieve Bloom, low lying rounded hills characterised by deep peat cover; and iii) South Tipperary, characterised by numerous very steep hills with exposed bedrock.

Figure 16 presents the scatter plot of elevation and slope angle for each recorded landslide point in the area. The absolute value of elevation itself does not offer the full picture as it depends on the general elevations of the study area. However, combined with the knowledge of the study area morphology, some interesting observations can be concluded. For example, the majority of landslides in Slieve Bloom are initiated in a tight range around 450 m of altitude and with slope angles between 5° and 12°. Observing the study area, this corresponds with the locations where relatively flat tops of the hills (with elevation between 450 and 500 m) with deeper peat cover make a convex break into the steeper hillside. These particular locations are therefore extremely susceptible to peat slides.

High peaks of Galtee, Knockmealdown and Comeragh mountains are responsible for the distribution of landslides in South Tipperary study area that sees landslides predominantly initiated on elevations between 500 and 800 meters. However, unlike at Slieve Bloom, majority of landslides are initiated on relatively high angles of over 30°. Given the prevalence of rock falls/slides/topples and the associated debris flows documented in the area, it can be concluded that steep (occasionally sub-vertical) rock outcrops and cliffs at the higher reaches of the ranges are the most susceptible to failures. It should be noted that the actual slope angles at source points are most probably higher than reported in Figure 16, as 20mx20m DEM used for extracting data averages the values found across the pixel, thus often underreporting sub-vertical areas.

The distribution for the SW Donegal study area with its varied terrain was used to check and validate the conclusions from the previous two areas. Indeed, the distribution is quite evenly spread, which translates well to multiple different terrain features and landslide mechanisms recorded in the area.

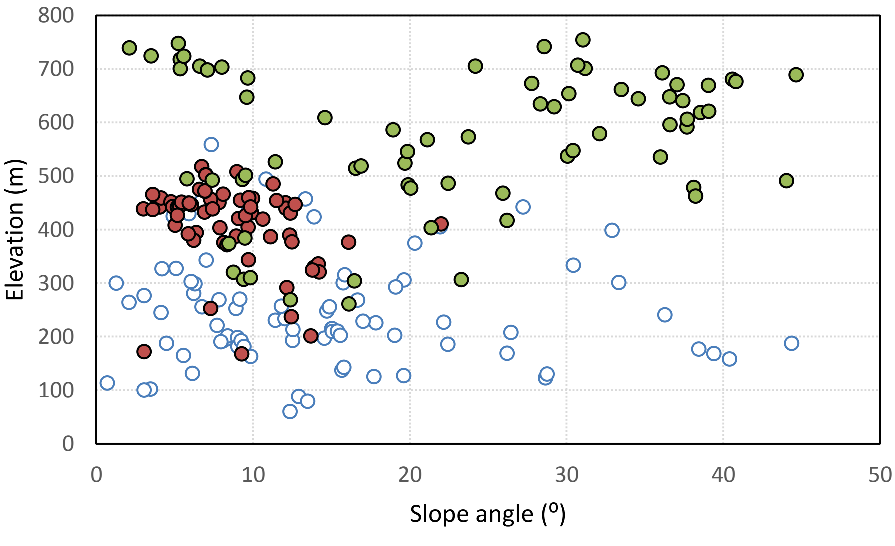


Figure 16 Summary of distribution of elevation and slope angles for the landslides in three study areas: SW Donegal (empty), Slieve Bloom (red) and South Tipperary (green)

3.2.5 Landslides affecting local road infrastructure

Transport infrastructure is the type of infrastructure most susceptible to landslides in Ireland due to its extents and reach in various areas including hilly terrains. Another reason is the existence of numerous man-made cuttings and embankments, often aged and installed using poor design and/or construction techniques, making them susceptible to failure. Media reports of blocked transport infrastructure, particularly local roads, are ubiquitous, especially following strong winter storms. While these events seldom cause serious physical damage to the infrastructure, the blockage of roads until the debris is cleaned or remediation actions carried out causes significant delays and indirect costs to local community. Furthermore, these events have the potential to cause direct damage and fatalities if the soil mass strikes a vehicle or vice versa.

While major peat and earth slides with long runouts that affect the road infrastructure can usually be easily identified through aerial imagery, the vast majority of slides that caused temporary road blockages are small failures occurring directly adjacent to roads. Analysis of landslides identified by GDG has shown that these slides were very seldom identified during aerial imagery phase of landslide inventory population. The reasons for this were mainly the very small size of these failures, and the complete clean-up of the deposit by local authority immediately after the failure. Some recent and well-defined slides were incidentally identified during the on-site validation phase, however it is assumed that the number of these slides is much bigger than reported. Underreporting these slides might lead to significant errors in the susceptibility analysis. As these slides on near-road areas yield serious consequences, it might lead to unacceptable underestimation of risks.

A good example of these slides was observed in the northernmost 3 km section of regional road R336 just south of Leenaun, Co. Galway, where slopes adjacent to road were composed of glacial tills and glaciofluvial sands and gravels. The west side of the road is cut into the base of a relatively steep till ridge with average slope angle varying between 30° and 45°. This natural slope is in places steepened by artificial sub-vertical cuttings (maximum height of 1.5 m) positioned directly next to the road. The natural slope face in this section exhibits many very shallow translational earth slides in sizes ranging from 5x5m to 20x20m with the spacing between two neighbouring landslides sometimes as little as 20 m. The landslide toes were observed to be always on or near the road level, suggesting that the road construction is an important factor in initiation for these landslides. The sliding distance seems to be limited to the range of a few decimetres. That might be attributed to two things: first, the hard layers of road surface prevent further slip of the solid landslide body. Second, very low height of the ridge (up to maximum 25 meters) mean that there is no upstream water-contributing area which can cause full saturation of downslope soil and subsequently transform soil slips into mobile debris flows. No deposit on the road was noticed at the time of inspection. This suggests that the landslide occurrences are old and/or that the local authority responsible for road maintenance is familiar with the issue. However, the sliding is very likely to repeat, especially during and immediately after heavy rainfall, which when coupled with the limited clearance between the slope and the traffic lane, can cause some material to be spread directly in the line of traffic, posing a serious threat to oncoming drivers. The road is unlikely to be damaged due to the small magnitude of the event, but the consequences for road users, and thus the indirect risk, are deemed very high.

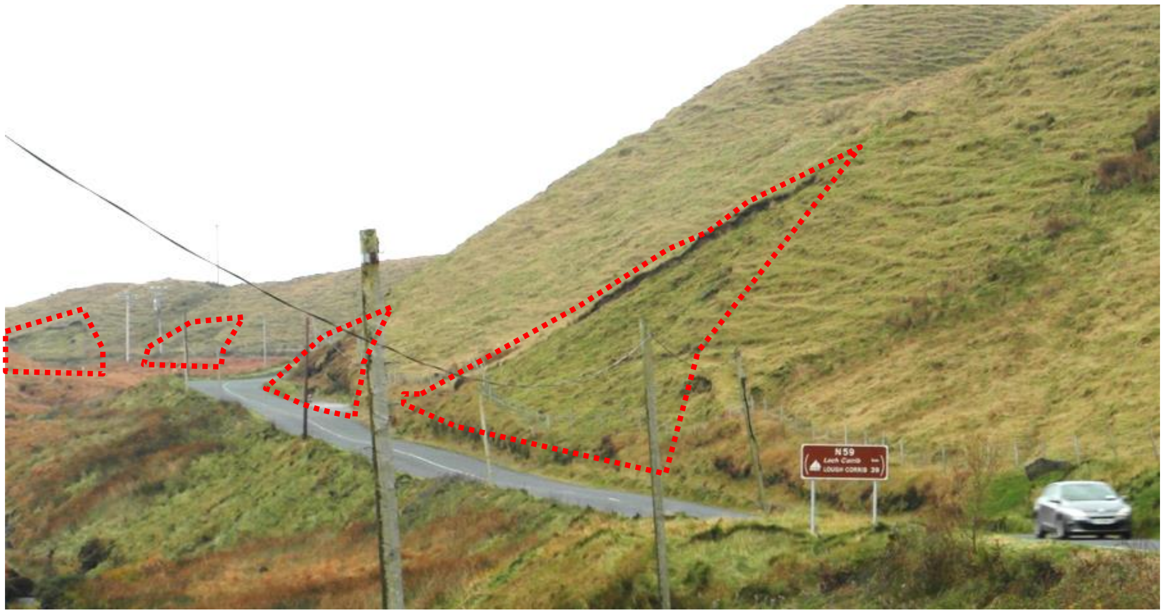


Figure 17 Shallow landslides along the regional road R336 in Co. Galway

The fact that these small landslides without visible run-out could not be identified during aerial imagery processing suggests a need for in-depth fieldwork analysis in the areas immediately adjacent to at risk infrastructure elements. It is recommended that a thorough review of local news reports is carried out as part of this process as some old slides might not be easy to identify. Another proposition for accounting for these slides is to introduce the additional factor 'distance to roads' in the future susceptibility, hazard and risk analyses.

4 Analysis of soil behaviour

This section gives a short overview of soil behaviour studies relevant for landslide assessment in Ireland. It is focused on shear strength and permeability characteristics of soils as these are the two of the most important geotechnical parameters contributing to the behaviour of soil masses. As peat and glacial till are identified as the two soil types most associated with landslides in Ireland, this section is focused on these soils. This section provides an overview of findings of previous research into these soils in Ireland.

The literature overview resulted in identification of knowledge gaps, or the soil behaviour topics that should be studied in more detail in order to gain more insight into landslide initiation processes in Ireland. The gaps identified here also form a suggestion for further investigation of soils and landslides in Ireland.

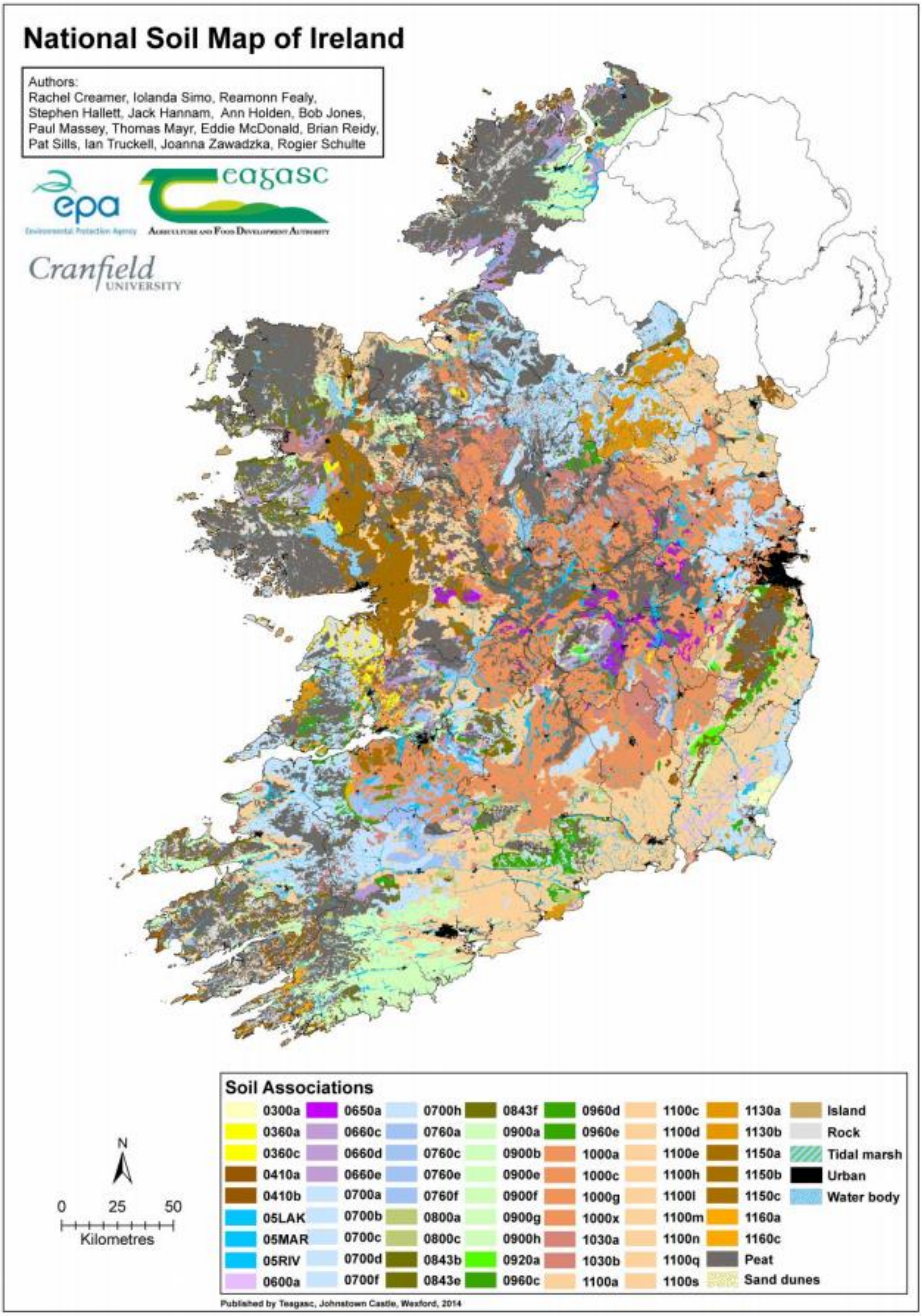


Figure 18 National Soil Map of Ireland (Simo, et al., 2014).

4.1 Properties of the soil

4.1.1 Peat

It can be seen in Figure 18 that Peat is widespread across Ireland. A large percentage of observed landslides occurred within peat deposits (for example 44% presented in Mouchel report (2011), which is similar to other studies). Given the portion of landslides that occur in peat, it is important to understand the soil parameters of this material in order to predict and control potential landslides. Precise identification of the peat parameters, such as shear strength is extremely difficult due to it`s organic origin (Long, 2005), as well as it`s fibrous structure (Long, 2005; Hebib, 2001). In addition to that, the applicability of site and laboratory investigation methods usually used for mineral soils is dubious (Long, 2005).

Peat is a highly organic soil type formed from decaying of plants and vegetation rich in carbohydrates to humus, a process known as humification (Timoney, Quigley, McCabe 2012). Peats can be classified into three simple categories in terms of their degree of humification (Hártlen, 1996):

(a) Fibrous peat which has a low degree of humification. This form will have a distinct plant structure and will produce a brown to colourless cloudy to clear water when squeezed.

(b) Pseudo-fibrous peat has a mid to high degree of humification. The plant structure is now less identifiable and a mushy mass will be extruded when squeezed.

(c) Amorphous is the classification used for the most highly humified peat. Very little, if any, of the plant structure remains and on squeezing no free water is released.

Mangan (1994) presented a simplified method of classifying peat, introducing fibrous, semi – fibrous and amorphous peat (Long, 2005).

Peat has a high-water content, is highly compressibility, non–homogeneous, has very low in situ stress and a low bulk density (typically 10-12 kN/m^3) (Boylan & Long, 2013). These properties make the behaviour of Peat very difficult to predict.

Organic content of Peat is very high, typically ranging from 80 to 99%. Moisture content is also typically very high and can often be many hundreds, even thousands of percent (Timoney, Quigley, McCabe 2012). The moisture content tends to reduce with increasing degree of humification of Peat.

Shear strength of peat is typically very low (generally 2kaA to 15kPa). This is a particularly important parameter in the assessment and modelling of Peat stability. A trend between moisture content, degree of humification and shear strength (both drained and undrained) of Peat was discussed by Long (2005) and is illustrated in Figure 19.

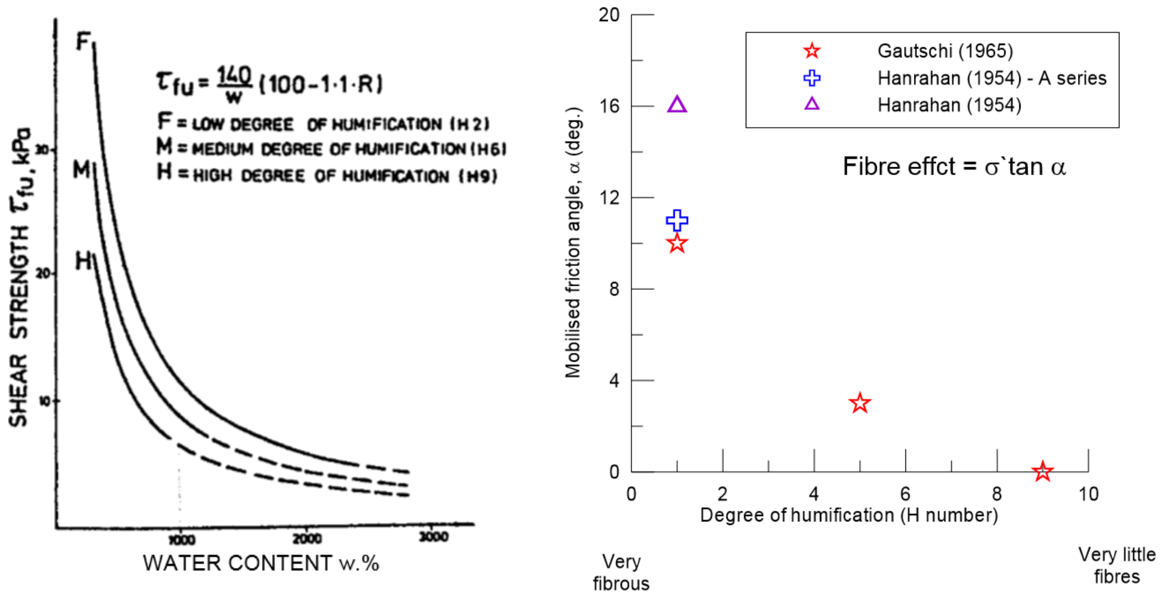


Figure 19 Trend between Shear Strength, water content and degree of humification (Long, 2005)

It was observed by various researchers, that there is an inconsistency in peat shear strength, depending on the test that was performed (Hebib, 2001; Farrell & Hebib, 1998). This is summarised in the below table.

Parameter/test	Description of test variables/ Findings
Friction angle, ϕ'	Friction angle obtained from triaxial test has the greatest value, whereas values obtained from Direct Shear, Direct Simple Shear and ring shear are decreasing.
Triaxial test	Results were overestimated because of the fact that peat is composed out of fibres, which may act as a reinforcement
Direct Simple Shear	Results are underestimated (but may represent the peat matrix in the most reliable way). This is caused by the orientation of the peat fibres – in the DSS test fibres are parallel to the shearing direction (Hebib, 2001)
$\frac{s_u}{\sigma'_{v0}}$	Relationship is non- linear and higher that in case of mineral soils Relationship of the laboratory test results are lower than field vane test

Long (2005) further illustrated this point by comparing shear strengths from various in-situ and laboratory tests on a blanket bog in the west of Ireland. This is shown in Figure 20.

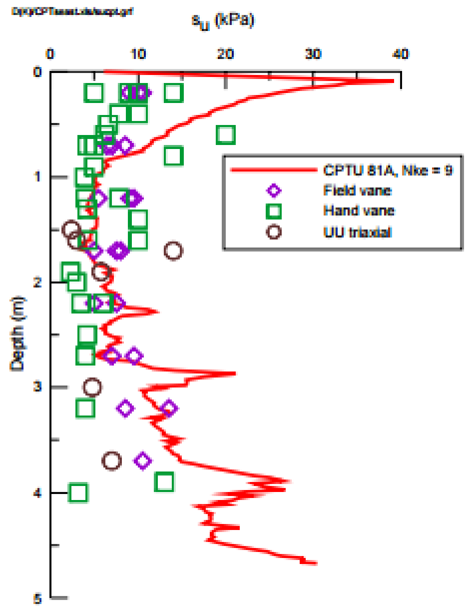


Figure 20 CPTU in blanket bog site in Western Ireland (Long, 2005).

4.1.2 Irish Glacial Tills

Failures within Glacial Tills are the second most common reason for landslides in Ireland according to Mouchel report (2011). Unlike peat, Irish tills are mineral soils, therefore their behaviour is easier to model and test.

Irish Tills deposited on land by The Irish Sea Glacier (McCabe, 2008) can be found in the soils across the country (Skipp, 1994). Glacial deposits usually are characterised as medium dense to dense with high content of gravels, cobbles and boulders (Long, et al., 2013 ; Skipp, 1994). Weak lenses of silt and sand can be found within this soils (Skipp, 1994).

The natural moisture content of tills is much lower than Peat. The moisture contents recorded in the below table range from 11 to 24 %. The bulk density of tills is much higher than Peat, typically in the range (18 to 22 kN/m^3).

Tills have higher shear strengths and stiffness than Peat. It can be seen from Figure 22 below that the shear strength can range from 20kPa to over 400kPa depending on depth, location and test method. Figure 21 illustrates that a wide variety of field stiffness have also been recorded depending on the location, and hence depositional environment, of the till.

Site Location	<63 µm (%)	LL (%)	PI (%)	Nat. Moist (%)	Till T (m)	SPT N	Load/ Fill Ht (kPa*/ m)	Settle ment (mm)	Field		
									E_v (MPa)	t_{95} (wks)	c_v (m^2/yr)
Tallaght, Dublin	39	24	10	10	3$^{(1)}$	55	1015*	12.8	84	16	30
Dublin Port Tunnel	40	28	13	10	31	55	100-170*	6.3	553	6	
M9 Kilcullen SP1	33	23	9	12	5.3	6	6m	49	10.8	5	16
M9 Kilcullen SP5&6	32	25	6	11	5.2	8	8.5m	95	7.7	4	20
M7/M8 20+090	42	25	9	17	3.7	30	7.3m	32	14.1	26	8
M7/M8 22+800 to 22+950	46	28	6	16	3.5	4	6m	27	13.3	12	15
M7/M8 23+200 to 23+600	45	24	9	15	10.8	22	5.9m	37	30.7	26	66
M7/M8 27+200 to 27+300	29	22	9	14	9.5	25	3.7m	35	16.6	33	40
M7/M8 27+770 to 27+870	29	20	8	14	10	20	8.9m	26	56	21	70
A2 Shore Rd S		45	24	21	4.8	29	8.9m +1.2m	55	14.7	42	8
A2 Shore Rd N	44	43	22	24	5.5	34	6.4m +2.9m	65	13.1	36	12
M6 Athlone WB Roundabout		36	14	22	2.2	12$^{(2)}$	10.5m	65	5.9	14	5
M6 Athlone Link Rd	95	31	14	18	3.2	8	5.7m +1.0m	55	6.6	14	11
M6 Athlone WBD	21	25	8	14	3.5	19	7.4m	60	7.1	22	8
Limerick Tunnel Clonmacken	36	34	14	18	6.2	13	3.0m +2.0m	78	6.9	39	14

Figure 21 Summary of Glacial Till Classification and Field Test / Monitoring Results (Buggy & Kissane, 2016).

Buggy and Kissane (2016) present an overview of properties of till derived from in – situ site investigations on various Irish development projects. It can be seen from Figure 21 that the geotechnical properties of a glacial till are variable properties and highly dependent of their deposited area.

Saturated permeability coefficient K_s is typically reported to be in the region of $1x10^{-11}$ to $1x10^{-8}$ in case where there is no permeable sand layers present in the soil. However Hughes et al. (2016) reported the saturated permeability of $1x10^{-6}$.

Figure 20 below presents the properties of the Dublin Boulder Clay. This soil is an example of a stiff to very stiff Irish till (Skipp, 1994) and over the years it has been well described and tested.

Peaks and dips visible on the CPT test result presented in Figure 22 are caused by the high stone content as well as various lenses containing sand and gravel (O'Kelly, 2014). Figure 23 presents typical parameters for this Till (Lehane & Simpson, 2000).

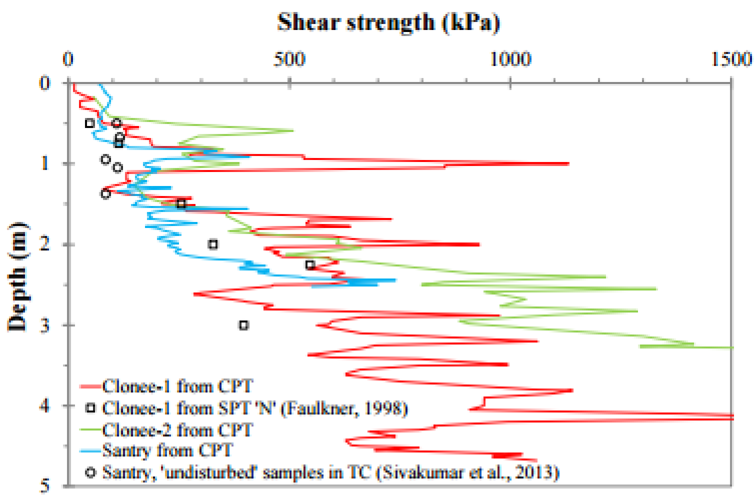


Figure 22 Strength profiles measure in triaxial compression (TC) and inferred from CPTu (N_{kt} = 15) and SPT data (O'Kelly, 2014).

Bulk density (kN/m^3)	21.5±0.5
Global water content (%)	11±3
Liquid limit (%)	25±4
Plastic limit (%)	14±2
Plasticity index (%)	11±2
Liquidity index	–0.2±0.03
Clay fraction (%)	15±5
Gravel fraction (%)	30±5
Permeability (m/s)	1×10^{-11} to 1×10^{-8}
Coefficient of consolidation, c_v (m^2/year)	40±20
Preconsolidation stress, σ'_{vy} (MPa)	1.3±0.3
In situ OCR	8–30
λ (reconstituted, intact)	0.04, 0.030±0.005
κ (reconstituted, intact)	0.008, 0.004±0.001

Figure 23 Typical properties of Dublin Boulder Clay (Lehane & Simpson, 2000).

4.2 Knowledge gaps

Conclusions from the section above show that Irish peats and glacial tills have been tested and described in various studies, with relatively well-determined classification and saturated shear strength behaviour. However, previous sections have drawn the conclusion that the majority of landslides identified across Ireland are related to surficial rainfall infiltration characteristics. Glacial tills in particular rely on the near-surface negative pore water pressures (suctions) in maintaining the stability. The role of unsaturated seepage characteristics is thus very important. However, there is a lack of information on unsaturated parameters in literature when it comes to Irish soils. The parameters that would be particularly beneficial for Irish geological and geotechnical community in modelling rainfall infiltration and sliding processes are outlined below.

1) Saturated permeability of surface layers.

Coefficients of saturated permeability reported for glacial tills usually come from testing of undisturbed samples taken from different depths. In general sampling too close to surface is avoided in order to avoid the 'disturbing' characteristics of tension cracks, vegetation roots, soil structure weathering, etc. These features can increase the 'normal' saturated permeability by several orders of magnitude. However, for rainfall induced shallow landslides which form the vast majority in Ireland, the surficial permeability that takes account of all these features is of much importance as the failure plane is frequently positioned in this 'disturbed' zone. Furthermore, the downward path of the wetting front created by rainfall infiltration goes from surface through this zone and is likely influenced by tension cracks that can act as a bypass to deeper layers. This also means that the concept of uniform saturated permeability might not be applicable. However as a start, the reliable range of saturated permeabilities for the surface should be determined and used when modelling shallow failures.

Looking specifically at Irish glacial tills, saturated permeability coefficient K_s is typically reported to be in the region of $1x10^{-11}$ to $1x10^{-8}$ in case where there is no permeable sand layers present in the soil. However Hughes et al. (2016) reported the saturated permeability of $1x10^{-6}$ for a surface layer of a road cutting in Northern Ireland. While this gives an indication of the preliminary values, more investigation is needed to give additional data on this characteristic.

2) Unsaturated parameters

Negative pore water pressures, or suctions, depend on the levels of water content relative to the maximum water content in the soil. The lower the water content in the soil is, the larger the suctions are. These suctions give an additional component to soil's shear strength, as described in Fredlund et al. (1978). However as these suctions fluctuate depending on water content which is influenced by infiltrated rainwater, slope stability depends directly on rainfall infiltration speed and capacity. These two features are an intrinsic characteristic of every soil and depend on soil particle size, void size distribution, soil skeleton composition and other parameters. In general, soils composed of small particles can generate larger suctions thanks to capillary forces.

The relationship between water content and suction is defined by a soil-water characteristic curve (SWCC). An example of different SWCCs are presented in Figure 24, and a typical SWCC for a glacial till site in Canada is given in Figure 25. SWCC can be determined in the laboratory on a sample cleaned of larger particles such as cobbles (which then gives more precise measurements but does not present the actual state of the soil in-situ), or on site using moisture sensors and tensiometers, which tend to give more coarse results. Once the SWCC is known, the unsaturated permeability curve can be derived from it (permeability decreases with the increase of suction).

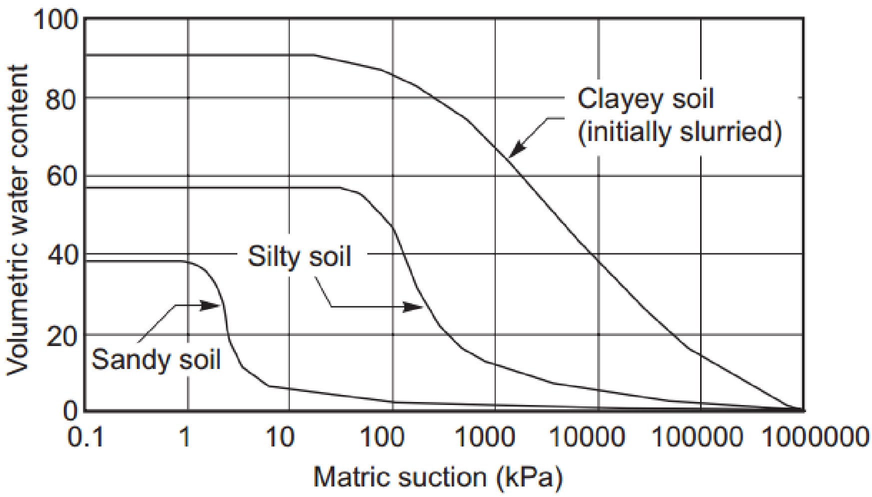


Figure 24 SWCC for three different soil types (source: (Fredlund & Xing, 1994))

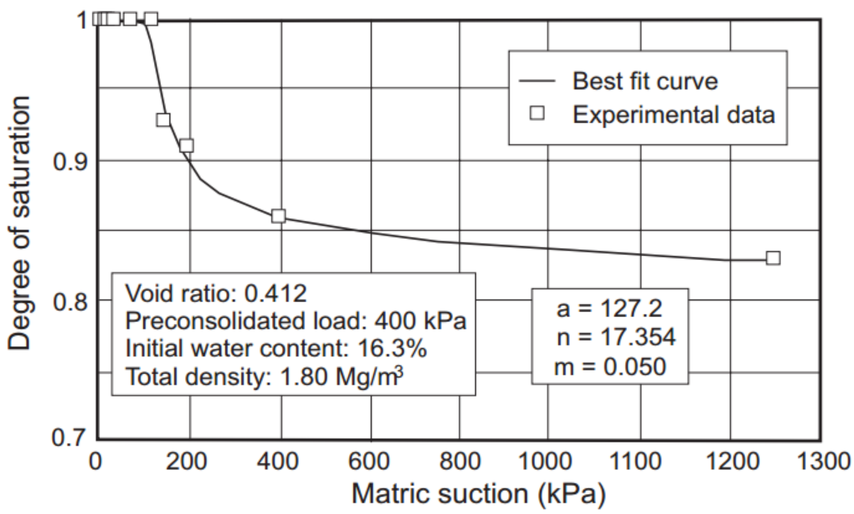


Figure 25 SWCC for a glacial till site in Canada (source: (Fredlund & Xing, 1994))

While SWCCs are well established for some glacial tills in Canada (Fredlund 1978, (Fredlund & Xing, 1994), Vanapalli et al. 1999) and there are examples available for glacial tills in UK (Toll et al. 2015), no research on SWCCs for Irish glacial tills have been carried out to date. This information would significantly improve the modelling and assessing of shallow landslides in Ireland.

5 Analysis of rainfall trigger thresholds

For rainfall induced landslides, the frequency of the triggering rainfall events may be used to indirectly describe the temporal aspect of landslide hazard (Corominas, et al., 2014). Critical triggering rainfall events can be described using rainfall thresholds. For rainfall induced landslides, the threshold is usually expressed as a minimum level of a combination of rainfall parameters that needs to be reached in order for a landslide to occur (Reichenbach, et al., 1998). Rainfall thresholds can be developed i) physically, based on numerical models (Iverson, 2000; Salciarini, et al., 2006) or ii) empirically (statistically), based on analysis of historical landslide events and accompanying rainfall. In relation to natural slope failures, empirically derived thresholds are particularly prevalent, with many examples found throughout the literature (Guzzetti, et al., 2007; Caine, 1980; Dahal & Hasegawa, 2008; Dahal & Hasegawa, 2008; Brunetti, el al., 2010, Guzzetti, 2008.)

While there is abundance of local, regional and national rainfall threshold available for different parts of the world, no thresholds have yet been developed for Ireland. In this section, preliminary rainfall thresholds for landslides on natural hillslopes in Ireland are developed based on the available data of landslide failures and accompanying rainfall data obtained from The Irish Meteorological Service.

5.1 Background

Various types of rainfall thresholds exist depending on measured rainfall characteristics/parameters used. Guzzetti et al. (2007) grouped the empirical thresholds into thresholds that use precipitation data describing a critical rainfall event, thresholds that include the antecedent conditions, and others. In the first group, the most common types of rainfall thresholds are identified as intensity-duration (ID) thresholds, thresholds based on the total event rainfall, rainfall event-duration (ED) thresholds and rainfall event-intensity (EI) thresholds. These are also often further normalised using mean annual precipitation (MAP) or rainy day normal (RDN) to disregard the effect of local climate and enable the comparison between thresholds from different study areas. A common feature to all of the minimum thresholds types is that they represent the lowest boundary in coordinate space of a pair of observed rainfall characteristics below which landslides do not occur. The thresholds are most commonly drawn graphically after the rainfall characteristics pairs of values have been plotted. However, for large datasets computer aided statistical techniques can be used ((Guzzetti, et al., 2007), Vennari et al. 2014).

Intensity-duration thresholds are the most common type of thresholds found in the literature. They are generally expressed by a power law:

$$I = c + \alpha \times D^{\beta} \qquad \textit{Equation 1}$$

Where I is rainfall intensity, D is rainfall duration, and c, α and β are fitting parameters. Negative β value sets a descending trend, simulating the decrease of mean intensity at longer durations. Each developed threshold is valid for a limited range of durations, usually provided along with the threshold.

Rainfall event – duration (E-D) thresholds generally exhibit an ascending trend as they present a cumulative measurement of precipitation during an event. Thresholds using antecedent rainfall aim to take into account not only the critical event rainfall but also the cumulative precipitation in a period preceding it; as antecedent precipitation sets the preparatory conditions for slope instability due to the increased soil moisture and groundwater levels. Existing antecedent rainfall thresholds (Glade, et al., 2000; Chleborad, 2000; Jaiswal & van Westen, 2009; Huang, et al., 2015) show that with an increased amount of the antecedent precipitation, the critical event precipitation required to trigger a landslide decreases. Different durations of antecedent rainfall are used, with most periods spanning between 3 and 30 days. A common practice is to test the influence of a set of different antecedent periods.

When constructing thresholds, some studies plot not only rainfall events that triggered landslides, but also a number of rainfall episodes that didn't trigger any landslides (Zezere et al. 2015, Gariano et al. 2015, Guo et al. 2016, Giannechini et al. 2016). The threshold is then constructed in a way to maximise the number of triggering events and minimise the number of non-triggering events above the threshold. In this study, the authors opted not to apply this approach because of data uncertainty with a large number of recorded landslides not being linked to a specific rainfall event, which would compromise the certainty of rainfall episode being a non-triggering one.

5.2 Data and methodology

The major sources of information available for natural landslides include the Geological Survey of Ireland's National Landslide Database (GSI 2016), research papers (Bourke and Thorp 2005, Long and Jennings 2006, Boylan, et al., 2008; Long, et al., 2011) and newspaper reports. While the National Landslide Database contains a reasonably large dataset of landslides with excellent spatial accuracy, the vast majority of landslides have no date recorded. This is understandable as the majority of landslides occurred in remote mountainous areas and were usually not reported unless they caused material damage or road blockage. This greatly reduced the number of appropriate landslide inputs available for developing rainfall thresholds. Following detailed interrogation of the available data, a database of 37 landslides with reliable time stamps was established.

Rainfall data was obtained from The Irish Meteorological Service (Met Éireann). The rain gauge network in Ireland is composed of 25 synoptic stations with hourly precipitation measurements and 423 rain stations with daily precipitation measurements. Hourly data from synoptic stations is available for the last 10 years, while the entire daily precipitation dataset from rain stations since their activation was obtained. The total number of rain gauges in Ireland corresponds to an average density of one rain gauge station every 157 km^2.

Hourly measurements from synoptic stations were obtained for 25 landslides that occurred between 2006 and 2015 along with the daily precipitation measurements from the rain station most relevant in terms of proximity, altitude, orientation and general setting. For 12 landslides that occurred before 2006 only daily rainfall measurements were available. For the 25 landslides with hourly readings a modified intensity was calculated using Equation 2. Only these landslide events have been used to construct I-D threshold, while the entire database was used to construct the critical –

antecedent rainfall thresholds. This equation is often used when assessing landslides on the rail network in Ireland, however, it should be noted that the breakdown of landslide types in this study differ somewhat from those on the rail network in Ireland. Approximately half of landslides are classified as peat failures, with the rest of them composed of shallow translational soil slides and debris flows. More accurate classification is hampered by the fact that some failures reported in National Landslide Database and newspapers lack detailed descriptions. Furthermore, some of the peat failure mechanisms involved shearing through the underlying mineral soil, making them essentially translational soil slides, often referred in literature as peaty-debris slides (Dykes & Warburton, 2007).

In developing any form of rainfall threshold, identifying the critical triggering rainfall from a continuous series of precipitation data is a crucial process. Critical rainfall represents the rainfall event during or immediately after which the landslide occurred. The start of critical rainfall is marked by a steep increase in cumulative precipitation plot immediately prior to the landslide event. In practice however it can sometimes be difficult to precisely identify the point of this increase. To do this process objectively and uniformly, definitions for determining the start of critical rainfall event are set in each study, with limits varying significantly depending on the study area's climate conditions. In this study, the start of the critical rainfall event was defined when hourly rainfall intensity exceeds 1 mm/h. To separate the critical rainfall from the antecedent rainfall, an additional requirement of 12 hours with hourly intensity <1 mm/h before the start of critical event also had to be met. Following this process, duration D and average hourly intensity I_{ss} for each of 25 landslides were collated using the precipitation data from the nearest synoptic station.

While the network of 25 national synoptic stations with hourly readings can provide useful data to assist with the initial analysis, the authors deemed it to be insufficiently dense for the detailed analysis intended in this study. For that reason, mean intensity values I_{ss} obtained from synoptic stations were modified using daily rainfall readings from the rain stations that were the closest to each failure location, thereby greatly reducing spatial uncertainty in the rainfall values. This was carried out by adjusting the I_{ss} with the ratio of cumulative daily rainfall on rain station (R_{rs}) and synoptic station (R_{ss}):

$$I = I_{ss} \times \frac{R_{rs}}{R_{ss}} \qquad \textit{Equation 2}$$

Due to the uniformity of the terrain over which the rail network operates and the relatively small catchment area of each synoptic station, the durations of a rainfall event spatially vary to a much lesser degree. This allowed the same value of critical rainfall durations to be adopted as those read in the synoptic station data.

5.3 Results

Asymptotic intensity-duration thresholds were then graphically fitted to the plot of 25 events with hourly measurements, disregarding two outliers (Figure 26). The threshold is defined with the equation:

$$I = 0.95 + 50 \times D^{-1.65}, (3 \leq D \leq 100)$$ *Equation 3*

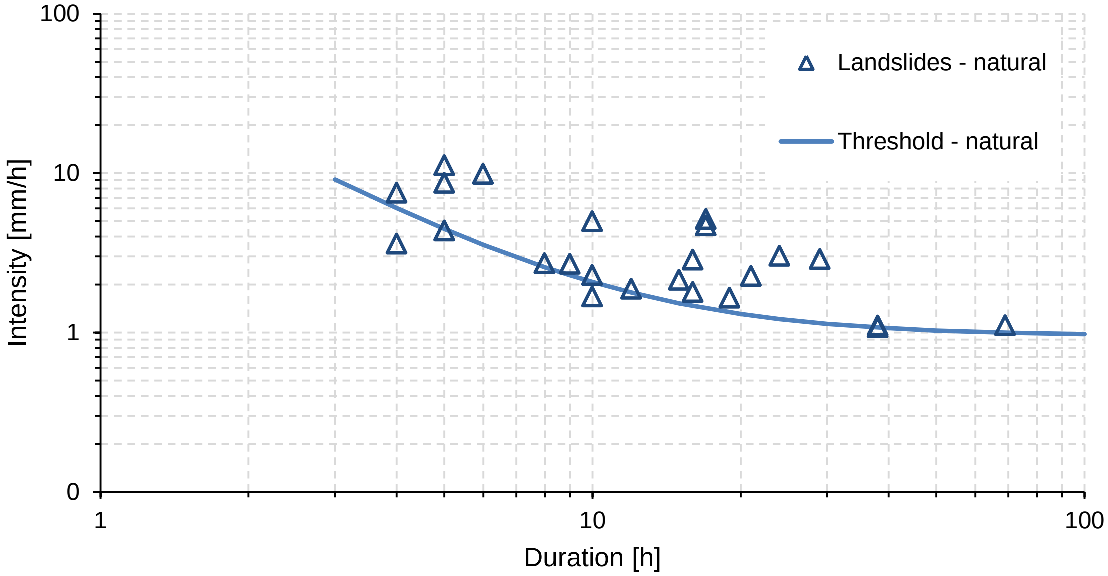
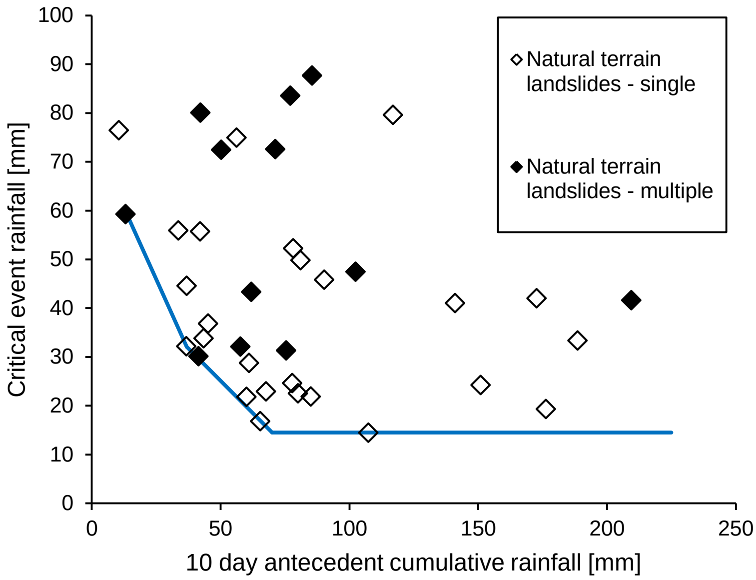


Figure 26 I-D rainfall threshold landslides on natural terrain in Ireland

The threshold was set with two outliers in order to capture the most probable landslide conditions. If the two outliers have been accounted for, the threshold would go "too low", generating a lot of false alarms or 'false positives'. It should be noted that not every rainfall that exceeds the threshold will automatically cause a landslide. This naturally depends on the terrain and slope features at the rainfall location. More interrogation is needed to estimate the probability of a landslide occurrence considering all of these variables. This threshold thus serves as a minimum requirement needed for landslide to happen. With more landslide data in the future, the threshold can be updated. The threshold is valid for the rainfall durations between 3 and 100 hours. More data on landslides caused by rainfall events with durations outside of this scope are needed to determine the threshold for these durations.

Figure 27 shows pairs of critical event – antecedent rainfall values and thresholds for 10 day and 30 day antecedent precipitation periods on two separate graphs. Both graphs show that for lower amounts of antecedent rainfall (up to 70 mm in 10 days and up to 220 mm in 30 days), a significant amount of critical rainfall is required to trigger the landslide on natural hillsides. Comparing the graphs for 10 day and 30 day antecedent rainfall, it can be seen that values on 10 day graph exhibit less scatter and that threshold is clearly discernible without outlier values. Furthermore, plotted natural landslides are grouped very densely in the area just above the threshold. This draws the conclusion that antecedent rainfall type of thresholds in Ireland are more appropriate for landslides on natural terrain and that mid-term antecedent period of 10 days can serve as a very useful indicator of rainfall triggering conditions.

One of the reasons for wide variation between existing thresholds worldwide lies in the selection of landslide events. Thresholds where all landslide events were included, including single and minor ones (as in this study), were shown to be lower than when only events with multiple or abundant landslides were collated in the database (Guzzetti et al. 2008, Brunetti, et al., 2010). To interrogate the effect of this, rainfall events causing landslides on natural terrain were classified into events that caused a single landslide (25 empty diamonds in Figure 27) and multiple or widespread landslides (12 full diamonds in Figure 27). Unsurprisingly, widespread landslides show strong connection with high amounts of critical rainfall. Critical rainfall of at least 30 mm is needed to trigger multiple landslides, and six out of nine events with cumulative rainfall of over 60 mm resulted in widespread landsliding. Further interrogation of these events shows high mean intensities and peak intensities attributed to these rainfall events. Widespread landsliding thus seems to be associated with strong intense rainfall events. This is especially important in light of more intense rainfall episodes being predicted in all scenarios for future climate in the 21st century (Sweeney, et al., 2008). Another thing in common to these events is that all but one recorded event occurred in conditions with relatively low antecedent rainfall. That is also evident in the fact that eight out of twelve occurred in, what Figure 2 suggests to be, a drier period countrywide (February – September). This can be partly explained by the drying and shrinkage of the material, causing cracking and opening preferential infiltration channels to critical depths (Long and Jennings 2006).



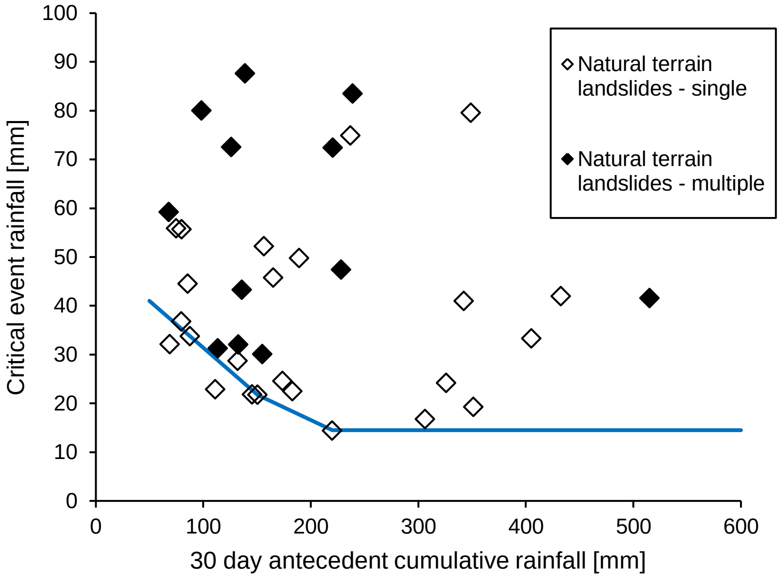


Figure 27 Cumulative – antecedent rainfall thresholds for landslides on natural terrain (straight blue line): a) 10 day antecedent period and b) 30 day antecedent period. Empty diamond – single landslide event, full diamond – multiple (widespread) landslide event.

5.4 Comparison with existing rainfall thresholds

The rainfall threshold for landslides on natural slopes developed in this study is representative of a national threshold as it is based on events that were recorded over the entire island of Ireland. In topographical terms they can also be considered as regional thresholds, given the size of the study area and the similarity of climatic and physiographic characteristics within it. This allows them to be compared to I-D thresholds proposed elsewhere in Europe and world. Figure 28 superimposes Irish I-D threshold with the range of 52 I-D thresholds collated by Guzzetti et al. (2007). These thresholds include global, regional and local thresholds from all over the world. Thresholds representing CADSES area (Central European Adriatic Danubian South-Eastern Space, essentially covering entire Central and South-Eastern Europe) were further singled out from the entire dataset. The Asymptotic nature of the Irish threshold makes it less straightforward for comparison with most of the thresholds, especially for very short (<5 hours) and very long (>50) durations. However, as 24 out of 25 interrogated landslide events (96%) have durations between 5 and 40 hours, this segment can be successfully compared to the collated thresholds. The Irish threshold is shown to be at the very bottom of both ranges, indicating that landslides in Ireland can be triggered by rainfall intensities lower than most other parts of Europe and world. The placement of Irish threshold among the lower group of collated thresholds also shows good agreement to the observed fact that global and regional thresholds are usually lower than local ones (Guzzetti, et al., 2007). Furthermore, the threshold for landslides on natural slopes in Ireland corresponds well to its counterpart developed by Guzzetti et al. (2007) for CADSES area and its subpart developed for severe mid-altitude climate.

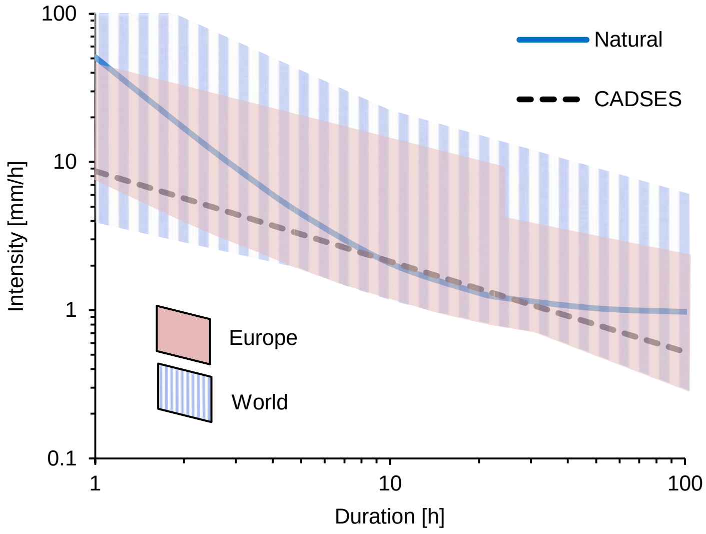


Figure 28 Range of thresholds collated by Guzzetti et al. (2007) in a) CADSES area (red) and b) world (striped blue). Threshold for natural slopes in Ireland (blue line); threshold for CADSES area (Guzzetti et al. (2007), dashed black line) superimposed.

6 Identifying the most appropriate monitoring methodology

The selection of the most appropriate monitoring methodology requires the consideration and understanding of the causes, trigger conditions, mechanism, stratigraphy, soil types, soil mechanical properties and ground water conditions associated with landslides. Each landslide is caused by a unique combination of these variables, therefore a monitoring strategy should only be designed once a sufficient understanding of these variables has been gained through desk studies, site walk overs, ground investigation and laboratory testing.

This chapter of the report reviews the available ground investigation, laboratory testing, monitoring techniques and equipment. The advantages, disadvantages and applicability of each method to the most vulnerable Irish soils (Peat and Glacial Till) are discussed. This is not an exhaustive list of techniques, it is simply a brief overview of those which are readily available and most commonly used in practice.

A discussion on how to combine these techniques to design an appropriate monitoring methodology and implement an early warning system is also given in this chapter.

6.1 In – situ testing

The main reason for performing site investigation is to identify the stratigraphy, soil types, soil mechanical properties and ground water conditions of the area under investigation. Soil properties typically investigated include particle size distribution, water content, density, Atterberg limits, permeability, shear strength and in organic soils, such as peat – state of decay. All of the information gained during this process are aiming to maximise the amount of data regarding ground conditions and use it to assess the susceptibility of the area to landslides, predict the likely failure mechanism and design an appropriate monitoring strategy.

Prior to site investigation, a desk study and site walkover should be completed in order to choose an investigation method best suited to the site. This process can also help to maximise the quality of the data obtained and do so in a cost-effective way.

The number of laboratory tests performed will directly depend on the number of samples obtained as well as project requirements and limitations. If possible, the following soil properties shall be identified: moisture content, bulk density, plastic limit, liquid limit, specific gravity, particle size distribution, triaxial test, shear box test, organic content (loss of ignition).

Methods of obtaining the information discussed above are discussed in the following sections.

6.1.1 Trial pits

Trial pits are a simple and cost effective intrusive means of obtaining a ground profile over a relatively shallow depth range (typically 1 to 5m). They are typically excavated using excavation plant but can be excavated using hand tools where access for plant is an issue. Disturbed soil samples can be taken for classification and environmental laboratory testing. In situ testing, such as hand shear vane, plate load and dynamic probe testing can be carried out within trial pits. Trial pits can be excavated in most soil types however the stability of the excavation can be compromised by groundwater ingress.

Trial pits are suitable for use in Peat and Glacial tills.

Figure 29 Trial Pit (http://www.wilson-bailey.co.uk/).

Advantages	Disadvantages
• Cost effective • Many tests can be carried out in a relatively short time period • Gives a wider view of the ground profile in comparison to boreholes • Allows for collection of disturbed samples for geotechnical and classification testing • In situ strength tests can be carried out within a trial hole • Suitable for a wide variety of soils • No sophisticated equipment or calibration required, just standard excavation plant	• Shallow depth range due to limited reach of excavation plant • Pits can become unstable in soft ground or when high groundwater • Only heavily disturbed samples can be collected • Only a limited number of in-situ tests can be carried out

Soil Type	Applicable
Glacial Till	Yes (but could refuse on large boulders or very stiff clays)
Peat	Yes (but trial hole can become unstable depending on the nature of the peat)

6.1.2 Cone Penetration Test (CPT)

Cone penetration testing is an intrusive investigation technique that involves pushing an instrumented cone through the ground and analysing the cone and skin resistance to determine the nature of the material through which it passes. A large amount of information can be gathered using a CPT including stratigraphy of layers, depth to firm layers, soil identification and mechanical soil characteristics. Additional sensors can be placed on the cone including pore pressure, environmental and seismic sensors. Although a large amount of data can be collected quickly using a CPT, a number of disadvantages include lack of a visual sample, limited penetration capacity of the cone, expense of specialist equipment and requirement for calibration. It is recommended that CPTs are carried out as part of a wider ground investigation which includes conventional boreholes, geophysics and laboratory testing so information gained form the CPT can be verified.

CPT equipment is generally mounted on specially constructed trucks (see below photograph). The test can also be carried out on smaller equipment such as tracked machines or trailers but these are not as widely available as the more conventional truck shown in the photograph below.

Advantages	Disadvantages
•A large amount of data can be gained relatively quickly •Can be used to identify stratigraphy of layers, depth to firm layers, soil type and mechanical soil characteristics •Additional sensors can be used to gain information on pore pressure, environmental and seismic sensors •Useful in soils where testing using conventional boreholes is difficult •Useful for contaminated sites as no soil is extracted from the ground during testing, eliminating any potential waste disposal issues	•No sample is obtained for visual description or lab testing •Specialist equipment and calibration is required •Test depths are limited by the capacity of the cone. Tends to refuse on cobbles, boulders, stiff clays or bedrock •Can be expensive to mobilise rigs •Significant post processing and interpretation of information required

Soil Type	Applicable
Glacial Till	Yes (but could refuse on large boulders or very stiff clays)
Peat	Yes (but choice of equipment on which the test equipment is mounted is important due to the soft nature of Peat)

Figure 30 CPT testing (http://www.insitusi.com/research/).

6.1.3 Boreholes

Boreholes are a site investigation method that involve drilling a relatively small hole (typically 75mm to 150mm in diameter) through the ground to extract samples for identification of stratigraphy, ground water level and extraction of soil samples for laboratory testing. There are many techniques available for drilling boreholes but the two most widely used are rotary coring and cable percussive (shell and auger). Boreholes can be drilled to significant depths to provide a deep ground profile. In-situ tests such as the Standard Penetration Test (SPT), pressure meter and double packer testing can be carried out in boreholes. The holes can also be instrumented to obtain information on groundwater and ground movement. Some of these tests are discussed in later sections of this report.

This study has shown that the boundary between strata is often the location where the failure zone within a landslide is found. Boreholes are a very useful site investigation technique for landslides as they allow for clear identification of strata boundaries. High quality testing for laboratory sampling can be obtained for classification, strength and stiffness testing in the laboratory. This combined with instrumentation to identify ground water level and ground movement make boreholes extremely useful for obtaining an abundance of information on numerous factors that contribute to landslides.

Boreholes are suitable for use in all soil types including glacial tills and peat.

Advantages	Disadvantages
• Many techniques available to suit all soil types, terrains and depth requirements • Allows collection of quality samples for detailed logging and lab testing • Allows for various in-situ testing techniques • Boreholes can be instrumented for ground water and ground movement assessment	• Can be relatively expensive • Gives information on a specific point therefore doesn't provide information variation across the site without multiple holes or use in conjunction with other methods • Bores can be time consuming to drill depending on ground conditions, depth and

	rig used

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

Figure 31 Rotary coring rig (left) and cable percussive rig (right) (photos from http://www.geotronuk.co.uk/wp-content/uploads/2010/12/com205-2a.jpg and http://www.dando.co.uk/photos/cable-percussion-drilling-rigs accessed 03/12/2016)

6.1.4 Geophysics – MASW and GPR

Multichannel Analysis of Surface Waves (MASW) and Ground Penetrating Radar (GPR) are non – intrusive methods that can provide information on stratigraphy, soil density and stiffness of the ground.

During MASW testing, surface waves are generated by introducing an impact load (and hence body waves) into the ground at various locations. Shear Wave velocity (Vs) is then measured using a series of Geophones. Tests performed on Irish glacial till (Long, et al., 2013) have proven a strong correlation between V_s and Undrained Shear Strength (S_u), therefore the application of this method may be a reliable supplement to an intrusive ground investigation, or in some cases a cost-effective substitute.

GPR works by sending a tiny pulse of energy into a material and recording the strength and the time required for the return of any reflected signal.

Geophysical methods are usually used as a supplement to an intrusive site investigation. It is generally best to preform geophysics prior to intrusive investigation as it can help to inform a more targeted, cost effective ground investigation.

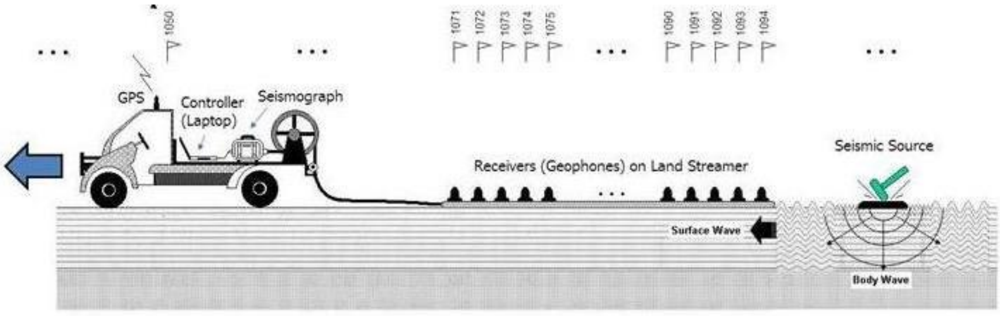


Figure 32 Multichannel Analysis of Surface Waves (MASW) (http://www.masw.com/WhatisMASW.html).

Figure 33 Ground Penetrating Radar (GPR) (http://www.perth-businessdirectory.com/wp-content/uploads/2016/05/Ground-penetrating-radars.jpg)

Advantages	Disadvantages
• Large areas can be covered • Information on numerous properties of the ground including stratigraphy, soil type, shear strength and stiffness can be gained • Cost effective if used as part of a wider ground investigation	• Results need to be verified by other means (eg boreholes and trial pits) • Specialist sophisticated equipment required • Geophysical expertise needed to interpret results.

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (for GPR, MASW not recommended)

6.1.5 Soakaway or Percolation testing

Soakaway or percolation testing is performed to estimate the in-situ permeability of a soil mass. The test involves excavating of a trial pit of a known size, filling the pit with clean water and measuring the change in water level over time. The permeability of the soil encountered in the trial pit can then be estimated from these measurements.

The location for a soakaway test needs to be relatively easy to access as excavation plant, a large water tank and a vehicle to tow them are required. This makes this test unfeasible for potential landslide locations on steep slopes, in remote locations, or where very soft ground (eg Peat) is present.

This test introduces a relatively large amount of water into a mass of soil. As water is known to be a trigger for landslides, the impact of using this test on potentially unstable slopes needs to be carefully considered prior to specifying it.

Advantages	Disadvantages
• Simple test with no requirement for sophisticated equipment and calibration • Measures permeability of a relatively large soil mass	• Introduction of large amounts of water to a slope can have a destabilising effect • Difficult to carry out test on steep slopes Difficult to carry out test on areas of very soft ground due to size of equipment needed • Difficult to carry out test in remote locations Permeability can be underestimated due to smearing of the sides of base of the pit during excavation • Ground needs to be sufficiently stable to stay open for the duration of the test

Soil Type	Applicable
Glacial Till	Yes
Peat	No

Figure 34 Percolation test (http://www.percolationtests.ie/).

6.1.6 Shear Vane Test

The Shear Vane Test is an in-situ test used to measure the undrained shear strength of cohesive soils. This test is unsuitable for granular soils. The equipment required to carry out this test is hand operated, easy to use, compact and light. This makes it suitable for use in locations where heavy plant and equipment cannot gain access. This is particularly useful for many potential landslide locations in Ireland. The test is very quick which allows a large number of readings to be obtained in a short period of time. It also gives a direct reading of shear strength without any interpretation of results. It is generally performed from the surface or within trial pits. It should be noted that this technique is most applicable to soft to medium strength clays and generally not applicable for materials with an undrained shear strength in excess of 100 kPa. Furthermore, due to the presence of fibres within a peat matrix, the shear vane can provide an artificially high strength value in peats due to the torsional stress path and added resistance provided as the fibres rotate around the vane.

Shear strength results from this test can vary greatly depending on the user. Results should be used as part of a wider investigation into the strength of the soil and not a standalone investigation technique.

This test is suitable for use in Peat and cohesive Glacial Tills.

Advantages	Disadvantages
• Simple test that gives a direct reading of shear strength • Light hand operated equipment which can be used in difficult to access locations • Quick test allowing a large amount of readings to be obtained in a short period of time	• Results can vary significantly depending on user • Limited depth range

Soil Type	Applicable
Glacial Till	Yes (Cohesive only)
Peat	Yes

Figure 35 An example of vane (http://www.controls-group.com/eng/soil-testing-equipment/shear-hand-vane-tester.php).

6.1.7 Hand Augering / Hand Coring

Hand Augers can be used to obtain shallow cores sufficient to prepare logs of a ground profile less than 5m in depth where the sides are expected to be stable. It is a hand-held tool that can be used in locations difficult to access with the heavy plant and drilling rigs. The method is suitable for both granular and cohesive soils. The hand auger can be difficult to advance through stiff clays and dense sands/gravels. It is also likely to refuse on cobbles and boulders typically found within glacial tills in Ireland. The effectiveness of this method within peat is heavily dependent on the nature of the peat.

Figure 36 Hand Auger (https://www.spaldings.co.uk/livestock/spear-jackson-hand-post-hole-auger)

Advantages	Disadvantages
• Simple method of obtaining a ground profile • Light hand operated equipment which can be used in difficult to access locations	• Limited depth range • Likely to refuse on stiff clays, cobbles and boulders

Soil Type	Applicable
Glacial Till	Yes (but likely to refuse on stiff clays, cobbles and boulders)
Peat	Yes (but it’s effectiveness is dependent on the nature of the peat)

6.2 Laboratory Testing

6.2.1 Shear box test

Shear box tests can be used to estimate the drained or undrained strength of granular or cohesive material. In shear – box tests a soil sample is placed between the two frames, subjected to a vertical load to mimic the effect of overburden, then a bottom frame is pulled in the horizontal direction to provide a shear force through the soil block. Observations are focusing on the load applied, as well as the displacement (Schneider-Muntau, et al., 2006).

Figure 37 Digital shear testing machine (http://www.controls-group.com/eng/soil-mechanics-testing-equipment/digital-shear-testing-machine.php).

6.2.2 Triaxial test

During a triaxial test a sample is subjected to the three dimensional stress, but loading is subjected vertically. This method is representing the conditions similar to the one occurring in the soil mass. Test is suitable for all soil types (Schneider-Muntau, et al., 2006; Barnes, 2000).

Figure 38 Triaxial test (http://www.matest.com/en/Products/soil/Triaxial-testing-equipment/traxial-tests/triaxial-automated-testing-system).

6.2.3 Constant Head Permeability Test

A constant head Permeability test can be performed on soils within a range of permeability of 10^{-2} and 10^{-5} m/s, such as sands, as well as sandy gravels. In addition to that test is suitable to use in disturbed or remoulded samples. Through the test a flow and a hydraulic head loss are observed until they reach a study state. Coefficient of permeability is calculated using values measured during the test – flow rate and head loss (Barnes, 2000).

Figure 39 Combined Constant Head and Falling Head Permeameter (http://www.controls-group.com/eng/soil-testing-equipment/combined-constant-or-falling-head-apparatus.php).

6.2.4 Falling Head Permeability Test

The Falling Head Permeability test is suitable for soils characterised by low or intermediate permeability. During the test water flows down a standpipe and through the sample. Hydraulic head is then a difference between a meniscus level in a standpipe and the overflow level. Figure XXX, above, Presents the permeameter that could be used for the aforementioned test (Barnes, 2000).

6.2.5 Moisture Content

Moisture content is an indicator of the state of soil and its behaviour. The value of a moisture content is calculated as a ratio of the mass of water to the mass of the solid particles, presented in percentage. A test is compiled of initial weighting sample, drying it in controlled temperature environment and weighting the dried sample (Barnes, 2000).

6.2.6 Atterberg Limits

Atterberg limit is describing the properties of plasticity and cohesiveness of fine soils, such as clays and silts. It describe a liability of soil to change or remould without changes in volume or breaking up (Barnes, 2000).

Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
A definitive cone penetrometer method is believed to be the most reliable. During the test a cone is falling onto a very moist soil. A cone penetration, as well as moisture content are measured, however the value of Liquid Limit is the value of moisture content observed at 20mm penetration.	Plastic Limit is defined by measuring the moisture content of the dried sample. Sample is dried until it crumbles or shears at 3mm diameter. The test result is highly dependent on the operator, as it requires to use a manual force.	Plasticity Index can be calculated by subtracting a value of Plastic Limit from Liquid Limit.

Figure 40 An exaple of Liquid Limit cone penetration method (http://www.sisc.com.vn/en/detail.php?module=product&iCat=2097&iData=221&#page=page-3).

6.2.7 Particle Size Distribution

Particle size distribution is performed by Sieving and Sedimentation. Soil is placed on the top sieve and during the process of shaking smaller particles are falling onto the bottom sieves, where each of the underlying allows smaller and smaller particles to pass. Particles which passed through all sieves can be subjected to an additional test – Sedimentation. During this test soil particles are suspended in fluid and are falling at different velocity. At 4 minutes a sample is taken and particles >20µm are expected not to be in a suspension (Barnes, 2000).

Figure 41 An example of an Electromagnetic Sieve Shaker (http://an.geotechnical-equipment.com/Pages/Search.aspx?s=Electromagnetic%20Sieve%20Shaker).

6.3 In – situ monitoring methods

The selection of monitoring methods presented below contains various intrusive and non-intrusive techniques. Selection of the most appropriate monitoring technique is dependent on a number of factors including nature of the site, access, ground conditions, slope angle, available budget etc. The selection of appropriate combinations of techniques is discussed further in Chapter 7 of this report.

6.3.1 Rain Gauge

A rain gauge is an instrument used in meteorology which measures the amount of precipitation fallen in a particular location during a certain period of time. It is not a direct landslide monitoring method, but allows observation of a how changes in precipitation influence slope stability. There are variable types of devices available on the market, some of which are automatic and some require direct measurements.

When installing a rain gauge, a precipitation collector shall be placed approximately one meter above the ground and no object or structure should influence the inflow. MetÉirann monitor rainfall in various locations across Ireland. Where MetÉirann rain gauges are not in close proximity to the landslide being monitored, one should be installed specifically for the site.

Figure 42 Optical gauge (automated system) and standard type rain gaugee (required direct readings) (http://www.nwclimate.org/guides/how-to-use-rain-gauge/).

Advantages	Disadvantages
• Popular and easy to imply monitoring method • Low cost • Reliable • Existing data can be requested from MetÉirann	• To high rainfall can introduce errors in readings • Readings can be influenced by evaporation or strong winds • As debris (leaves) can block the collector entrance, therefore instrument require maintenance

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

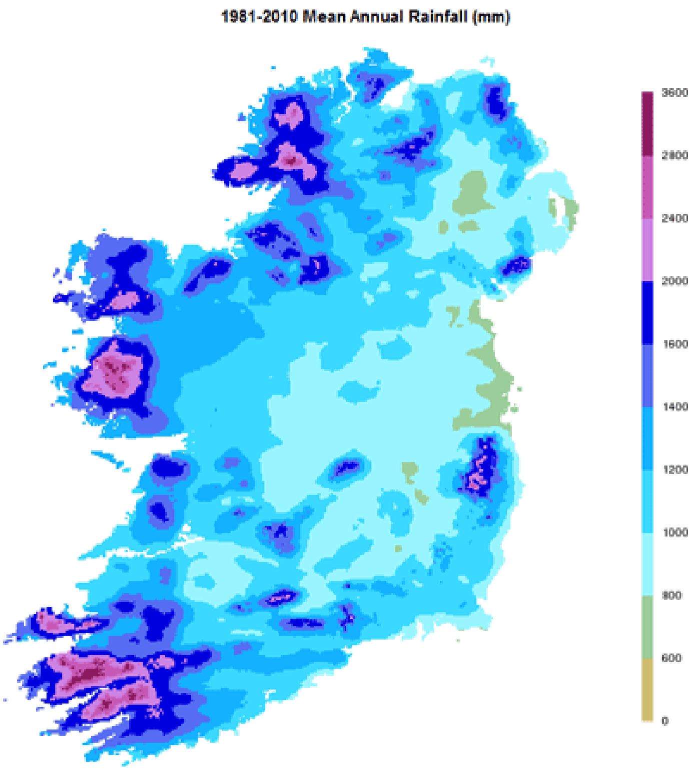


Figure 43 Mean Annual Rainfall (mm) in Ireland (http://www.met.ie/climate-ireland/rainfall.asp).

6.3.2 Weather Stations

In addition to local rain gauges, a full weather station can be installed to measure additional components of weather. Relevant parameters include the barometric pressure, the solar flux, the temperature, wind speed, wind direction and humidity. These values can be used to determine relevant parameters such as the local Soil Moisture Deficit (SMD), which is calculated as a derived parameter based on the weather patterns and soil type. A weather station should ideally be installed with a robust housing capable of resisting the weather. The housing should also be secure against theft and human interference. A local datalogger complete with telemetry system should also be installed to facilitate remote transmission of the data without the need for manual visits to the site. In addition, the power supply should contain a solar panel and a battery pack for full redundancy. The site location should be carefully selected to ensure adequate reception for the GPRS modem.

6.3.3 Extensometers

Extensometers are devices used to measure the amount and rate of movement in either the horizontal or vertical direction. Many types of extensometer are available, most of which are installed inside the borehole. One of the most popular extensometer is the Magnet Extensometer. Along the length of an extensometer, several magnets are coupled to the surrounding soil. Base readings are taken of the position of the magnets on installation. As soil movement occurs the magnets move relative to their initial position. The readings are made by drawing the probe through the access pipe. This probe beeps as it passes through the magnetic field of the magnets in the borehole and the location/depth can be read from a graduated cable. This process can be repeated over time to gain an understanding of both the magnitude and rate of movement of the soil mass.

Figure 44 Magnet Extensometer (http://www.slopeindicator.com/instruments/ext-magnet.php).

Advantages	Disadvantages
• Easy to use	• Requires manual readings

•Quick data collection process •High level of accuracy •Does not require post processing	•The process of installation can damage surroundings •Monitoring is carries out only in specific localisation •Vertical or horizontal movement can be observed but device cannot detect both at the same time

Soil Type	**Applicable**
Glacial Till	Yes
Peat	No (Access to peat areas can be difficult)

6.3.4 Inclinometers

An Inclinometer is an instrument used to monitor lateral movements of the ground. The inclinometer device itself consists of an instrumented torpedo shaped probe. The Inclinometer`s probe is suspended on a cable and is lowered into a plastic grooved casing which is encased within grout within a borehole. The grooved casing has a cruciform set of grooves in which the torpedo wheels run. Usually, one set of grooves are aligned with the direction of greatest expected movement. The torpedo is lowered and raised four times with the instrument being rotated through 90 degrees between each reading. This allows the plastic casing shape to be defined in two orthogonal directions with an error check for each set of readings. The movement of the ground can then be deduced form changes in shape of the plastic casing over time.

Figure 45 Example of digital inclinometer system (http://www.geokon.com/GK-604D).

Advantages	**Disadvantages**
•Easy to use	•Requires manual readouts

•Quick data collection process •Accurate •Can identify depth of failure plane of landslide	•Care must be taken in the selection of the grout to use within the borehole as the stiffness of this material can affect readings

Soil Type	Applicable
Glacial Till	Yes
Peat	No (Peat likely to flow around grout and inclinometer installation)

6.3.5 Crackmeters

Crackmeter is a device which measures the ground movement across an existing crack. Either side of the crack a gauge is anchored to the ground. When movement occurs, a slider changes its position and an applied voltage measures the slider and an end point.

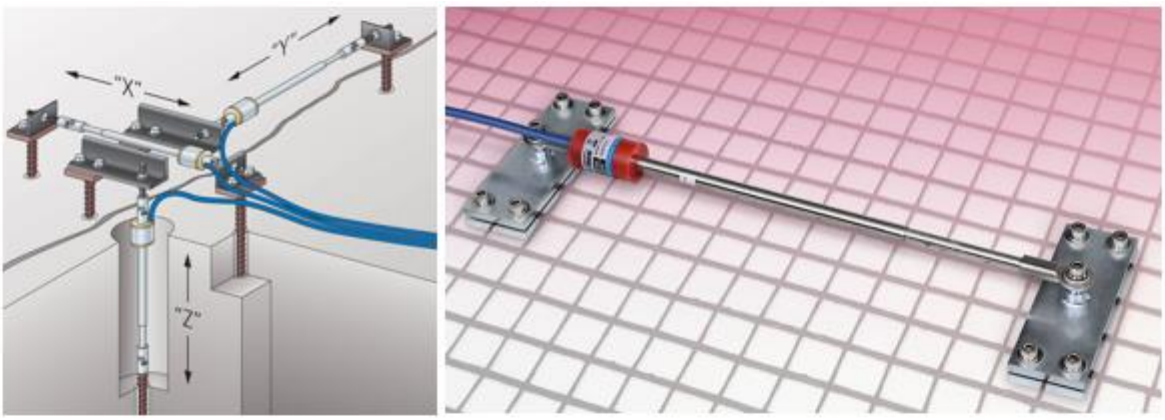


Figure 46 Example of Crackmeter (right) and an example of usage (left) (http://www.geokon.com/4420).

Advantages	Disadvantages
•Easy to use •Quick data collection process •Accurate •Can be connected with a datalogger	•Installation may be difficult •More suitable to stiff soils/rocks as well defined cracks tend to appear in these landslides.

Soil Type	Applicable
Glacial Till	Yes (only for very stiff tills where a defined crack can be seen)
Peat	No (Peat slides tend to be sudden and it is not likely that a well-defined crack will be visible for a long period prior to failure)

6.3.6 Standpipe Piezometers

A standpipe piezometer is an instrument that measures ground water level. A standpipe needs to be installed within a borehole. It consists of a plastic pipe with a perforated zone which allows ground water to flow into the pipe. The piezometer device is located inside the pipe in the zone subjected to observation and the piezometers filter is attached to a riser pipe which comes to the surface. The observations of water level are conducted using a sounder or a water level meter (http://www.geokon.com/4590). A water level meter is often used to measure the water level within a standpipe.

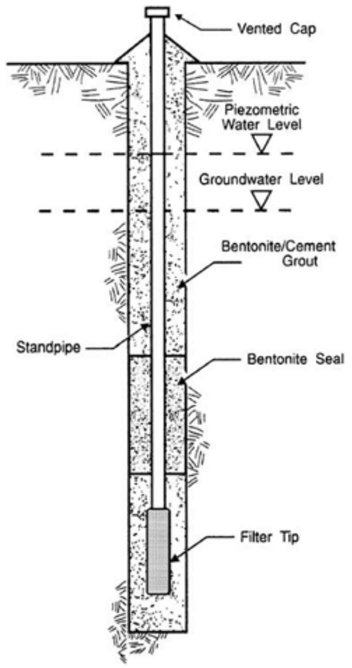


Figure 47 Standpipe Piezometer (http://www.risknat.org/projets/riskydrogeo/docs/guide_pratique/Acivite1_Ateliers/Presentations%20Atelier1/A1P13-Coastal%20changes/programs/instability.html).

Advantages	Disadvantages
•Easy to use •Reliable •Accurate •Allow to take samples of ground water •Cost effective •No electronic components	•Easily damaged during construction •Require to prevention of rainwater run off to the Standpipes •Monitoring is carried out only in specific localisations. •Manual readings •Response time is directly dependant on the soil`s permeability

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.7 Vibrating Wire Piezometers

This device is installed in order to monitor pore water pressure. There is a wide range of Vibrating Wire Piezometers available. These devices are commonly used, widely applicable, and can be installed inside a borehole, embedded in fill or suspended in a standpipe. Readings of the water pressure is transmitted as a frequency and can be taken using readout or a datalogger (http://www.geokon.com/4500-Series).

Figure 48 VW Piezometers (http://www.geokon.com/4500-Series).

Advantages	Disadvantages
•Reliable •The frequency signal can be transmitted through a very long cable, up to several kilometres •Filter stone ahead of the diaphragm allows water to pass but protects ingress of soil particles •High Accuracy •Easy to operate •Inbuilt temperature sensor monitors temperature	•Require calibration •Water sample cannot be collected Relatively expensive •Require maintenance

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.8 Tensiometer

Tensiometer is an instrument that measures the potential or tension of water held in soil. It consists of porous ceramic cup closing the Tensiometer, inside which is a vacuum. The water from the soil moves inside the tensiometer in order to equilibrate and a vacuum causes the readings. The reading from the Tensiometer gauge increases, when soil dries, and as water potential decreases – tension increases (http://www.earthsystemssolutions.com/). During an installation operator must assure that sensor is in the direct contact with soil.

Figure 49 Dial - Gauge Tensiometer (http://www.earthsystemssolutions.com/).

Advantages	Disadvantages
• Simple • Reliable	• Cannot be used in a freezing soil conditions • An ingress of air with water or during dry conditions is possible and can distort results

Soil Type	Applicable
Glacial Till	Yes
Peat	No

6.3.9 Water Content Reflectometers

This device was designed to measure the volumetric content of water in the soil. Installed probe generates an electromagnetic pulse and measuring the time needed for the impulse to return. The Water Content Reflectometer can carry out various functions depending on the angle of insertion, for instance probe placed vertically is measuring the water content in upper 30 cm of the ground, horizontal orientation measures passing or wetting points, whereas 30° inclination detects the water content in top 15 cm of the soil (https://www.campbellsci.com/cs616-reflectomer).

Figure 50 An Example of Water Content Reflectometer (http://www.iarc.uaf.edu/research/highlights/2008/northern-alaska-2).

Advantages	Disadvantages
•Can be connected with a datalogger •Does not require periodic maintenance • Highly accurate •Fast response time •Suitable for a long-term monitoring	•Probe installation may affect the results •Temperature dependant

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (note, organic soil can attenuate a signal)

6.3.1 Theta probe

Theta probe is a moisture content sensor. The device is buried in the ground and connected to a datalogger. Connecting the sensor to a source of power induces an electromagnetic wave transmission from the steel rods to surrounding soil. Depending on the water content, soil's permittivity changes and is detected and measured by the device.

Figure 51 ThetaProbe (http://www.delta-t.co.uk/product/ml3/).

Advantages	Disadvantages
•Can be connected to a datalogger •Can be calibrated to specific types of soil	•If used in hard soils, device shall be installed into pre – formed holes •Not suitable for temperature measurements •Readings may be affected by roots, animal's burrows, stones, and subsoil drainage

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes (note, organic soil can attenuate a signal)

6.3.2 Tiltmeters

Tiltmeter is a device designed to measure tilt in structures. It is installed permanently attached to the structure in order to perform a long term monitoring. The device is very precise and can measure very small movements. The device can be connected to a data logger.

Figure 52 Tiltmeter (http://www.geokon.com).

Advantages	Disadvantages
•Combine a high range with a sensitivity and very high calibration accuracy •The output produced, a frequency, can be transmitted over long cables •Sensors are less likely to be influenced by the effects of the moisture intrusion •Easy to obtain biaxial measurements by installing two devices together one at 90° to the other •In build shock absorbers protect sensors from shock loadings	•Shock sensitive – shocks can cause several offsets •May require a damping fluid if the output is unstable

Soil Type	Applicable
Glacial Till	Yes (if a sensitive structure is being affected by a nearby landslide, or potential landslide in Till)
Peat	Yes (note, sensitive structures are rarely constructed on Peat therefore the situations in which this tiltmeter could be used is limited)

6.3.3 Time Domain Reflectometry (TDR)

Time Domain Reflectometry is a method of detecting, as well as interpreting, rock and soil mass movements. TDR requires the installation of a cable inside a borehole, which is then encased in grouted. A voltage pulse is sent through the cable and can be reflected if the change in the characteristic impedance of the cable has changed. Changes can be caused by the crimps, kinks, presence of water, as well as by the broken cable (Kane, W.F., 2000).

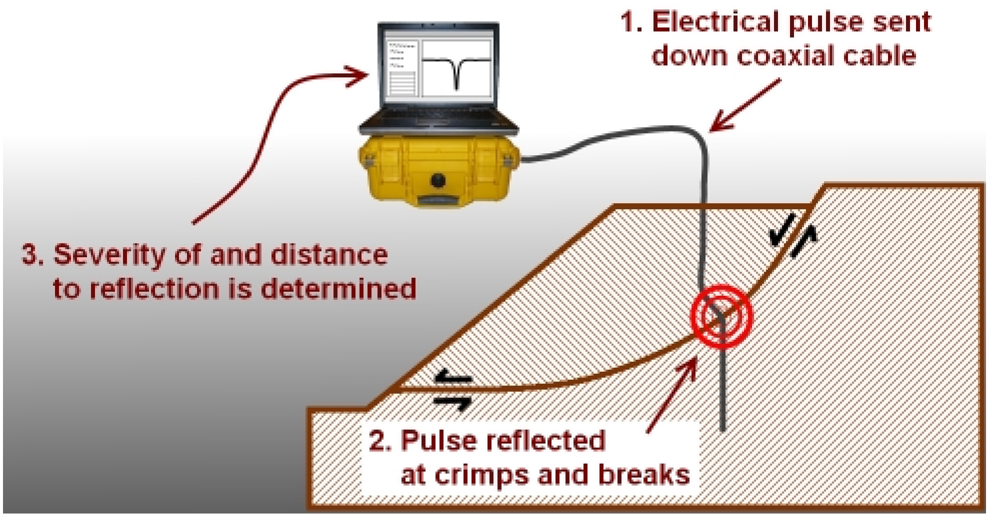


Figure 53 Principles of TDR (http://www.kanegeotech.com/instrumentation/).

Advantages	Disadvantages
•Easy to use •Quick data collection process •Remote access •Does not require excessive funds •Collected data indicates the depth of slip surface	•Cannot be used for monitoring tilt as TDR can be damaged by shearing only •To achieve the best results should be installed in the back of a structure, eg: retaining wall •Requires the installation of long probes •Magnitude of movement as well as the direction are not measured

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.4 Laser scanning

Laser Scanning is a widely applicable method which can be used to survey discontinuities as well as surface deformation and displacements. The scanner captures the 3D data imaging of the area, which are extremely precise (6 mm in position and 4mm in distance for every 50m). Recorded scans are saved on the instrument and need post processing. A map or 3D model can be produced using the scanner results. For the purpose of use of this system on landslides, numerous scans should be taken as a baseline reading with repeat readings at regular intervals to detect movement of the landslide over time.

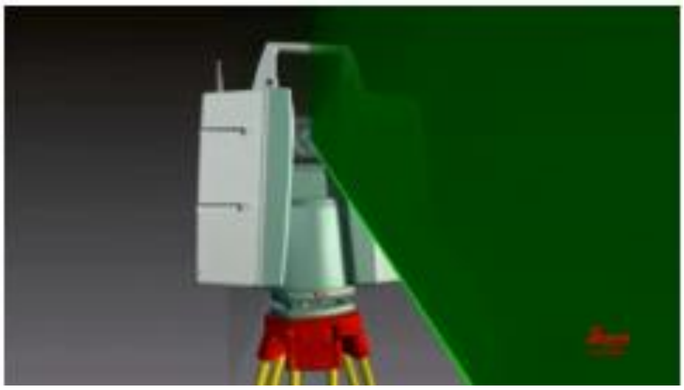


Figure 54 Example of Laser Scanner Equipment (http://leica-geosystems.com).

Advantages	Disadvantages
• Easy to use • Quick data collection process • Accurate positioning and precise measurements • Does not require excessive funds • Non-intrusive method	• Post processing requires specialised software • Changes can be observed only when comparing with previously acquired data • Not suitable for permanent installation • Require the usage of highly specification software • Require geodetic monitoring points to be set up

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.3.5 Radar Interferometry InSar (Synthetic Aperture Radar Inferometry)

Radar Interferometry is a technique of mapping ground deformation using captured images made by orbiting satellites. Pictures are made in a time space from similar vantage points. Collating images with each other can provide a visual of the change in the topography (potential deformation) over time (USGS website). Soldata provides a service, during which up to 4 measurements per month can be made. Measurements can be as precise as 3mm in movement and 1mm a year in displacement rate.

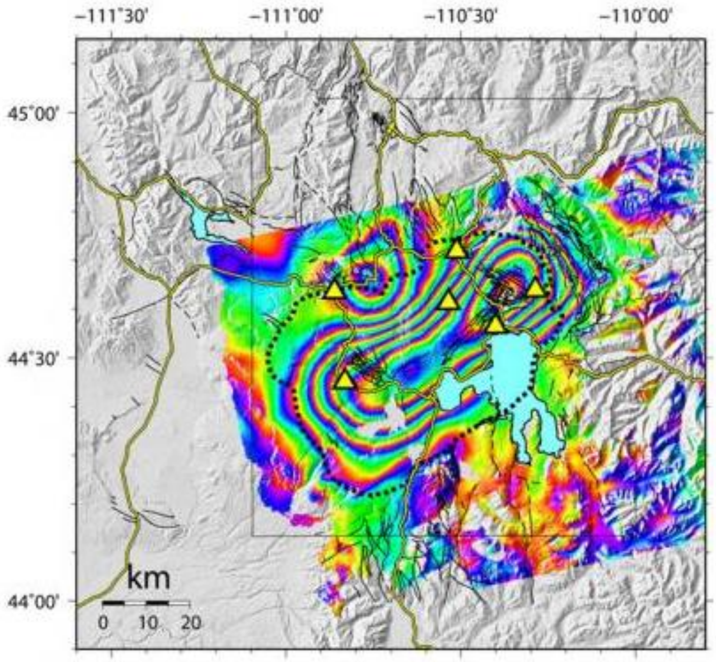


Figure 55 Example of ground movement map - observations of Yellowstone area Sept 2004 - Aug 2006) (https://volcanoes.usgs.gov/vhp/insar.html).

Advantages	Disadvantages
•Applicable regardless of weather conditions and day/ night light •Good application on a large-scale projects •Very high density of points (up to 10 000 points/km2) •Method can be applied in areas of difficult accessibility. •Easy comparison of slope mass movements with stable area •Non-intrusive •Data from the past may be acquired	•Changes can be observed only when comparing with previously aquired data •Only displacements along line of sight (LOS) in 2D between satellite and field can be measured. •The technique is not applicable in vegetation covered area. •Highly specific software. •Real time monitoring is not possible.

Soil Type	Applicable
Glacial Till	Yes
Peat	Yes

6.4 Suggested approach to proposing an appropriate monitoring strategy

The most appropriate monitoring methodology does not need to be expensive, but does require the landslides triggering factors to be fully understood, as well as to be tailored to the site conditions. A good monitoring methodology will be simple, robust and orientated to survey relevant parameters. An additional factor, which is worth noting is the seasonal dependencies of slope movement.

A monitoring strategy is a combination of the monitoring itself and the site and laboratory investigation and desk studies carried out to identify the pertinent parameters that require monitoring. A desk study should gather all existing available information regarding site and neighbourhood likely to be affected by a potential landslide. Basing on data coming from the historical sources, geological survey, heritage and environmental organisations as well as weather reports, the significance and likelihood of a landslide could be assessed. Based on the findings of this study, an appropriate site investigation could be designed to further develop the understanding of the site.

As a supplement to the information gathered during the desk study, prior to the site investigation a walk over is advisable. During the site visit, manifestations of an instability, such as displaced features, leaning posts and fences, scour should be noted (Bromhead, 2006).

A site investigation shall include a combination of the methods discussed in the previous sections of this report. The advantages and disadvantages of each method should be assessed against the nature of the specific site being investigated. Whichever combination of methods are used, the designer should ensure a thorough understanding of stratigraphy, soil types, soil mechanical properties and ground water conditions is gained.

In order to achieve the greatest benefit from a monitoring strategy, detailed modelling work should be carried out to assess the likely failure mechanisms and triggers based on the information from the site-specific investigation.

Once the above information has been obtained, then the monitoring regime itself can be designed. Depending on the strategic position of a potential landslide and the cost associated with predicted damage (property and infrastructure damage, heritage loss and environmental changes), the cost of chosen monitoring method should be appropriate. In the locations of low importance, for example isolated barren regions, simple solutions will be sufficient. In locations of high importance, for example densely populated urban areas or adjacent to critical infrastructure, a robust monitoring strategy combined with an early warning system is recommended.

Ideally, a monitoring strategy should involve monitoring of rainfall, ground water level and deformation of the ground. As the most common landslide triggering factor in Ireland is rain, available and relevant meteorological data should be gathered and monitored against trigger levels tailored to the nature of the area being monitored (Wieczorek & Snyder, 2009). If no monitoring station is available within an acceptable distance of the site, one should be installed at the site. As many landslides are triggered due to loss of matic suctions as the ground water table level rises, a suite of piezometers and tensiometers or Theta Probes should be installed to monitor these variables. Regular deformation observations using InSar or Laser scanner should be performed.

Surface and below ground movement should be taken monitored using strategically placed inclinometers and crackmeters.

6.5 Early Warning System

The key to the success of an Early Warning System is to apply a set of activities which help to manage risk. Early warning systems have been used in a number of countries including USA, Italy and Hong Kong. This section draws on the experience gained from these countries and looks at their potential applicability to Irish landslides.

In Hong Kong, a Slope Safety system has been put in place which applies the following points (Ho, et al., 2016):

- Create a landslide catalogue including risk assessment and repair order
- Inspect listed slopes and prepare safety recommendations
- Regular slope maintenance
- Mitigate the risk of the instability
- Introducing educational campaign (raising awareness)

This process allows information to be gained on the landslides in the area and a proactive approach to mitigation of instability to be implemented.

This approach has been further developed for a major landslide in Torgiovannetto in Central Italy. Here a well-known and studied landslide with potential to cause significant damage to both a provincial and region roadway has been heavily instrumented as part of an early warning system (Intrieri et al, 2011). The monitoring system on this landslide consists of 13 wire extensometers, 1 thermometer, 1 rain gauge and 3 cameras. Studies, site investigation and analysis has been carried out on this landslide to determine trigger levels for potential landslide movement. These trigger levels were based on kinematics of the landslide. If the velocity threshold set by this analysis is exceeded by two or more sensors, the attention level would be entered, causing improved monitoring and surveillance. Following this more detailed monitoring and surveillance, if the kinematics continue to exceed the threshold or worsens, an alarm is issued and the road is closed. The measures implemented here are ideal for situations where critical infrastructure could be majorly impacted.

In the USA, the United States Geological Survey (USGS) have introduced live monitoring systems to a number of landslides. The system used provide continuous, real-time monitoring to some sites and periodic monitoring to others. The most recent measurements are provided online for a number of the sites. Instruments monitored include rain gauges, geophones, pore pressure sensors and slope movement sensors. The live monitoring allows appropriate mitigation measures to be taken when pre-defined trigger levels are reached. Possible alarm measures include SMS, media, sirens and police door to door visits (http://landslides.usgs.gov/monitoring/ access 07/12/2016).

DiBiagio and Kjekstad (2007) discussed a general approach that should be taken to implementation of early warning systems. They identified that EWS should comprise the following activities

- Monitoring, including data acquisition, transmission and maintenance of the instruments;
- Analysis and forecasting, which can be done by using thresholds, expert judgment, forecasting methods and so on;
- Warning, i.e. the dissemination of understandable messages alerting for the impending threat;
- Response, concerning if people are able to understand and how they react to the warning.

They also summarised their suggested approach in a flow chart as shown below in Figure 56.

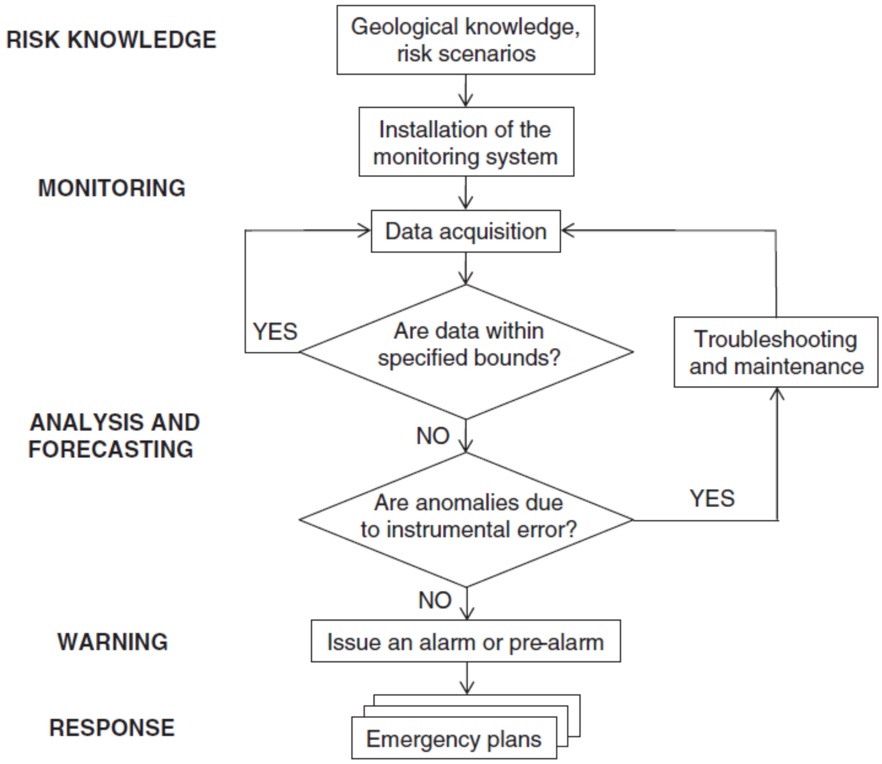


Figure 56 Example of an Early Warning System (DiBiagio and Kjekstad, 2007).

The above approach could be applied to Irish Landslides. Although the geology and triggers of Irish landslides differ from those discussed above, the general approach can still be applied. For example, rainfall levels have previously been identified as a key contributor to Irish landslides and hence this could be set as a trigger. Ideally, a series of triggers could be set of parameters including a combination of rainfall, soil moisture, pore pressure, water table level, displacement and any other parameters deemed critical to the stability of a particular landslide.

Monitored data is not only used to activate warnings and alarms, but also in order to adjust the thresholds, and to define the landslide model. An accurate analysis of a landslide should start from the analysis of its time histories and the correlation between different parameters. The use of innovative instruments, such as ones mentioned in the previous chapter, should ideally connect to a data loggers allow real-time monitoring, which reduces the intervention time. Measured data gained during the desktop study, ground investigation, laboratory tests as well as monitoring is logged, can be reviewed and used for better understanding of the landslides occurrences.

Office of Emergency Planning have prepared "A National Risk Assessment for Ireland" (Department of Defence, 2012), a response arrangement for major emergences, each of which has a five stage emergency management plan. A five-staged classification of likelihood, as well as five staged classifications of impact could be adopted by local bodies when assessing a risk of a landslide occurrence.

The below table presents Likelihood classification (Department of Defence, 2012).

Ranking	Classification	Likelihood
1	Extremely Unlikely	May occur only in exceptional circumstances; Once every 500 or more years.
2	Very Unlikely	Is not expected to occur; and/or no recorded incidents or anecdotal evidence; and/or very few incidents in associated organisations, facilities or communicates; and / or little opportunity, reason or means to occur; May occur once every 100-500 years.
3	Unlikely	May occur at some time; and /or few, infrequent, random recorded incidents or little anecdotal evidence; some incidents in associated or comparable organisations worldwide; some opportunity, reason or means to occur; may occur once per 10-100 years.
4	Likely	Likely to or may occur; regular recorded incidents and strong anecdotal evidence and will probably occur once per 1-10 years.
5	Very Likely	Very likely to occur; high level of recorded incidents and/or strong anecdotal evidence. Will probably occur more than once a year.

The below table presents impact classification (Department of Defence, 2012).

Ranking	Classification	Impact	Description
1	Very low impact	Life, Health, Welfare	Limited number of people affected; 0-4 fatalities and limited number of minor injuries requiring first aid treatment.
		Environment	Simple, localised contamination.
		Infrastructure	<4M Euros.
		Social	Localised disruption to community services or infrastructure (<48 hours).
2	Low impact	Life, Health, Welfare	4-8 fatalities; considerable number of people affected; serious injuries with hospitalisation and medical treatment required. Localised displacement of a considerable number of people for 2-8 days. Personal support satisfied through local arrangements.
		Environment	Simple, regional contamination, effects of short duration.
		Infrastructure	4-24M Euros.
		Social	Community functioning with considerable inconvenience.
3	Moderate impact	Life, Health, Welfare	Significant number of people in affected area impacted with multiple fatalities (8-20), multiple serious or extensive injuries (20), significant hospitalisation. Large number of people displaced for 2-8 days or possibly beyond; up to 4000 evacuated. Regional resources required for personal support.
		Environment	Heavy contamination localised effects or extended duration.
		Infrastructure	24-80M Euros.
		Social	Community only partially functioning, some services available.

4	High impact	Life, Health, Welfare	20 to 50 fatalities, up to 100 serious injuries, up to 16000 evacuated.
		Environment	Heavy contamination, widespread effects or extended duration.
		Infrastructure	80-200M Euros
		Social	Community functioning poorly, minimal services available.
5	Very high Impact	Life, Health, Welfare	Large numbers of people impacted with significant numbers of fatalities (>50), significant injuries in the hundreds, more than 16000 evacuated.
		Environment	Very heavy contamination, widespread effects of extended duration.
		Infrastructure	>200M Euros.
		Social	Serious damage to infrastructure causing significant disruption to, or loss of, key services for prolonged period. Community unable to function without significant support.

In general, further research is required into early warning systems in Ireland. A number of trial sites and monitoring systems need to be identified and a number of pilot projects carried out to inform future decisions on the implementation of landslide monitoring systems in Ireland.

7 Monitoring strategy and pilot project outline

7.1 Detailed monitoring example

Landslides are complicated events which are dependent on several different factors. Therefore one single monitoring solution will not be globally applicable to every scenario. However, considering the prevalence of shallow translational earth and peat slides in the previous chapters and the driving influence of rainfall in triggering such events, an example pilot strategy is outlined below which can be applied to the majority of landslide susceptible areas. It is proposed that a dedicated landslide area is selected which is highly pre-conditioned toward slope instability or has evidence of existing movement and this slope is used to demonstrate the effectiveness of various monitoring approaches, including physical sensor systems and remote monitoring including drone surveys.

Framework for Pilot Programme:

- Prepare shortlist of pilot programme objectives ;
- Develop technical constraints for the study area (eg. soil type, etc.) ;
- Develop practical constraints for the study area (eg. access, security, …) ;
- Short-list demonstrator sites based on specific prioritisation criteria ;
- Complete desk study of every possible site ;
- Select demonstrator site and validate using detailed site visit ;
- Complete Site Investigation (drilling and geophysical) ;
- Prepare accurate maps (topographical and geological) of the demonstrator site ;
- Develop detailed intrusive monitoring regime ;
- Develop non-intrusive monitoring regime ;
- Analyse results, interpret results and report to ensure the system is functioning ;
- Tweak system to enhance the “live” component toward an Early Warning System
- Establish IT systems (applications and web portals) for public data access in a filtered format for lay understanding.

Proposing Monitoring Regime:

- Weather station: Considering the strong correlation between rainfall, soil moisture and landslide occurrence, installation of a local weather station is critical to the success of a pilot project. This weather station should be installed in an appropriate location to ensure representative data in attained for the slope of interest. Therefore the aspect and microsite location is important.
- Direct measure of Soil Suctions: As the most common landslide trigger is due to decreasing soil suctions in the upper soil layers near ground surface as the soil moves from a partially saturated to a fully saturated state due to rainfall infiltration, this is a critical parameter to measure. Soil suctions can be measured directly using tensiometers. Tensiometers should be placed over at least three different depth ranges (0.5, 1 and 2m depth).
- Indirect measure of Soil Suctions: As soil suctions are difficult to measure directly due to the accuracy, reliability and robustness of tensiometers it is proposed that supplementary

measurements are taken for redundancy by using soil moisture measurements as a proxy for soil suctions. For example, tensiometers can be susceptible to very small interferences such as frost effects, whereas theta probes that measure the soil moisture are much more robust. During the early phases of the monitoring regime the theta probes can also be validated against the tensiometer measurements to confirm the accuracy of the proxy approach.

- Direct Movement Analysis: Establishing a direct measurement system that is capable of monitoring movements at a mm scale is not trivial and most systems do not have the accuracy needed to measure slow ground movements. Early stage Fibre Optic Systems have been used for infrastructure applications and could be deployed to measure local strains. In addition, survey markers/pegs should be used to determine movements at the pilot site.
- Remote Data (Drone): It would be very worthwhile establishing a fly over drone survey for both photographic records and x,y,z coordinates. A pre-programmed flight path would allow comparative surveys to be undertaken at 3-6 month intervals to determine whether there is any mass movement.
- Remote Data (InSAR): Satellite imagery should also be used as a comparator to the drone survey and site intrusive data. The relative accuracy and applicability of the various techniques should be compared following 12 months of data capture.

The main objectives of a pilot project are to establish an R&D demonstrator site for landslide research and for proving new technologies for sensors, remote data capture and early warning systems. A provisional monitoring regime was outlined above which aims to capture the landslide trigger mechanisms as well as the resulting movements.

The minimum type and number of intrusive sensors and monitoring devices used during this scheme are as presented in the Table below:

Monitoring Method	Minimum Number of devices	Reason
Tensiometer	3	To measure soil suction
Theta Probe	3	To measure soil moisture (proxy for suction)
Weather Station	1	To measure and record meteorological conditions
GP 2 Data Logger Controller	1	To measure and feed – back control
FBG Monitoring Gauges	2 strings with FBGs at 10m intervals over 100m	To measure movements

The overall cost range of monitoring ranges from €45,000 to €80,000 for a scheme outlined above.

8 Suggestions for Future Work

There are two main outcomes from this work, which we feel would benefit from further investigation. The first is around bias factors that we think are likely to affect future landslide susceptibility mapping and the second is around monitoring approaches for ground movements (i.e. a pilot monitoring study).

a) Landslide Susceptibility Bias Factors: In order to develop and calibrate the landslide susceptibility maps, it is necessary to train or validate the maps based on the density of landslides occurring at sites with specific characteristics. We have identified a few factors which may skew the results slightly, such as apparent peat slides (based on quaternary mapping) that are actually natural earth slides occurring 500mm below peat surface. We think the overlying peat may precondition the earth to failure by opening up preferential drainage pathways into the subsoil below. Also, there are areas of rock outcropping that suggests there is rock at ground surface (based on mapping) but the actual landslide is occurring on a veneer of peat.

To address these issues, we suggest that a Quality Assurance exercise is undertaken for the GSI susceptibility maps to see if these biases have any impact on the predictive capability for new landslide identification.

b) Pilot Slope Monitoring Programme: As outlined in section 7, we feel that there is merit to establishing a demonstration site and pilot monitoring regime. One of the things that we have been exploring is the possibility of deploying a system that could act as an early warning mechanism for slope instability and an alarm mechanism in advance of landslides occurring. There are two aspects to this, dealing with slow moving natural landforms (peat creep, etc) and rapid landslides such as bog bursts. One of the things we would be keen to do is to select a slope that is heavily preconditioned to movement and set it up as a trial monitoring site where we could test different instrument systems. In particular, what we would like to do is the following (i) install intrusive sensors in the slope to pick up physical measurements of pore pressure change, movement, etc. (ii) install an on-site weather station to get local rainfall measurements, humidity, barameterics, etc. (iii) undertake regular drone flyovers including drone based lidar data for vector difference mapping and (iv) use regular satellite imagery (INSAR) to track movements remotely.

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