Risk assessment and management of unstable slopes on the national forest estate in Scotland

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Abstract. The National Forest Estate in Scotland has a wide range of geotechnical hazards present, primarily landslides, which may cause a significant risk to people and key infrastructure. UK land owners are increasingly required to understand the risks associated with their land and how their activities may affect landsliding and, in particular, where landslides originating from their land may impact third party assets. A Geographic Information System (GIS) based landslide susceptibility assessment by the British Geological Survey (BGS) identified a number of sites in the National Forest Estate as being susceptible to landslide hazards. Coffey Geotechnics Ltd and the BGS are currently undertaking “ground-truthing” of selected sites to identify and characterise the hazards, pathways and elements at risk. A “Slope Stability Appraisal of Risk” system was used to assign a risk category to areas identified during the “ground-truthing” phase which need to be managed. This system is based on the combination of hazards, receptor type, vulnerability and pathway in a similar manner to that of the Australian Geomechanics Society. A long term strategy for risk management of unstable slopes is under development by Forestry Commission Scotland to provide strategic guidance on future land management and guidance for existing felled sites. Options for risk management include: maintenance of existing systems i.e. drainage; silviculture where establishment of woodland can assist in slope stabilisation; and engineering works such as barrier systems, retaining structures and rock remedial works.

1. Introduction

The National Forest Estate (NFE) in Scotland currently extends to 650,000 hectares of land. The terrain is variable across the estate, but includes a high proportion of mountainous landform, steep slopes and geological diversity. [1].

Compared with many countries, the United Kingdom (UK) has a low level of landslide hazard; however, due to the high population in the UK and the density of critical infrastructure, the tolerance for landslides is considered to be low. In 2010 Forestry Commission Scotland (FCS) commissioned an ambitious programme of work – ‘The Slope Stability Project’. The project was targeted at identification and quantification of the landslide hazard and development of risk mitigation measures for the NFE and any adjacent third party assets. As part of this the British Geological Survey (BGS) was commissioned by FCS to undertake a desk based study using Geographical Information Systems (GIS) to target sites for further assessment [2]. This work is detailed in ‘Landslide hazard assessment and characterisation for forestry asset management in Great Britain’ [3]. The total area of forest on steep slopes amounts to some 40,000 hectares, and of these approximately 17,500 hectares has been identified as being potentially unstable [1].

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2. Hazard Assessment

The 17,500 hectares of potentially unstable land are currently being subject to an on-site ‘ground truthing’ geotechnical assessment, by Coffey Geotechnics Ltd and the BGS, to identify and characterise the types of hazards, triggers and propagating factors. There are two main categories of hazards identified during the assessments; natural hazards and man-made hazards.

Natural hazards observed in the NFE include: formation of debris dams in stream beds and at culvert inlets due to gully erosion sediment, landslides and trees debris (figure 1); landside failures in the forest and above the tree line; debris flows both channelised and open slope (primarily channelised, figure 2); rock falls due to weathering, discontinuity controlled failures, root jacking (figure 3) and windthrow, and boulders and rock material resting on slopes and against trees (figure 4). Each of these hazards has the potential to adversely affect the surrounding land whether that is on or outside the NFE.

Man-made hazards observed in the NFE are commonly associated with construction of forest roads. Forest roads are typically built for timber extraction and as such, must be relatively low cost to construct [4]. Historically, constructing cost effective roads across steep and challenging terrain led to practices such as building roads out onto trees dropped against tree stumps (‘high stumps’). Whilst this method is acceptable in the short term, over time the trees and stumps rot away leading to stability issues for the outer edge of road embankments and the presence of loose and poorly compacted fill.
Good drainage is fundamental to any forest road especially in areas of high relief where landsliding is a common problem. In such areas the drainage can be affected by minor instability, which may lead to drainage issues and subsequent larger scale instability. A forest road should not inhibit the flow of existing watercourses and it should be designed to cope with foreseen issues such as transportation of sediment, debris (e.g. brash) and storm events.

3. Risk Assessment
As an aid to risk assessment and risk management each site, once assessed, was split into discrete Areas based on the hazards and exposures identified. The Slope Stability Appraisal of Risk (STAR) system developed in 2008 [5] was used to assign a risk value, risk category and action to each Area. The STAR system is based on the combination of hazards, receptor type, receptor vulnerability and pathway in a similar manner to that of the Australian Geomechanics Society [6]. Risk (STAR Value) = Hazard x Receptor Vulnerability x Receptor Type x Pathway

The definitions and values for the Hazard, Receptor Vulnerability and Receptor Type are presented in Table 1. The Hazard is an estimation of the significance of the slope feature with the potential to do harm with a value of 5 having the maximum potential for harm. The Receptor Vulnerability is an estimation of the damage that could be caused by the hazard with a value of 5 being the maximum damage possible. The Receptor Type is the kind of receptor which the hazard could potentially affect. An undeveloped area where people are not present has been assigned a value of 1 (minimum) and an area in which numerous people could be present has been assigned a value of 5 (maximum). The Pathway is an estimation of the likelihood of the Hazard interacting with the Receptor Type with a value of 1 being almost certain and a value of 0 being barely credible.

| Values | Hazard Description                              | Receptor Vulnerability | Receptor Type                          |
|--------|-------------------------------------------------|------------------------|----------------------------------------|
| 1      | Minor failure / erosion / weathering - typically slopes < 25°. | Little or no effect    | Undeveloped land                       |
|        | Moderate slope failure - typically slopes < 25°. | Nuisance or minor damage | Unoccupied / Infrequently visited building / Public rights of way |
| 2      | Small rock fall individual blocks <0.1m³.       | Significant damage     | Roads / Footpaths                      |
| 3      | Substantial slope failure – typically slopes 25° to 40°. Moderate rock fall <10m³. | Major damage / Major Injury | Residential property / Commercial buildings (single to few lives) |
| 4      | Large slope failure – typically slopes at 25° to 40°. Large rock fall 10 to 50m³. | Total loss / Loss of life | Major public buildings (many lives)   |
| 5      | Major slope failure – typically slopes at > 40°. Major rock fall >50m³. |                         |                                        |

The STAR values therefore range between a minimum of 0 and a maximum of 125. The STAR values, the corresponding risk category and actions are given in Table 2.
Table 2. STAR Values.

| Risk Value | Risk Category   | Action                                                                 |
|------------|-----------------|------------------------------------------------------------------------|
| <10        | Low             | Normally accepted                                                      |
| 10 to <25  | Low to Moderate | Significant Risk - need to be made aware of hazards and monitor        |
| 25 to <75  | Moderate to High| Significant Risk requiring remedial measures / risk management actions  |
| 75 to <100 | High            | Significant Risk requiring major remedial measures                      |
| 100 or >   | Very High       | Significant Risk requiring urgent action                               |

4. Risk Management

4.1. General
There are different levels of risk management and remedial works which can be applied to the sites depending on the outcome of the risk assessment. Low risk sites can typically be managed with general inspections and maintenance of infrastructure. Low to Moderate risk sites can typically be managed with maintenance and refurbishment of existing infrastructure and drainage along with implementing control measures, such as preventing public access to forest roads during foresting operations. Moderate to High, High and Very High risk sites are likely to require further inspection to fully characterise the hazards. It is likely that these will require remedial works to reduce the risk to a level that can be managed effectively.

Studies in steep forested areas throughout the world have noted an increase in landsliding after vegetation is removed from the slopes; Endo and Tsuruta [7]; Megahan et al. [8]; Wu and Swanston [9]; Bathurst et al. [10]; Preston and Crozier [11]; Jakob [12]; Dhakal and Sidle [13]. This is important to consider when planning foresting operations and subsequent risk management strategies. FCS are currently developing a Guidance Report for Sustainable Management on Steep Slopes. The guidance will cover two main areas of concern; steep ground working and slope stability. These are not mutually dependant; however, they are linked. The guidance will outline underlying principles of slope stability; provide strategic and tactical guidance on future land-use management in respect to steep slopes; provide guidance for existing felled sites on steep slopes; identify good practice in planning and management on steep slopes and identify appropriate silvicultural and geotechnical management systems to meet site specific challenges [1].

4.2. Silvicultural

4.2.1. Land Management. Most forests on the NFE are already well-established. Many of these are in the process of being re-structured and as this takes place it will be important to establish what the objectives of management should be given the nature of the site. On unstable sites where there is a clear threat to third party assets, public health and safety, or environmentally sensitive areas, then slope stability will be the principal objective. In these cases foresting will be driven by risk management rather than commercial pressures.

4.2.2. Protection Forests. The role of forests as protection systems has seen increased research over the last decade; Motta & Haudemand [14]; Brang [15]; Hurand & Berger [16]; Dorren et al. [17]; Stokes [18]. In the European Alps, and in parts of the Scottish Highlands, rockfalls tend to be low magnitude / high frequency events with single rocks (<5m3) being displaced [19 & 20]. In such cases trees are effective as protection systems and can assist in reducing the velocity and the rebound heights of falling rock [21]. This has been seen throughout the site assessments, even where the trees offer
only a relatively thin protection band. The NFE acts, to some extent, as a natural protection system to the elements at risk by creating a barrier against falling rock debris, and also acts to stabilise superficial deposits and reduce surface water run-off intensity. On such critical sites, as the trees are removed this barrier is lost, which coupled with the potential for foresting operations to disturb boulders and rock debris on slopes and rock material from crags, may lead to an increased potential for hazard and receptor interaction. Hence, in critical locations specific management actions and even artificial protection systems may be required to manage the risk.

4.2.3. Tree Removal. The removal of trees from a site can be the trigger for the onset of instability, but it is also the opportunity to influence the stability of a site for the future. Once trees have been removed from a site there is a period of time during which the roots of the pre-existing trees will exert a beneficial influence on the soil. The deterioration of the old root system occurs over a number of years but the flexing action of the stems in the wind will be removed. This offers a window of opportunity to establish a crop of successor trees either through natural regeneration or by planting. Newly established trees contribute little in the way of rooting strength to the soil until around eight or nine years of age. It is important that on potentially unstable sites a successor crop is established before the integrity of the old root system becomes severe [1].

4.2.4. Mixed Root Development. The establishment of woodland has been identified as having a positive effect on slope stability with a growing body of scientific literature supporting it [22]. This has long been recognised in European countries where the protective capacity of forest cover has underpinned silvicultural practice. Soil protection is provided by grasses and herbaceous species, but this is greatly enhanced by the addition of shrubs and trees with woody root systems [23]. Tree roots can help to bind loose friable material and loose rocks on slopes, but can lead to ‘root jacking’ and rockfall hazards on rock crags or cuttings. They can also assist in intercepting water and controlling its movement through the soil.

The development of a rooting system on unstable sites can be beneficial in reducing the opportunity of soil movement; however, if carried out in the wrong way this can also exacerbate the problem. Root systems that are shallow and form an extensive plate can create a shearing plane. Add to this the tall thin stems that are prone to excessive movement in wind, can create the opportunity for windthrow and the subsequent exposure of unstable slopes. A variety of different tree species with various rooting structures binds the soil and rock horizons both horizontally and vertically (figure 5) and a varied canopy protects the forest from catastrophic windthrow [1].

Figure 5. Mixed root development to assist with slope stabilisation.
4.3. Geotechnical

For risk management and remedial works there are four principal methods available: avoidance; removal; control and containment; and strengthening. Avoidance, i.e. moving the infrastructure away from the unstable slope is typically not a practical option in the NFE, especially where third party land is involved.

4.3.1. Removal. Where there is a limited number of well-defined hazardous features then removal is considered appropriate. Based on past experience in the NFE the biggest cause of instability is due to water on the slopes. In the majority of cases the water could have been controlled by implementing an adequate drainage system or in the cases where drainage is already present, in having sufficient inspection and maintenance regimes in place. This will form part of the Guidance Report for Sustainable Management on Steep Slope [1]. Removal of material build-up in the culverts and ditches can ensure that water is allowed to flow through the sites freely, preventing water backing up in the slopes which could lead to a build-up of pore pressures and possibly, landslides. Removal of tree and rock debris from the gully beds can prevent the creation of debris dams. Material can back up behind such dams until eventually the dam fails suddenly releasing significant quantities of debris and water downslope. Such debris dam failure can lead to significant downstream erosion, obstruction of culverts and potentially debris flows.

With regards to rock crags and boulders, where failures do not have the potential to significantly undermine material or exacerbate other potential failures then removal of key hazard areas is recommended, otherwise control and containment should be considered. Removal of trees from the crest of rock crags within the NFE can prevent ‘root jacking’.

4.3.2. Control and Containment. Forest Research, the research agency of the Forestry Commission, has been investigating protective barrier systems to assist with natural hazards and foresting on steep slopes [24]. Due to the proximity of major roads to the NFE, installation of protective barrier systems will need to be in conjunction with traffic management. Forestry Commission have been working closely with Transport Scotland (governing body in charge of Scottish road network) in some areas to enable effective traffic management with as little disruption as possible to drivers. Protective barrier systems considered by Forest Research include rolling blockades of Heavy Goods Vehicles (HGV), Roman Army style ‘Armadillo’ rolling barrier system and catch fence systems (figures 6 & 7). The rolling blockade using HGVs would consist of a row of HGV trailers modified and strengthened to provide barriers or catch fences. The trailers would also be ‘weighted’ to reduce movement or overturning during any debris strike. Such systems would be positioned in the lane of the road nearest to the forest area, allowing the far lane to remain open to traffic. Any expected rock or landslide within design parameters would be contained by the barrier [24].

Due to the hazards and risks associated with access and construction activities on steep slopes, it has been identified that reducing the construction activity on the slope would be desirable and reduce costs. Forest Research has been undertaking research on the stability of trees on steep slopes [25] and the anchorage capacity of coniferous trees [26], to develop a temporary catch fence design utilising trees as substitute ‘fence posts’ and upslope fence post support anchorages. This would reduce the need for foundations, posts, erection of posts and the installation of anchorages.

4.3.3. Strengthening. Where localised failures have the potential to undermine the slope or infrastructure in the NFE then strengthening is considered to be appropriate. In past experience on the NFE, strengthening is typically required for embankment failures along forest roads where slopes below are too steep to build out onto. In these cases strengthening options such as gabion walls and soil nailing have been utilised (figures 8 & 9).
5. Conclusions
Following an initial GIS based screening of the landslide susceptibility across the NFE Scotland a ‘ground truthing’ exercise is currently under way to validate and further characterise the landslide hazard and risk associated with the higher susceptibility sites identified, thereby enabling prioritisation and budgeting to be undertaken.

Based on the terrain, the hazards and the elements at risk encountered during the ‘ground truthing’ it is clear that management of the NFE need to consider long term management not just the completion of the next phase in the foresting cycle. Guidance is currently being developed and updated by FCS to inform planning and foresting operations for steep and potentially landslide susceptible terrain.

In many of the sites most susceptible to landsliding manipulation of natural processes followed by land use management is likely to be more successful and cost effective than intrusive engineering solutions. However, there are a number of critical sites which require engineering works to mitigate or manage the risks.

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