PUBLISHED PROJECT REPORT PPR794

Some Aspects of the Interaction between Landslides and Forestry Operations

M G Winter

Prepared for: Transport Scotland
Project Ref: TS TR MFA 2012-005

Quality approved: B Shearer (Project Manager) M G Winter (Technical Referee)
Disclaimer

This report has been produced by the Transport Research Laboratory under a contract with Transport Scotland. Any views expressed in this report are not necessarily those of Transport Scotland.

The information contained herein is the property of TRL Limited and does not necessarily reflect the views or policies of the customer for whom this report was prepared. Whilst every effort has been made to ensure that the matter presented in this report is relevant, accurate and up-to-date, TRL Limited cannot accept any liability for any error or omission, or reliance on part or all of the content in another context.

When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) and TCF (Totally Chlorine Free) registered.

Contents amendment record

This report has been amended and issued as follows:

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Description</th>
<th>Editor</th>
<th>Technical Referee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft 1c</td>
<td>28/05/2014</td>
<td>First draft</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Draft 1d</td>
<td>13/06/2014</td>
<td>Review</td>
<td>B Shearer</td>
<td></td>
</tr>
<tr>
<td>Draft 1d</td>
<td>15/07/2014</td>
<td>Review</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Draft 1e</td>
<td>15/07/2014</td>
<td>Issue to customer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Draft 1f</td>
<td>09/06/2015</td>
<td>Customer comments addressed</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Draft 1g</td>
<td>10/06/2015</td>
<td>TRL Review</td>
<td>B Shearer</td>
<td></td>
</tr>
<tr>
<td>Draft 1i</td>
<td>06/07/2015</td>
<td>TRL Publication Approval</td>
<td>H Viner</td>
<td></td>
</tr>
<tr>
<td>Draft 1j</td>
<td>13/10/2015</td>
<td>Additional customer comments addressed</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Draft 1k</td>
<td>15/11/2015</td>
<td>FES stakeholder comments addressed</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Draft l</td>
<td>23/08/2016</td>
<td>Final customer comments incorporated</td>
<td>M G Winter</td>
<td></td>
</tr>
<tr>
<td>Issue 1</td>
<td>24/08/2016</td>
<td>Published</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ISSN: 0968-4093
Abstract
The interaction between forestry activities and landslides is well-established. Forestry activities can have a significant adverse effect upon instability, but equally well-designed planting that fully considers the local context of the site can have a positive effect on instability. The effects of instability are a cost to the Scottish economy as a whole, whether the impacts of events are on farm or forestry land or they adversely affect infrastructure. Better understanding, and positive collaboration, between the professional roads and forestry communities can only assist the process of managing and mitigating such hazards. To this end the first aspect of this work has been undertaken to generate high-level liaison between Forestry Enterprise Scotland (FES) and Transport Scotland to promote strategic cooperation and mutual understanding with respect to policy, planning and operations. The second aspect of this work has been to examine practices, particularly those from Canada and the wider Pacific North-West, in respect of planting, harvesting and construction approaches that could help to reduce landslides hazards consequential to forestry activities. This report briefly outlines the headline benefits from the drive towards more strategic collaboration and sets out some potential areas of improvement to forest practices in Scotland. The latter must, of course, be seen in the broader context that instability is but one factor in determining forest policies and practices.
1 Introduction

Rainfall-induced debris flows, a form of landslide, are a particularly common occurrence in Scotland. In August 2004, for example, a series of such events was associated with monthly average rainfall significantly in excess of the norm. Some of the resulting landslides affected important parts of the trunk (strategic) road network, linking not only cities but also smaller, remote communities (Winter et al. 2005; 2006).

Roads in Scotland provide vital connectivity links to communities, including those that are remote. Severance of these communities from access to services and markets as a result of, for example, a landslide or flooding, has significant economic and social consequences. While landslides can occur at almost any time of year, summer (July and August) and winter landslide seasons (October/November to January) have been identified (Winter et al. 2009).

While such events are primarily rainfall-induced (snowmelt can play a role in some circumstances), the effects of forestry have frequently been identified as, at least, partial causes or propagators of debris flows in areas such as the Pacific NW of the USA (Brunengo 2002). Logging, or deforestation, can have a dramatic effect on the drainage patterns of a slope, for example, reducing root moisture uptake, canopy interception, slope reinforcement due to the root systems, and the physical restraints on downslope water flow. Such effects were particularly noted, by the author of this report, as being amongst the factors in the triggering of a translational landslide (not a debris flow) at Loch Shira adjacent to the A83 trunk road near Inverary, Scotland, in December 1994 (Winter & McMillan, 1995). Equally, well-designed planting that fully considers instability can promote reductions therein.

The first part off this work has been to promote and undertake high-level liaison between Transport Scotland and Forestry Enterprise Scotland (FES), who are responsible for the trunk (strategic) road network and the national forest estate, respectively. This is intended to promote strategic cooperation and mutual understanding with respect to policy, planning and operations including those issues that are directly relevant to landslides and instability.

The second aspect of this work has been to examine practices, particularly those from Canada and the wider Pacific North-West, in respect of planting, harvesting and construction approaches that could help to reduce landslides hazards consequential to forestry activities. This report briefly outlines the headline benefits from the drive towards more strategic collaboration and sets out some potential areas of improvement to forest practices in Scotland. The latter must, of course, be seen in the broader context that instability is but one factor in determining forest policies and practices.
2 Strategic Collaboration

In Scotland, the trunk road network is managed by Transport Scotland, an Executive Agency of the Scottish Government, and operated by their contracted Operating Companies. The forest estate is variously owned and managed by a range of private individuals and organisations and Forestry Enterprise Scotland (FES) on behalf of the Scottish Government.

Better understanding, and positive collaboration, between the professional roads and forestry communities can assist the process of managing and mitigating landslide hazards. In order to promote better understanding, and positive collaboration, between the professional roads and forestry communities a series of regular (six-monthly) strategic, high-level liaison meetings has been instigated between senior Transport Scotland and senior FES personnel.

This has helped to ensure that the outputs from the Transport Scotland landslides programme are available to FES and that the outputs from the FES Steep Ground Harvesting Project (one of the Projects managed under the auspices of the Steep Ground Management Programme Board) are available to Transport Scotland. Some of these documents are referred to in this report. This can only assist the process of managing and mitigating landslide hazards and promote strategic cooperation and mutual understanding with respect to policy, planning and operations.

More direct benefits have been achieved by raising levels of awareness of the hazards associated with old and large (over-mature) trees that are themselves potentially unstable at the A82 Loch Ness-side and by helping to generate collaboration and closer working at the A82 Glen Righ site.
3 Planting

In the majority of cases planting of large numbers of trees is undertaken with the specific intention that these should be later harvested for commercial gain. This tends to lead to single-species stands of plantation forest. There are, of course, exceptions and these include the planting of areas to regenerate multi-species woodland.

Single-species planting may aid the stability of some shallower slopes, especially if it is sited lower on the part of the slope so as to aid the arrest of debris flow in the run-out zone. It also may act as an inhibitor to the relatively small translational slides that so often trigger debris flow. However, it is important that the rooting systems are appropriate to the relevant conditions.

The effects of vegetation planting on slope stability are well known (e.g. Coppin & Richards 2007; Norris et al. 2008) and in general tend to be positive. The three main benefits that may be incurred were reviewed by Winter & Corby (2012) as follows:

1. Canopy interception of rainfall and subsequent evaporation.
2. Increased root water uptake of the water that does infiltrate into the soil and subsequent transpiration via the leaf cover.
3. Root reinforcement.

The degree to which these effects are beneficial varies with the type of vegetation, and trees may be more beneficial than shrubs, which, in turn, may be more beneficial than grass. This is, however, very much a first approximation, and other factors need to be taken into account.

The first two benefits are typically described as evapotranspiration (e.g. Nisbet 2005; Smith et al. 1998). Nisbet, citing Calder et al. (2003), notes that UK studies have found that canopy interception by conifer trees may be between 25% and 45% of rainfall compared to between 10% and 25% for broadleaved species. The results reported by Keim & Skaugset (2003) from the Pacific North-West broadly support this, suggesting interception rates of between 21% and 83% during peak rainfall, with associated attenuation of the water that subsequently reaches the ground. The attenuation due to forest canopies effectively delays the delivery of precipitation at ground level smoothing out the effects of intense rain storms in much the same manner that engineered drainage attenuation schemes delay and smooth the delivery of water that may otherwise exceed the capacity of the drainage system to deal with it and cause flooding.

The latter benefit, of root reinforcement, has been the subject of much research in the geotechnical engineering community and attempts have been made to model such effects (Greenwood et al. 2004; Sonnenberg et al. 2010). The three-dimensional, spatial complexity and the variation in root diameter and strength (spatially, materially and temporally), has limited the practical ability to incorporate the effect of root strength in design. Notwithstanding this, it must be acknowledged that root reinforcement has the effect of increasing stability, albeit that defining that effect in a numerical sense for design purposes proves somewhat elusive.

In order to maximise the effects of roots on stability in shallow soils, it is important that a significant proportion of the roots penetrate vertically, or near-vertically, rather than just spreading laterally to form a raft (e.g. Rice 1977). Where such rafts form, the translational slides that initiate debris flows may be larger and cause higher magnitude events with the potential to cause greater damage. Indeed, Coppin & Richards (2007)
illustrate that such root systems are typical of many sucker species, that are fast developing but have largely weaker root systems that may not have a positive impact on longer-term stability.

The effects of forestry operations have frequently been identified as, at least, partial causes of debris flows in areas such as the Pacific NW of the USA (Brunengo 2002). In particular, logging or deforestation can have a dramatic effect on the drainage patterns of a slope, reducing root moisture uptake, slope reinforcement due to the root systems, and the physical restraints on downslope water flow for example. The effects of clear-fell harvesting were noted, by the Author and colleagues, as one factor in the triggering of a translational landslide (as opposed to a debris flow) at Loch Shira adjacent to the A83 trunk road near Inverary in December 1994 (Figure 1). The Ministry of Forests in British Columbia has conducted work (e.g. Rollerson 1992; Rollerson et al. 2001; 2002; Millard et al. 2002) to establish the likely post-logging landslide activity in key areas; this work is predicated upon the assumption that such activity will increase post-logging.

![Image](https://via.placeholder.com/150)

**Figure 1. Translational landslide at A83 Loch Shira. The head of the landslide is located just below the middle of the image and above that point former plough lines left over after forest harvesting may be seen. (Image dated 1995.)**

Other potential dis-benefits of vegetation planting as an effective means of stabilisation are, to some degree, alluded to above. These include the fact that the effects of vegetation take some years to become established and then those effects increase further over time. In the case of commercial forestry the effect will then recede in the wake of deforestation as canopy cover is removed, root water uptake is prevented and roots rot. There are also potential detrimental effects caused by ditching and ploughing works undertaken during planting and/or undertaken subsequent to harvesting including at the time of re-planting. In addition, mature trees can themselves become unstable and be subject to windthrow (whereby trees are felled by either uprooting or stem breakage by the action of wind loadings) a subject that is discussed in detail by Ziekle et al. (2010) (Figure 2). This most frequently occurs when the established wind-firm edge...
is removed (e.g. by felling, thinning or access development) but can also be caused by high wind events (typically >20 year return period).

In parts of Canada, after the first harvest of planted forests, a practice of planting mixed species replacement woodland and encouraging the establishment of natural regeneration has been followed. This has led to stands of progressive mixed-age, mixed-species trees which are less prone to windthrow. An example of such forests can be found above the eastern shore of Mabel Lake near Vernon (in the Okanagan Valley in British Columbia, BC, Canada) (Figure 3). While this then leads to complications associated with the variable maturity of the species of the tree, and thus readiness for harvesting, it does promote the development of differential root structures whilst discouraging the adoption of clear-felling operations and reduces the likelihood of windthrow occurring after selective felling. (In coastal areas a different approach is taken as selective felling in such locations is more likely to promote windthrow, due to the much more exposed nature of the forest edges and the associated long fetch, see Section 4.2.)

Indeed, in BC, slopes that are visible from public roads tend not to be harvested and certainly tend not to be clear felled. It is recognised that the density of the public road network, means that much more of the forest will be visible from the Scottish network and that this might render such an approach unworkable. In addition, the over-maturity of many areas of trees adjacent to the Scottish road network means that there is little option other than to harvest these stands. In addition, the maximum harvest size block in BC is normally limited to 40 Ha primarily in order to limit the visual impact if felling; the author is not aware of any formal limit on felling area in Scotland. If clear felling is planned for steep ground then it must be carefully considered in the light of the potential for increased instability.
Figure 3. Mixed-age, mixed-species planting on the valley sides of Torrent Creek above Mabel Lake near Vernon in the Okanagan Valley in BC.
4 Harvesting

The inevitable consequence of commercial forestry is harvesting (Figure 4). In Glen Croe, opposite the Rest and be Thankful site, one of the consequences of clear-felling is a progressive increase in the rate of erosion on the south-west side of the glen as the slope morphology adjusts to the loss of the trees.

![Figure 4. Photo-merge of the A83 and the west side of Glen Croe viewed from the south-west facing slopes of Beinn Luibhean showing single-species, managed, commercial forestry including areas of clear-felling.](image)

Whilst harvesting can induce instability this potential is compounded when the area of harvesting is on steep ground. Often over mature trees can themselves become a hazard (Figure 5) necessitating harvesting for reasons of safety as well as for commercial purposes.

![Figure 5. Unstable trees and rock outcrops on the slopes to the west of Loch Ness, to the north of Altsigh. The A82 trunk road runs immediately at the base of the slope.](image)

Catch fences have been used for the purpose of arresting stray materials including parts of trees and boulders during harvesting (e.g. at Glen Righ above the A82 trunk road). Other potential options have been researched as part of the Steep Ground Harvesting
Project, but not implemented including rolling blocks of weighted HGVs on the road
below and rolling Roman style steel ‘Armadillo’ shelters (Nettleton et al. 2012; Anon.
2008a). The anchorage capacity of coniferous trees is increasingly used to create
temporary catch fences which can be deployed rapidly and with minimal on-slope
construction activity (Nicol et al. 2006; Nettleton et al. 2012), the trees being used as
‘in-built’ fence posts.

4.1 Pre-Harvest Assessment

The importance of an assessment of instability issues prior to harvesting cannot be
overemphasised. Foster et al. (2012) describe the initial approach used by FES, as
developed from the Scottish Road Network Landslides Study methodology (Winter et al.
2009). This represents a first stage of identifying sites with hazards that relate to third
party assets. Thus, the sites of greatest interest are identified prior to either a
‘Geotechnical Appraisal’ or a more detailed ‘Geotechnical Assessment’, the approaches to
which have been developed since the publication of Foster et al. (2012) by FES, Coffey
Geotechnics and the author.

The hazard and risk assessment work being conducted by FES is part of their wider
approach to forestry operations on steep ground which includes the over-arching Steep
Ground Project and the operationally-led A82 Project (MacIntosh & MacLeod 2013). The
A82 Project follows on from the A82 Management Strategy (Anon. 2012) which
additionally sets out the planned approach to minimising the negative impacts of the
operations to harvest the mature commercial forests adjacent to the A82 trunk road
between Glencoe and Inverness.

The approach to such assessments is embedded in professional practice in BC and clear
guidelines for the management of terrain stability in the forest sector are set-out by the
Association of Professional Engineers and Geoscientists of BC (APEGBC) and the
Association of BC Forest Professionals (ABCFP) (Anon. 2008b; 2010a). The two sets of
guidelines are focussed on terrain stability in the broader forestry context, but discussion
of the content sits best here in the context of harvesting in Scotland.

It is also important to note that the practices set out in these two codes are in direct
response to legislative actions:


These Acts were passed with the express intention of setting higher standards for forest
road construction, enforcing stricter rules for terrain stability to minimise the potential
for landslides following harvesting, and requiring assessments by engineers and
geoscientists before logging or road building on steep terrain (G Horel, Personal
Communication, 2012).

The 2008 (Anon. 2008b) document provides guidance on establishing, implementing and
updating a Terrain Stability Management Model (TSMM). A TSMM should exist for all
areas of commercial forest and may comprise a document including one or more of a
map(s), chart(s), diagram(s) or text, the scope of which will be a function of the size of
the operating area, the complexity of the terrain conditions affecting stability, and the
management objectives for the area. It is intended to provide guidance on:

- When and where a Terrain Stability Assessment (TSA) should be carried out.
The management of terrain stability, whether or not a TSA has been carried out or not.

Establishing risk criteria for specified elements at risk.

For selecting forest development strategies that are consistent with the risks.

Establishing a consistent and logical decision-making process to analyse and document decisions concerning the management of terrain stability.

The 2010 (Anon. 2010a) document establishes a standard of care for carrying out a terrain stability assessment, assists in establishing the contractual scope of work and describes the skill sets required of those who carry out such assessments. It is additionally made clear that those carrying out such assessments must be members of the APEGBC or ABCFP, as appropriate. While the Register of Ground Engineering Professionals (RoGEP) in the UK is currently seeking to achieve a similar, but much broader, end result in ensuring that appropriately qualified and experienced people control ground engineering work, the position in BC reflects the much more legislated status of Engineers, Geoscientists and Foresters. In particular, the two sets of guidelines are predicated upon adherence to the requirements of the Engineers and Geoscientists Act, RSBC 1996 c 116 as amended and the Foresters Act, RSBC 2003 c 19.

A TSA is carried out in order to:

- Assess the potential for operations to affect or to be affected by landslide hazards.

- Depending on the requirements of the forest professional, evaluate risk and/or provide options or recommendations to manage hazards or risk related to operations.

There are many similarities between the system used in BC and that developed by FES. However, it is worth comparing the two schemes.

Areas in which a TSA is undertaken might be deemed broadly equivalent to those that are deemed to require either a Geotechnical Appraisal or Assessment in Scotland, while those areas for which a TSA is not deemed necessary might be deemed equivalent to those areas for which neither a Geotechnical Appraisal or Assessment is considered necessary, having been subject to an initial GIS-based assessment. This gradation from the GIS-based assessment to Geotechnical Appraisal and Geotechnical Assessment encompasses an element of tailoring the overall assessment to the complexity and severity of the issues present in a given area much as the TSMM and TSA are tailored to such criteria in BC.

Where the key differences seem to lie is that in BC there is a large professional community that deals with terrain stability. The individuals involved in such work seem to be from engineering, geoscience and forestry backgrounds as might be also implied from the genesis of the two key controlling documents (Anon. 2008b; 2010a) for such work. The closer operation of the professions does seem to mean that the stability assessments have a more direct focus on operating procedures and risks than is possible in Scotland, where these issues are covered but at a more superficial level and third party risk provides a stronger focus. To a large extent this is appropriate as the higher population and infrastructure density in Scotland mean that third party risks are, perhaps, more prominent than is the case in BC. Such risks are indeed the main focus of the FES and were the initial driver for the GIS-based assessments.
4.2 Harvesting

This section is not intended to provide a comprehensive review of the available harvesting techniques. It is intended to highlight some of the issues that may be of interest from the point-of-view of instability and some of the alternative techniques that may be more or less suitable where instability is likely.

Perhaps the most widely known, and used, silvicultural system is that of clear-felling. As the name suggests this involves clearing a planted area of trees. If the size of the block is such that there is a number of different coupes to be felled at different times, this leaves trees in adjacent areas. Such trees may well have been previously protected from the effects of wind by those trees removed during the harvesting operations and subsequently become subject to windthrow (Ziekle et al. 2010). Windthrow can expose the soil in and around the roots of the tree allowing the ingress of water and leading to instability. In addition, the trees themselves may be a hazard if there is the potential for downslope movement of felled timber although this can be managed by commencing felling on the leeward side and working progressively towards the wind rather than opening up a windward edge.

Ziekle et al. (2010) give very useful information on the causes of windthrow as well as the hazards and risks associated with the phenomena. Their work on best practice, while couched in terms perhaps more familiar to the environment in BC in which they are intended to be applied, are useful in more generic terms and include, while not being limited to:

- Avoid block layouts on exposed knolls and ridges.
- Avoid unnecessary exposed peninsulas of planting.
- Avoid narrow leave strips (strips of trees remaining after harvesting, including buffer zones between the land and watercourses (riparian areas).
- Leave setbacks (areas without trees) of, usually, 10m minimum on the edge or breaks into gullies, escarpments or incised streams to limit the potential for debris flow initiation.
- Avoid leaving a large fetch (or distance across which wind may flow unobstructed) particularly in the direction of the prevailing storm winds.
- Feather the edges of stands either during planting or, more likely, during harvesting of adjacent stands.

Most of the guidance given by Ziekle et al. (2010) may be adapted for the design of both new planting and for the harvesting of existing planting.

As noted earlier, in parts of Scotland the risks to the road network from forestry relate to the large trees that have become over-mature. These are large trees that have the potential to uproot, whether due to windthrow or not, and reach the trunk road. While the trees are potentially unstable, harvesting creates additional, potentially greater risks to both the trunk road and the workers engaged in felling.

The actual options available for harvesting on steep ground are inevitably limited. Standing Stem Harvesting, which utilises a helicopter to access and cut the trees, has been used in BC (Cleaver 2001). However, there is a number of issues associated with the technique that would also most certainly prevent its widespread adoption in Scotland. These include the following:
The high cost of the technique (Cleaver 2001).

The limited availability of payload helicopters in Scotland.

The lack of local take-off and landing zones that do not involve the helicopter crossing the trunk road. It is understood that the low altitude and the loads involved would trigger a request from FES for the trunk road to be closed if a crossing were involved.

The need for extensive preparation of the trees which must be limbed, topped and rigged for flight prior to felling (although conventional felling of trees could be undertaken prior to using the helicopter for extraction). The need for these processes eliminates many of the potential advantages in terms of worker and road user safety and also raises questions regarding the likely lack of suitability of the technique for trees that might well be marginally stable.

A video overview of the Standing Stem Harvesting technique is available at: https://www.youtube.com/watch?v=1IamWAKibtk.

Other forms of helicopter logging are available and Dunham (2006), for example, estimated that these were used to harvest about 8Mm$^3$ of timber in BC each year. However, the main advantages were cited as the extended operability limits and operable land base and the main disadvantages as the increased difficulty and cost of operations.

FES estimate that around seven percent of the total Forest Enterprise Scotland (FES) timber production over the next 20 years is located on steep ground (around 266,000m$^3$ per year) and that a significant proportion of the sites will produce high quality Spruce, Douglas Fir or Scots Pine sawlogs. Their own investigations of the potential for helicopter logging (MacIntosh & Tuer 2013) produce similar conclusions to those set out above. While the focus is on the A82 corridor, the conclusions are thought to have a wider applicability in Scotland. These estimated costs were higher than those reported by Cleaver (2001) in BC, even allowing for inflation, with the primary disadvantage being the risks associated with safety. However, the estimated costs were considered by FES to be considerably underestimated and £150/m$^3$ or more was thought to be likely.

The lack of large payload helicopters in the UK was also highlighted as a potential issue. It seems clear that with the relatively small amounts of timber on steep ground, compared to the 8Mm$^3$ tonnes harvested annually in BC, and the relatively good accessibility of the harvest sites to the road network and markets that major investment in large payload helicopters would not be worthwhile.

The FES Steep Ground Harvesting project has led to the procurement of a contract skyline winch team as the primary means of harvesting on the most challenging steep ground and FES have appointed a contractor to undertake the work within the A82 corridor.

This skyline system relies on a skilled chainsaw operator felling the trees which are then attached or ‘chokered’ to the skyline winch cables by a chokerman on the hillside who is in radio contact with the skyline winch operator higher up the slope. The work is physically demanding with the chainsaw operator, in particular, being required to climb up and down the hillside on rough terrain while carrying saw, fuel, breaking bar, high-lift wedges and a sledge hammer. The wedges and sledge hammer are used to assist in the
takedown of large or leaning trees and a hydraulic ‘Tree Jack’ is increasingly used as a less physical method of tree takedown.

The most powerful skyline winch available to the contract is presently mounted on a 35 tonne Volvo excavator base and is able to pull trees up to 700 metres downhill and over 1km uphill and has a certified mainline pulling capacity of up to 7 tonnes. The skyline winch team is capable of producing between 300 and 400 tonnes of timber per week, potentially without the complications of traffic management on the road below, depending on the trees being harvested and the difficulty of the site.

Perhaps of primary concern, from the perspective of the trunk road network, for all such techniques is the control of material on the slope. The common practice of leaving piles of brash on the slope to rot down over a period of time is not considered acceptable from the point of view of instability by MacIntosh & Saunders (2013). They outline a proposed approach to brash management on steep slopes, and particularly on sites adjacent to the A82, which is essentially one of removal. It should be noted that this is a proposal and it is clear that FES will ultimately base decisions at each site on a number of factors which include risk (safety & environment), visual aspect and, to a lesser extent, cost.

MacIntosh & MacLeod (2013) outline a proposed approach to the use of permanent catch fences as the sole method of preventing trees, debris and small items reaching the road during harvesting. It is presumed that such fences would be designed for rockfall protection purposes where such risks were present, although this is not explicitly stated. A trial of such an approach is proposed by MacIntosh & MacLeod (2013) to test whether the use of catch fences in place of traffic control would:

- Cause less overall disruption to road users, accounting for the disruption during installation of the fences which from experience does seem to be much less disruptive.
- Reduce the costs of risk mitigation.
- Result in higher outputs and therefore lower overall harvesting costs per unit volume.

It is important that the residual risk to road users from silvicultural operations, once the fences are installed, are fully articulated and understood. This will allow an evidence-based decision on a site-by-site basis that establishes the need, or otherwise, for traffic management during felling operations taking full account of any mitigation measure including catch fences.
5 Forest Road Construction

Forest, and other, roads can have a clear adverse effect on instability.

Following the A887 Invermoriston debris flow events in 1997 (Figure 2), Nettleton et al. (2005) noted that damage to the road surface, drainage, forestry tracks, culverts, vehicles and the hotel buildings had occurred. They also observed, at forest road culverts, increased erosion of the forest road embankment on the upstream side, apparently due to insufficient wing walls. On the downstream sides major scour had taken place apparently due to a combination of venturi flow behaviour on the exit from the culvert, and from overtopping of the embankment.

![Figure 6. Debris flow at Invermoriston (A887) in August 1997. (Courtesy of Northpix.)](image)

A similar effect was observed following the debris flow events at the A9 in August 2004. The old A9 road, which is located above the current A9 and the associated cut and natural slopes, had the effect of slowing and focussing surface flood water from the hillside above. This caused the water to flow over the edge of the old road at only a few points rather than in a more dispersed fashion and was reported as being instrumental in driving the erosion that caused the 2004 debris flows that closed the road (Winter et al. 2006) (Figure 7).

These two simple examples strongly suggest that the control of water and thus the provision of appropriate and adequate drainage, incorporating sufficient erosion protection, is the key to minimising the adverse effects of forest and other roads on hillside integrity.

Keller & Ketcheson (2011) provide useful guidance on reducing the risk of storm damage on low-volume roads such as those used for forestry purposes in the UK. They recommend a risk-based approach which, while beyond the scope of this report, seems to be an effective way forward. Of particular interest in the context of the current work is the retrofitting of existing undersized culverts with an armoured overflow dip to allow the passage of storm water without diversion of the stream or washing out of the fill.
Keller & Ketcheson (2011) point out that structures for crossing streams, including culverts, fords and low water crossings, and bridges, require hydrologic and hydraulic design to determine both the type and size of the structure. Culverts often fail because of a lack of capacity, deterioration (over time), or blocking. Impacts from failures may include degraded water quality, bank erosion and channel scour, effects on aquatic and riparian organisms, traffic delays, and costly repairs. To minimise the risk of failure each site must be analysed for flow capacity; sediment and debris passage; and potential for structure, bank, and channel scour. For some structures, adequate aquatic/riparian organism passage also needs to be ensured. Pipe capacity can be improved with the addition of a concrete headwall and/or a smooth lining and by ensuring that the inlet is not damaged; a smooth pipe lining is unlikely to be suitable in all situations including at locations where migratory fish are likely to pass up the stream. If a pipe might block and diversion potential exists, an armoured dip can be constructed over or near the culvert (Figure 8) to accommodate overtopping without washing out the structure or diverting water down the road, thus preventing additional damage (Furniss et al. 1997).

If a channel may carry considerable debris or the watershed has a history of instability, the potential for culvert blocking exists. A trash rack can be added in the channel or onto the culvert to trap or pass debris over the pipe before it becomes blocked. A variety of trash racks have been used. However, they are an additional structure that requires cleaning and maintenance and they can become a barrier to fish if not properly designed and maintained.

Keller & Ketcheson (2011) also highlight the more general need to ensure the passage of water from the upslope to the downslope side of a road. In this context they recommend the use of road cross-drain structures such as rolling dips (Figure 9) to move water across the road from the inside ditch to the slope below the road and off the road surface. Such cross-drain structures should be spaced frequently enough to remove surface water before erosion occurs. Clearly for such an approach to be successful sufficient drainage on the downslope side must be present. They do have the advantage
on low-volume roads, such as forest tracks that they require less maintenance than a system of ditches and culvert cross drains, which require more maintenance and can easily become blocked.

Figure 8. An existing undersized culvert fitted with an armoured overflow dip to pass water without stream diversion or washing out the fill [adapted by Keller & Ketcheson (2011) from Furniss et al. (1997)].

In a companion paper, Keller (2011) demonstrates a robust construction approach to the minimisation of erosion in the area around a culvert formed through fill at a natural stream channel (Figure 10). This incorporates an overflow for periods of high flow and control measure specifically to prevent downstream erosion. This arrangement is intended to minimise the consequences of stream overtopping both from high upstream flows and from surface water from the road itself.

Keller (2011) also highlights the use of high flow capacity, low water fords as effective means of allowing the passage of both water and debris whilst effectively reducing the

Figure 9. A rolling dip used to move surface and ditch water off the road and prevent water concentration (from Keller & Ketcheson 2011).
potential for erosion or wash-out of the road construction itself (Figure 11). This form of construction is perhaps best suited to relatively flat ground close to the valley bottom.

In similar fashion, in areas where there is vertical clearance between the stream bed and the road, gridded (vented) bridge decks may limit erosion by relieving water pressures and thus the downstream venturi effect (Figure 12). In the example shown in Figure 12 this is complimented by reinforced concrete wing walls to further reduce the potential for erosion and it is important that the entire area of the structure that is potentially wetted is protected against erosion. Keller & Sherar (2003) provide more detail on many of the issues discussed by Keller (2011) and Keller & Ketcheson (2011).

![Figure 10. Erosion prevention at a fill stream crossing (from Keller 2011).](image1)

![Figure 11. Erosion prevention ford at a stream crossing, Water Crossing, Palo Duro Canyon, TX, USA.](image2)
Many other publications relating to low-volume and unsealed roads also emphasise the importance of drainage and drainage-led solutions to the perennial problem of water-induced instability. ARRB (Anon. 2009), for example, suggest the use of brush and shrubs at the site of an off-road drain in areas where the slope below is relatively stable and provide useful guidance on the design of low-water fords (floodways), causeways and bridges such as that illustrated in Figure 11. Anon. (2002; 2010b) provide extensive advice on planning, design and construction for drainage features (including fords), in a wetter and colder climate and includes an extensive discussion of the approach to the design and construction of log culverts (Figure 13). These have the advantage of utilising site-won materials for their construction and thus avoiding the import of large quantities of expensive materials such as concrete to what are often rather remote sites.

An environment-led approach is described by (Gesford & Anderson 2007) and includes some practical guidance on the prevention and minimisation of erosion. Gesford & Anderson (2007) make the important point that water should be shed from the road at frequent intervals in order to minimise the volume of water shed at any one location and the consequential erosion potential. The maximum culvert spacing for forest roads is set at between 75m and 350m by Anon. (2010b), depending upon the erosion hazard and the gradient of the road. Seemingly implicit within this guidance is the need for care to be exercised to ensure that the water shed from the road surface to a drainage system appropriate to the specific environment, so as to minimise erosion of slopes below the road.

Note that the differences between Anon. (2002) and (2010b) are not entirely clear. However, Anon (2010b) is intended for internal use and the use of the guidance therein is broadly mandatory for Ministry staff while Anon (2002) is specifically described as ‘not cited in regulation’. For the purposes of this report the guidance given is considered to be broadly similar and is not contradictory.
It is important to note the foregoing examples from British Columbia (and elsewhere) are governed by totally different regulatory and legislative protocols compared to those extant in Scotland. Many of the examples illustrated here might not fit within the framework of good practice that exists within the United Kingdom but might well provide examples of how innovative approaches to controlling and managing the effective passage of water and debris might be approached. In addition consideration must be given to the type and size of plant that will use the forest road to ensure that the structures used are appropriate.
6 Summary and Conclusions

This report presents the results and outcomes from a number of activities relating to the influence of forestry on landslides and instability.

The effects of forestry operations have frequently been identified as, at least, partial causes or propagators of debris flow. Logging, or deforestation, can have a dramatic effect on the drainage patterns of a slope, for example, reducing root moisture uptake, canopy interception, slope reinforcement due to the root systems, and the physical restraints on downslope water flow. Equally, well-designed planting can promote reduced instability.

Rainfall-induced debris flows, a form of landslide, are a particularly common occurrence in Scotland. In August 2004, for example, a series of such events was associated with monthly average rainfall significantly in excess of the norm. Some of the resulting landslides affected important parts of the trunk (strategic) road network, linking not only cities but also smaller, remote communities. The effects of such instability are a cost to the Scottish economy as a whole.

Better understanding, and positive collaboration, between the professional roads and forestry communities can only assist the process of managing and mitigating such hazards. To this end high-level liaison between Forestry Enterprise Scotland (FES) and Transport Scotland has been initiated to promote strategic cooperation and mutual understanding with respect to policy, planning and operations.

Well-designed planting of slopes that fully considers instability, can undoubtedly bring stability improvements through the attenuation of rainfall by canopy interception, increased root water uptake and root reinforcement. In particular, well-designed planting will consider the mix of root depths and patterns that will optimise stability and is likely, on steep ground, to comprise a mix of species. Planting must, of course, be seen as part of a long-term strategy and the benefits of planting can be difficult to quantify in a manner that can reliably contribute to design.

The planting plan must also account for either the eventual harvesting of commercial forest planting or for the long-term management of non-commercial planting. In the latter case such management is essential to avoid the development of over-mature trees that can become a hazard in themselves. The design of such planting should also reflect the local landscape character, particularly in areas of high landscape value and/or sensitivity.

When trees are harvested from a steep slope one of the consequences can be an increase in the potential for instability, for the reasons highlighted in the foregoing paragraphs and also as a result of any damage that may have been incurred on the slope as part of the harvesting operations. A system of pre-harvest stability assessment has been introduced by FES for steep ground. This builds upon the Scottish Road Network Landslides Study (Winter et al., 2009) and hazards that relate to third party assets are identified (Foster et al., 2012). Those sites that present the greatest potential risks are subject to further assessment (Nettleton et al. 2015) and the results incorporated into the harvesting plans.

Harvesting on steep ground above a road is potentially problematic and the pre-harvesting assessments are, in part, designed to allow issues that relate to this activity to be highlighted and incorporated into the harvesting plan. In addition to the control of large timber, the control or removal of the large quantities of brash that are generated is
necessary. Windthrow is an issue that must be considered at all stages of forest operations and is an issue whether harvesting takes place or not.

Forest roads, much like public roads, can introduce issues that can contribute to instability. In particular, the control of water is essential, and the adoption of some of the techniques outlined in Section 5 could be beneficial in reducing instances of instability and erosion during times of intense rainfall. These particularly focus upon the effective transfer of water and/or debris from the upslope to the downslope side of the forest road by a combination of road level and/or culvert drainage. In all cases the road level and downstream surfaces are protected against erosion, be it by means of logs, natural stone or concrete. Section 5 gives a partial overview of highlights of the techniques and more detailed study of the individual techniques and forms of construction will be necessary – many of these will be encapsulated in the forthcoming United States Department of Agriculture USDA document on Storm Damage Risk Reduction for Low-Volume Roads.

Practices in respect of planting, harvesting and construction approaches that could help to reduce landslide hazards consequential to forestry activities have also been examined. Thus some associated potential areas of improvement to forest practices in Scotland have been identified. These must, of course, be seen in the broader context that instability is but one factor in determining forest policies and practices. The following considerations are recommended:

- The use of single-species planting on slopes where the risk of debris flow initiation is low and on shallower slopes below steeper slopes, inhibiting shallow translational slides and acting as a barrier to debris flow run-out.
- The use of a mix of planting and natural regeneration following harvesting on steep slopes. This promotes a variety of root structures depths and patterns thus providing maximum benefits to instability. It also leads to stands of progressive mixed-age, mixed species trees that are less prone to windthrow.
- The use of clear fell harvesting on steep slopes should be avoided where possible, although it is recognised that it cannot be avoided in many situations due to climatic conditions and a lack of previous management. If clear felling is planned for steep ground then it must be carefully considered in the light of the potential for increased instability. The use of mixed-species planting actively discourages clear felling.
- The use on forest roads of suitably designed bridges and other forms of stream crossing that are appropriate to the likely volumes of water and debris that might be discharged will help to avoid blockages that can lead to later releases of larger volumes of material. Some examples from North America have been given and it is recognised that these persist in a different regulatory and legislative environment and appropriate forms would need to be sought for use in the Scottish context.

Over the last three years (to 2015) FES has developed internal guidance to establish an approach to working on steep slopes. Long Term Management on Steep Slopes comprises two documents relating long term management on steep slopes (Anon., 2015a) and for operational working (Anon., 2015b). These seek to achieve a balance between managed risk and long term cost against a background of legal compliance and good environmental practice. The guidance has been developed by a range of specialists in the fields of hydrology, forestry, civil engineering and soil science.
Acknowledgements

The author would like to thank the following people for their efforts in providing information and data relevant to this work: Kevin Turner and Tim Smith (Westrek Geotechnical Services Ltd), Glynnis Horel (G M Horel Engineering Ltd), and Martin Lawrence (BC Hydro). I would particularly like to thank Kevin Turner, Martin Lawrence and Tim Smith for their friendship and hospitality during my study visit to British Columbia in 2012.

Grateful thanks for permission to use images in this report are due to Gordon Keller (Figures 8, 9 and 10), formerly US Department of Agriculture, and to Brian Chow (Figure 13), Chief Engineer at British Columbia Ministry of Forests and Natural Resource Operations. All other unattributed images (including Figure 2) are by the author.

The author is grateful for helpful comments from Morag Mackay and Angus Corby (Transport Scotland), and Les Bryson, Kim Leech, Ben Lennon and Alex McLeod (FES).
References


Anon. 2008a. Felling and extracting large trees on steep ground adjacent to major roads — a case study on the A82. *Internal Project Information Note 13/07*. Dunkeld: Forest Research.


