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A83 Rest and be Thankful: Ecological and Related Landslide Mitigation Options

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Contents

Abstract

In recent years a number of debris flow events have closed the A83 trunk road in the vicinity of the Rest and be Thankful. The damage caused has been both difficult and costly to repair, and the associated closures have caused traffic delays with attendant socio-economic impacts. This report examines the merits of a number of ecological and related landslide mitigation options for the south-west facing slopes of Beinn Luibhean in Glen Croe above the A83 trunk road. The use of explosives, and issues related to livestock and vegetation planting are discussed and an outline scheme for planting, developed by Forestry Commission Scotland and others in collaboration with the Authors, is briefly described. The planting scheme has the potential to reduce instability in the long-term but must be considered as part of a broader strategy that incorporates other aspects of land management, including stock control, and appropriate engineering measures.

1 Introduction

The Transport Scotland Scottish Road Network Landslides Study (Winter et al., 2005, 2009) undertook a hazard identification and ranking exercise and also set out the approach to the management and mitigation of debris flow events. While the primary approach was one of management, or exposure reduction, provision was also made for a more active mitigation, or hazard reduction, approach to be applied for the highest ranked sites such as the A83 Rest and be Thankful.

Debris flows are a regular occurrence in the general area of the A83 at the Rest and be Thankful. For over 20 years the first Author has observed such events on a regular, approximately annual, basis as they affect the area between Ardgarten and west of Cairndow. In recent years, broadly since 2007, these events have occurred in a somewhat more concentrated area, affecting the westbound approach to the Rest and be Thankful (Figure 1). These events are sourced on the south-westerly facing slopes of Beinn Luibhean (Figure 2).

Figure 1. Map showing the notional geographical limits of debris flow occurrence affecting the A83 trunk road in the general area (blue lines) of the Rest and be Thankful and the approximate limit for events since 2007 (red lines). Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2012. All rights reserved. Ordnance Survey Licence number 100046668.

Figure 2. The A83 on the approach to the Rest and be Thankful showing the south-west facing slopes of Beinn Lubhean (image dated October 2007).

Transport Scotland has initiated a major study to examine longer term solutions to the A83 Rest and Be Thankful landslide problem and to address broader route issues. Jacobs were appointed to examine engineering options and have been advised by TRL, drawing on earlier involvement in the Scottish Road Network Landslides Study (SRNLS).

As part of the aforementioned A83 study, Transport Scotland gave an undertaking to examine potential ecological solutions to the problem based around tree-planting and other forms of re-vegetation of the south-westerly facing slopes of Beinn Luibhean. It was also envisaged that this part of the work would examine some of the alternative solutions that have been proposed including those that advocate the use of explosives or livestock as part of the solution.

This report addresses these proposed solutions and suggests ways forward where appropriate.

2 Use of Explosives

It has been suggested that Transport Scotland should "… just fix the … hillside - dynamite it! Like they do in the rest of the world …".

It is not entirely clear what inspired the correspondent to suggest this approach but a degree of observational experience of rock blasting in either a quarry or infrastructure context seems most likely. Certainly there is a variety of forms of blasting that is used for varying purposes in the context of rock bodies and slopes. These include, in the quarrying context, blasting to break apart large bodies of rock to allow further processing to produce aggregate, for example. The detailed explosive charges can be configured to better approximate the target aggregate size range required. In an infrastructure construction context blasting is used to form cuttings (Figure 3) either using bulk blasting techniques or pre-split techniques, the latter producing a smoother and lower maintenance final face, although one that is not necessarily in keeping with adjacent naturally weathered rock slopes and outcrops (Figure 4). Blasting is also sometimes used to scale loose material from existing rock slopes.

Figure 3. Rock blasting adjacent at the A83 Artilligan (image dated May 1997).

The hillside at the Rest and be Thankful comprises a layer of soft soil that overlies the rock strata. It is the soil material that forms the debris flows that create such a problem when they block and otherwise affect the road. As a consequence it is this material, the product of weathering and previous slope movements, which would need to be blasted. This presents a somewhat different picture compared to blasting rock.

There are no known cases of blasting such soil materials to affect their removal in the technical literature. There are a number of instances in which blasting of rock has triggered slides in soft, soil material and blasting has been used on one occasion to attempt to trigger a sub-lacustrine slide in Canada, in the 1980s, albeit with rather unpredictable results.

Figure 4. Pre-split rock cut slope on the A830 near Arisaig.

Notwithstanding the foregoing blasting, involving near-shore soft sediments, has been used in a very particular scenario in Norway. When a large amount of fill is to be placed on the sloping, soft sediments just offshore (for example in connection with road construction along the fjords), the soft soil is replaced with rockfill down to bedrock by intentionally inducing failure. As much rockfill as possible (i.e. safety factor just in excess of 1.0) is placed on the clay, and the foot of the rockfill is blasted to induce failure. The disturbance caused by blasting and the weight of the fill mobilizes the soft sediments such that they flow downslope; the rockfill above the clay then sinks replacing the clay. This process is repeated until the desired geometry is reached. Of course, once one starts a submarine slide in this way, the effects can be quite unpredictable. A similar effect has been induced in soft quick clay sediments by rock blasting on the foreshore, albeit with somewhat less intent.

The concept of blasting of slopes with soft material prone to debris flow is new to both the Authors and those experts in this field who have been consulted during the preparation of this report. A number of concerns have been expressed regarding this proposed approach, as follows:

- That blasting may merely increase the area without vegetation cover (i.e. bare soil will be exposed) allowing water to infiltrate and erode the remaining soil cover more effectively causing further instability.

- That further marginally stable areas would be created as the soil is partially disturbed.
- That, in places, the rock would be fractured creating material that is more easily weathered and that will later become unstable.
- That the soft wet soils, including peat, present on the hillside will simply absorb the blast energy.
- That the process will be only very partially effective but, in the process of creating more unstable material as described above, will destroy the natural appearance of the hillside.
- It should also be noted that even if, as seems highly unlikely, blasting were effective in removing all of the soft soils, this would leave a very unsightly hillside comprising exposed rock that would itself be highly vulnerable to weathering that would then create more loose and unstable material and likely have a detrimental impact on the appearance of the attractive character of the wider Glen Croe area.

Indeed, when one considers the amount of potential soft material on the south-west slopes of Beinn Luibhean this could be of the order of a few million cubic metres. Typically the largest (rock) landslide volumes that have been treated in Norway, for example, are of the order of 20,000m^3 as at Fatlaberget (20,000m^3 in two stages) and 10,000m^3 at Skjerping (Figure 5). Certainly the general view is that there is little experience of blasting larger (rock) landslide volumes in the order of 100,000m^3, let alone several million cubic metres.

Figure 5. Dust cloud caused by blasting at Skjerping, Norway in 2010. The cloud travelled around 7km down the valley and fjord of Nærøydalen. (Photograph by Paulsen, courtesy of Ulrik Domaas, Norwegian Geotechnical Institute.)

Other issues that must be considered include the removal of the material resulting from the blast and the safety of workers involved in the operations. Perhaps the greatest concerns with this type of operation, apart from the relative unlikelihood of success, are the unpredictability of the movements of the materials during the process, particularly with respect to size of any landslide event triggered and its likely runout distance, and the means by which the very large amounts of blasted material may be removed from site and disposed. In addition, blasting on such a scale is likely to cause a significant dust cloud. Figure 5 shows the dust cloud from the Skjerping blasting operation in Norway in 2010 – in this case the dust cloud travelled approximately 7km down the valley and fjord of Nærøydalen. This raises the prospect of a dust cloud that could travel from the Rest and be Thankful as far as Lochgoilhead, Arrochar, the far shores of Loch Fynne or Loch Long, or even Loch Lomond depending on the prevailing wind direction at the time of blasting.

Clearly it is essential that each case of instability should be evaluated on its own merits, but an approach founded in proven technology seems most appropriate.

3 Livestock

The introduction of sheep to graze the hillside has been suggested as having the potential to lessen instability of the hillside from three perspectives:

- To keep the height of the grass down to help reduce the build-up of snow in the winter (Section 3.1).
- To prevent un-grazed grass dying off and weighing down the slope (Section 3.2).
- Sheep forming compacted paths as they traverse the hillside thus creating drainage run off (Section 3.3).

A further issue relating to the potential damage that animals can do to the slope surface is also addressed in this section (Section 3.4).

3.1 Reducing the Height of Grass

Certainly snow melt is a recognised cause of landslide activity. This concept that short grass will either hold or maintain snow pack is an interesting one. Certainly ground roughness (in the form of boulders, logs and low level, woody shrubs) is recognised as having an anchoring effect on snow pack, reducing avalanche risk (e.g. http://www.avalanche.ca/cac/library/glossary/a-z?index=E) at least for relatively shallow depths of snow. However, there appears to be little evidence that short grass will have a similar effect.

Notwithstanding that, it does seem likely that the action of water and gravity on the slope will tend to lay long grass downslope. During the winter months this grass will, most likely, be wet and could well help in moving snow downslope; this is likely to be a function of snow depth and slope gradient and whether this will occur for the relatively shallow depths of snow normally encountered in this area is not entirely certain.

It is also pertinent to note that the actual amounts of snow at the Rest and be Thankful generally tend to be relatively small, amounting to a few centimetres to a few tens of centimetres at any one time. It is by no means clear that any of the events in recent years at the Rest and be Thankful have been caused by a build-up of snow and its subsequent melting.

3.2 Un-grazed Grass

The second suggestion may well have resulted from an observation of the movement of a raft of soil covered with vegetation following an episode of instability. Certainly it is not reasonable to suggest that the additional mass of long grass, even when saturated, would be sufficient to cause instability and any contribution that it might make to that process would be very small indeed.

3.3 Sheep and Runoff

The effect that sheep and other animals such as cattle and deer have on the stability of slopes is perhaps more substantive. Deer, sheep and other animals tend to follow defined routes and Nettleton et al. (2005a; 2005b) highlight the deleterious effects of deer tracks on slopes above the A890 at Stromeferry (Figure 6) which do, indeed, create preferential drainage paths on the slope. These tend to be linear, flatter benches on the hillside, often broadly parallel with the contours and are often located at breaks of slope. This disrupts the flow of water and creates preferential drainage routes and increases infiltration with an overall negative effect upon stability. This can cause water to flow along the path spilling over onto the slope, concentrating the flow at a low point potentially causing erosion. This phenomenon has been directly observed on forest roads on the slopes above the A887 at Invermoriston by the first Author. In addition, Winter et al. (2006; 2009) reported just such an effect as the old A9 concentrated flow in the manner described causing erosional failures that affected the A9 trunk road in August 2004 (Figure 7). Observations in the Rest and be Thankful locality and elsewhere confirm that sheep similarly follow contour-parallel paths with similar disadvantageous effects.

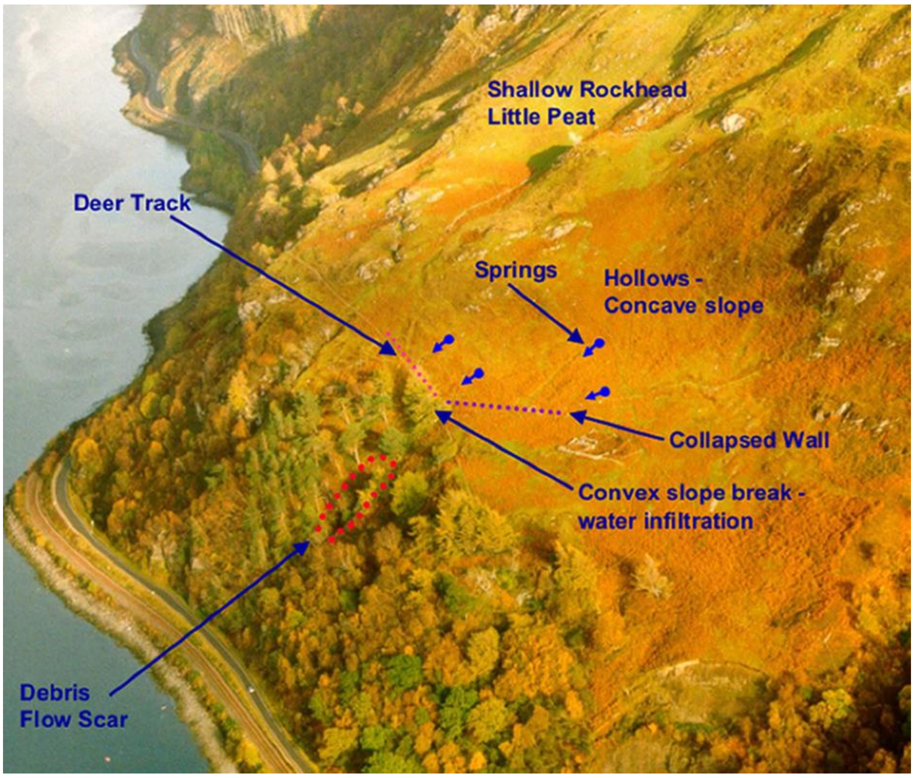

Figure 6. Aerial oblique photograph of the location of the October 2001 debris flow on the slopes above the Stromeferry Bypass. Contributory factors are highlighted including the effect of deer tracks in concentrating water flow. (From Nettleton et al., 2005a.)

The detrimental effects of the over-grazing of sheep on low level vegetation (grass sward) is highlighted by Coppin and Richards (2007) in the form of increasing the amount of bare ground and dramatically reducing root growth. (They also highlight the fact that appropriate grazing can have beneficial effects in stimulating sward growth.)

It thus appears that increasing the number of livestock, and the associated grazing pressure, on the hillside is unlikely to improve either drainage or stability. Indeed, current grazing on the hillside is understood to comprise around 200 head of sheep, with a further 40 to 50 head of cattle (beef suckler) during the summer months and an unknown transient deer population (Raynor and Nicoll, 2012). (It is understood that a sheep, or sheep, triggered one of the tilt meters that were installed after the 1 December 2011 event.)

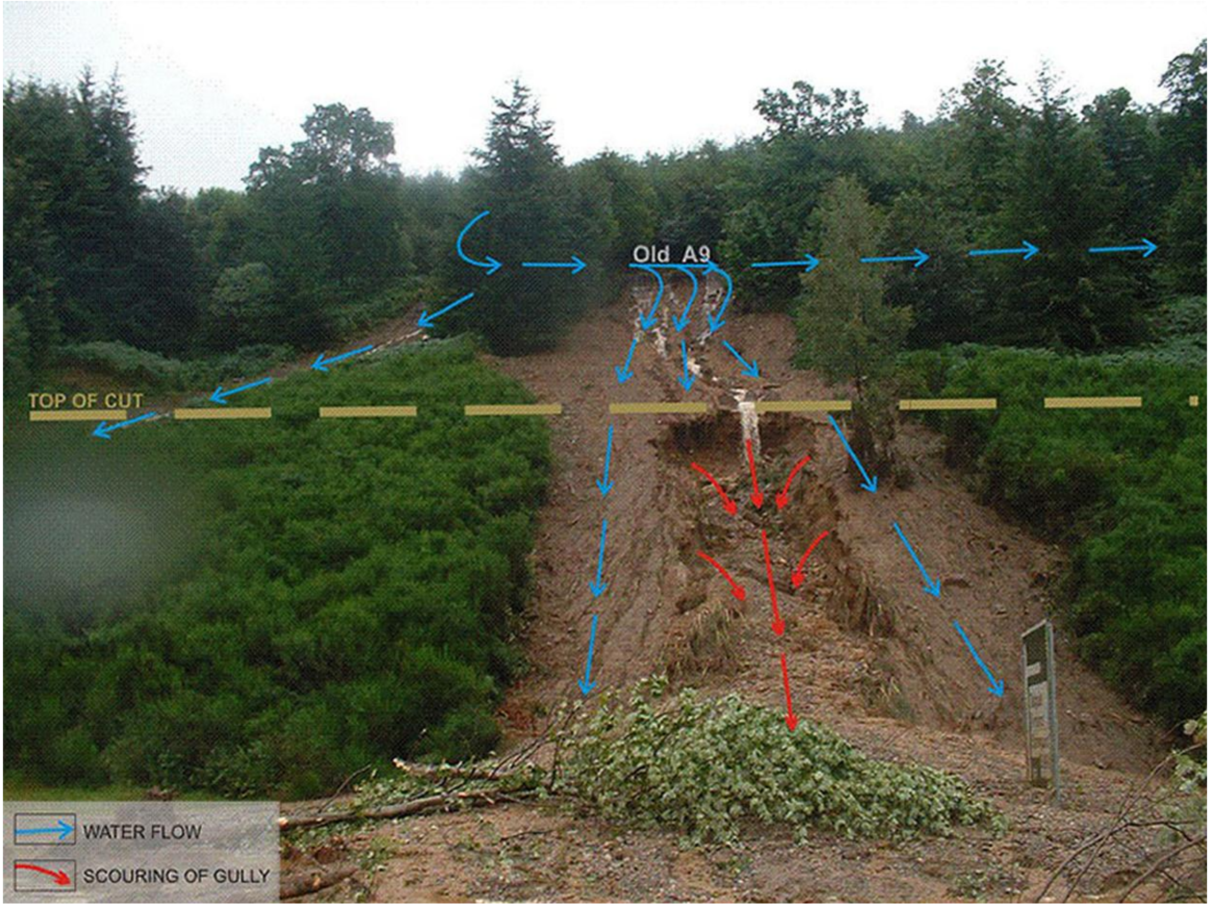

Figure 7. Influence of old A9 on debris flow at A9 Dunkeld. The central flow is shown and the northern flow can also be seen on the left of the picture. In each case water has flowed along the old road and spilled over the edge at a low point causing erosional debris flows. Photograph dated 11 August 2004. (Courtesy of Alan MacKenzie, BEAR.).

3.4 Damage from Animal Hooves

In addition to the issues surrounding drainage there is also the potential impact of animal hooves compacting (densifying) soils. Perhaps the most well-known piece of research work in this arena was published by Meehan (1967) and investigated the efficacy of elephants in compacting soil; it is titled the 'The uselessness of elephants in compacting fill'. Meehan found that elephants, like other individual animals and groups of animals, step in the same locations – much as children tend to follow in each other's footsteps in snow. This means that any beneficial effect is highly localised and leaves large areas of uncompacted (loose) soil in the immediate surrounds. This effect is not helpful in terms of minimising slope instability and can be observed in muddy fields in which cattle graze; the rule tends to break down in areas where the animals are forced together such as at gates, and at watering and feeding areas where hoof marks tend to become contiguous.

It is widely accepted that prolonged grazing can have long-lasting effects upon hillslope morphology. Innes (1983) concluded that over-grazing by sheep at Beinn Achaladair (north-east of Bridge of Orchy) may have been a contributory factor in the occurrence of landslides. DEFRA (2005) advise that when hoof prints exceed 50mm in depth on sites at risk of erosion then stock should be removed and Raynor and Nicoll (2012) note that this limit is exceeded at the Rest and be Thankful site. SNH (Andrews and MacDonald, Undated) also note the potential for erosion by sheep and note that this can occur locally for even relatively light stocking levels. Trimble and Mendle (1995) demonstrated that heavy grazing compacts the soil, reduces water infiltration (on smooth surfaces), increases the flow of water across the hillside (Hortonian flow) and increases soil erosion. More recent work by Morandi et al. (2012) demonstrates that the shearing action of cattle hooves can have a significant detrimental effect on the strength of the near-surface soil and associated root systems. Cattle, sheep and red deer are all present on the south-west flank of Beinn Luibhean.

Andrews and MacDonald (Undated) acknowledge the damage that may be inflicted upon land by the action of sheep grazing but also note that the "evidence for red deer causing increased peat hagging and other types of erosion is anecdotal and no objective data exist." However, they do accept that as the animals are heavier than sheep they have the "potential to cause similar effects at somewhat lower stocking densities, especially on steep slopes." In this context a careful consideration of the likely mechanical effects of animal hooves is appropriate.

When pressure is applied to the ground by a plate, or a hoof, vertical stresses are generated in the ground. The stress contours are illustrated in Figure 8 for a square area in terms of the pressure (q) applied by the plate, or by the hoof (the contours for a circular plate are similar but stretch horizontally a little further, that is they appear to be a little more bulbous). If the value of the pressure (q) is increased, for a given size of plate, then so does the vertical stress in the ground at a given depth. At a depth of around 1.5 times the width (B) of the plate the stress in the ground is around one-fifth that applied to the plate. Thus for a constant pressure a larger plate (which would require an increase in the load) will create greater stresses at a constant depth and stresses in deeper parts of the soil.

Table 1 compares the estimated mass, the consequent forces applied by the animal and by each hoof, the estimated hoof areas, and the resulting pressure applied by each hoof for cattle, red deer and sheep.

Clearly if each type of animal has the same hoof area then cattle (being heaviest) would exert higher pressures on the ground than would red deer, which would in turn exert higher stresses in the ground than sheep (being lightest).

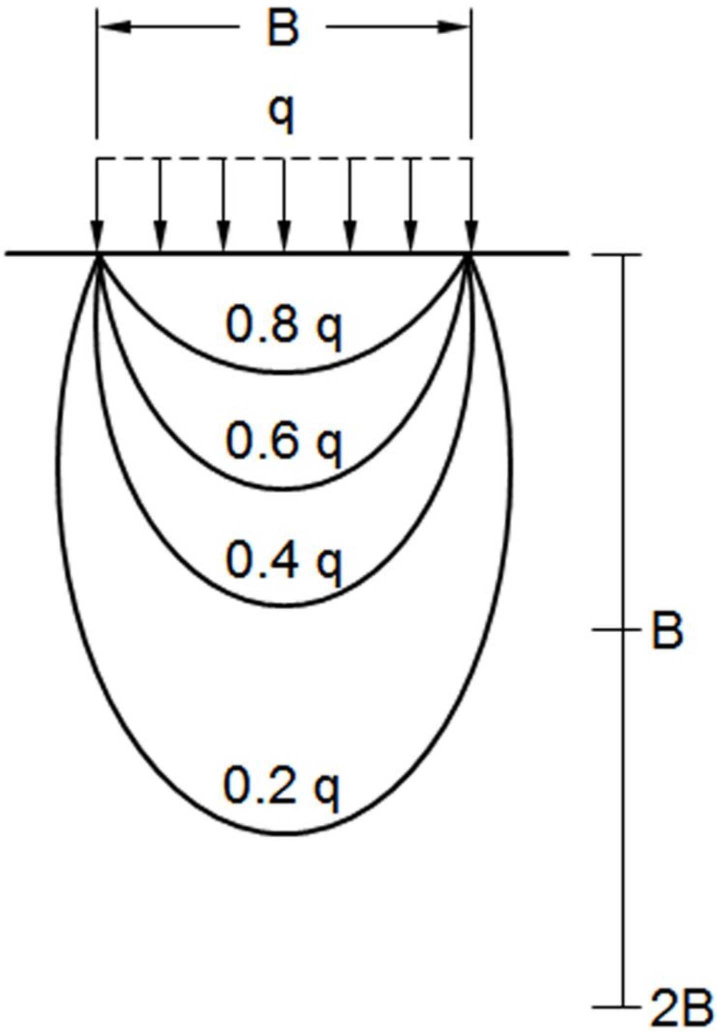

Figure 8. Sketch of Boussinesq contours of equal vertical stress under a square plate or footing (after Craig, 1983): not to scale.

Table 1. Estimated mass, force exerted per hoof and hoof area for cattle, red deer and sheep.

	Body mass at maturity (kg)	Total Force (kN)	Average force per hoof (kN)	Average hoof area (mm^2)[4]	Average pressure per hoof (kN/m^2)
Cattle	450[1]	4.5	1.1	17,100	64
Red deer	170[2]	1.7	0.4	1,571	255
Sheep (hill)	68[3]	0.68	0.2	1,155	173

[1] Upper part of Jersey range (272 to 454kg), lower part of Hereford range (454 to 907kg): http://en.wikipedia.org/wiki/Cattle
[2] Average of male (160 to 240kg) and female (120 to 170kg) mass ranges: http://en.wikipedia.org/wiki/Red_deer
[3] 150lbs: http://www.cals.ncsu.edu/an_sci/extension/animal/4hyouth/sheep/sheepfacts.htm
[4] Personal communication from Tony Waterhouse of the Scottish Agricultural College (SAC): Cattle, 150mm by 145mm; red deer 50mm by 40mm; Sheep, 42mm by 35mm. Area (*A*) is calculated by assuming an oval/ellipsoid shape, $A = \left(\frac{\pi}{4}\right).a.b.$

Note: The numbers given in this table are approximate and while they may be open to challenge in their detail, it is considered that they are sufficiently accurate so as to allow the qualitative picture that is required to be built up.

However, this is not the case and it is clear that cattle with large hooves apply the lowest pressure to the ground, followed by sheep and then red deer which exert the highest pressures on the ground.

A number of points may be drawn from this:

1. The pressures exerted on the ground surface by cattle hooves affects the widest area (15 times that of sheep hooves) followed by red deer hooves (which affect an area around 1.4 times that of sheep hooves) and finally sheep hooves which affect the least area.
2. The pressures exerted on the ground surface are greatest for red deer hooves (around four times that exerted by cattle hooves) followed by sheep hooves (around 2.7 times that exerted by cattle hooves) and finally cattle hooves which exert the lowest pressures on the ground surface.
3. The vertical stresses developed in the ground as a result of cattle hooves will reach to much greater depths, as the value of B is greatest, followed by red deer and then sheep for which the value of B is lowest. Indeed, the vertical stress will reach a value of 0.4q as a result of cattle hooves at a depth of around 15 times that for sheep hooves and for red deer hooves that value will be reached at a depth of around 1.4 times that for sheep.
4. Assuming that the vertical stress, $\sigma = 0.4q$ at a depth of B (which is a reasonable approximation from Figure 8), then at this depth the stress developed by red deer hooves will be around four times that developed by cattle hooves and for sheep hooves it will be around 2.7 times the same figure.

This rather complex picture points to a relatively simple conclusion. The effect of cattle hooves is likely to affect greater depths of soil than those of either sheep or red deer, but that significantly greater stresses are applied to the surface (and the near surface) but over smaller areas by the action of sheep hooves and especially the action of red deer hooves. It therefore seems likely that all three types of animals can cause significant damage to the morphology of a slope. Further, the effects of the hooves of cattle will extend to greater depths while those of sheep, and even more so those of red deer, will be intense but nonetheless confined to a shallower depth.

This does seem to indicate that the effects of hoof shearing described by Morandi et al. (2012) for cattle could well be pertinent at the Rest and be Thankful and could be extended to the action of sheep and red deer hooves. Taken together with other evidence presented in this section it seems clear that livestock grazing has a negative effect on stability rather than the positive one. Further it seems prudent to recommend that if vegetation planting is to form part of an on-going strategy to address instability (Section 4) at this location then efforts should be made to limit the presence, or exclude completely, livestock and in particular deer.

4 Vegetation Planting

4.1 Benefits and Dis-benefits of Vegetation

The effects of vegetation planting on slope stability are well known (e.g. Coppin and Richards, 2007; Norris et al., 2008) and in general tend to be positive. The three main benefits that may be incurred are:

1. Canopy interception of rainfall and subsequent evaporation.
2. Increased root water uptake of the water that does infiltrate into the soil and subsequent transportation 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 and 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 with a view to incorporating them into design (Greenwood et al., 2004; Sonnenberg et al., 2010). In general these attempts have been less than successful and while it must be acknowledged that root reinforcement has the effect of increasing stability, defining that effect in a numerical sense for design purposes proves elusive.

Ongoing work by the University of Dundee and the James Hutton Institute (formerly known as The Scottish Crop Research Institute) has focussed on the development of simple numerical and experimental models and approaches the root strength problem in four main phases, as follows:

1. Numerical simulation and validation of (single) root pull-out.
2. Numerical simulation and validation of (single root) direct shear.
3. 3D cluster root modelling.
4. Direct shear and centrifuge slope testing with real plants (willow).

The work being undertaken has the potential to significantly aid our understanding of the nature and magnitude of the contribution of root reinforcement. However, it remains a relatively long-term aim to produce factors that can be used to increase the soil design strength used in slope design and instability calculations. It is important to note that even when such factors are available they will be specific to fully mature vegetation of specific types and will not account for lower strengths during establishment; root water uptake effects; lower strength as the vegetation becomes over-mature, dies back and rots; or other types of vegetation. Notwithstanding this, if planting is to go ahead then there may well be the opportunity for the development of collaborative work.

In order to maximise the effects of roots on stability in shallow soils, such as those encountered at the Rest and be Thankful, 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.

The effects of forestry 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 deforestation were noted, by the first 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 9). Indeed 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.

Other potential dis-benefits of vegetation planting are, to some degree, alluded to above. These include the fact that the effects of vegetation take some years to become established and then 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. In addition, mature trees can themselves become unstable and 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 10). This most frequently occurs when the established wind-firmed 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). Certainly there are locations above the A82 in Scotland (Figure 11) where the stability of over-mature commercial forestry has become cause for concern.

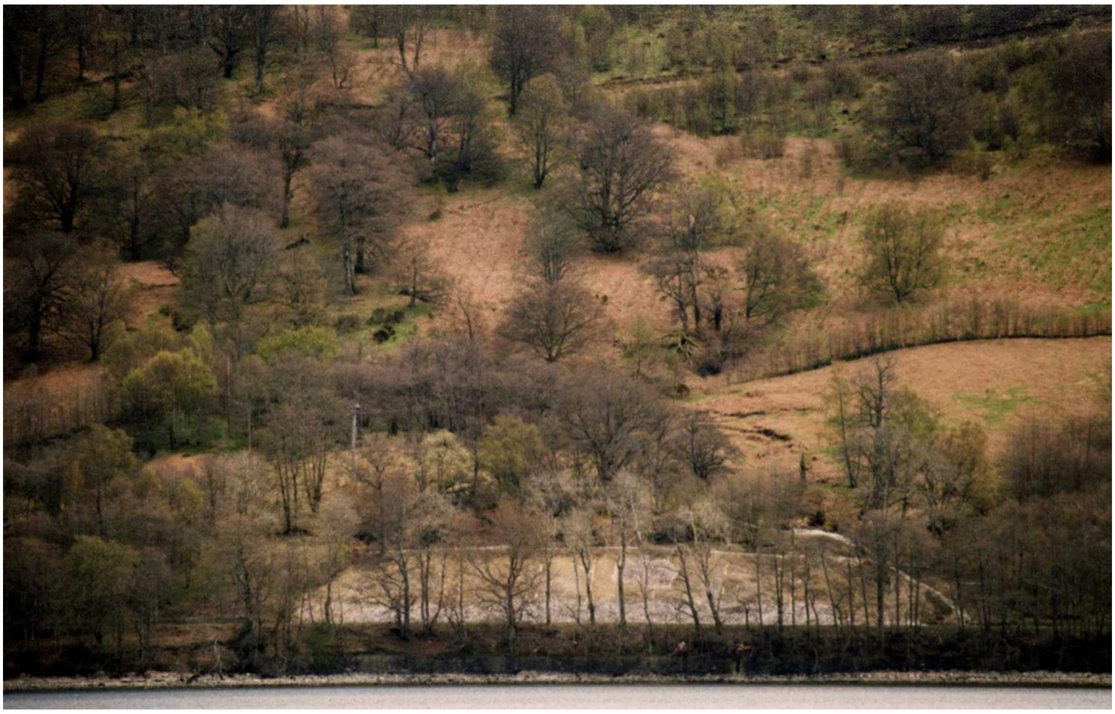

Figure 9. Translational landslide at A83 Loch Shira. The head of the landslide is located just below the middle of the image and above that point former plough lines left over after forest harvesting may be seen. (Image dated 1995).

Figure 10. Windthrow can be clearly seen at the edge of the forested area. The harvesting in the foreground of the photograph has removed the wind-firmed edge of the plantation leaving newly exposed trees vulnerable to the effects of the high winds. (South of A85 Crianlarich to A828, image dated December 2012.)

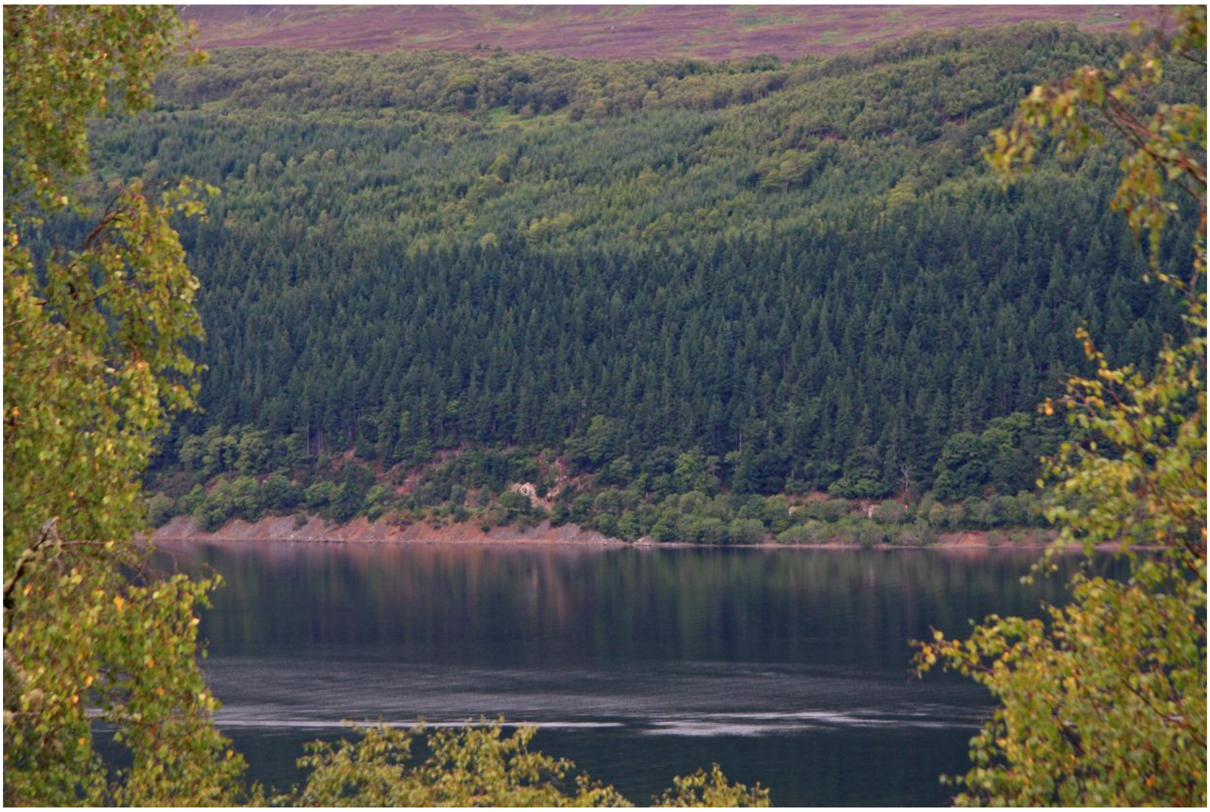

Figure 11. In this image the A82 runs just above the loch side and larger specimens of tree can be seen on the cut slope to the centre-left of the image and on the steep slope above the cut slope. In places such trees are potentially unstable.

4.2 Potential for Planting

Perhaps the most obvious form of planting for the Rest and be Thankful site would be commercial, managed, single-species plantation (e.g. Figure 12). There are, however, a number of obstacles to this approach. The average slope at the Rest and be Thankful, at around 36°, is at the margins of what would be viable for such managed, commercial activities. In addition, this form of planting would produce relatively uniform trees that would grow to a commercially viable size before being harvested, thus eliminating the beneficial effects. If the trees were to be left in-situ then there would be the potential for the trees to become over-mature and potentially present a hazard resulting from windfall. It is also clear that steepness would be an obstacle to both harvesting and management of the trees on the slope.

Submissions have been received from a number of parties (including Lithgow, 2012) and consultation meetings have taken place with those who desired to attend such meetings. The comments and suggestions received have been carefully considered and taken into account in the formulation of the approach set-out in the following paragraphs. Importantly the approach has been developed in close consultation with key experts from the Forestry Commission Scotland (Raynor and Nicoll, 2012) and the Royal Botanical Gardens (Sinclair and Bennell, 2012).

Figure 12. Photomontage of the A83 and the west side of Glen Croe viewed from the south-west facing slopes of Beinn Lubhean showing single-species, managed, commercial forestry including areas of clear-felling.

What must be clear at the outset is that the planting of non-native species has been discounted on the basis that this contravenes requirements of the Wildlife and Natural Environment (Scotland) Act 2011. It also became very clear during the consultations that a single species (monocultural) approach would be inappropriate from a variety of points of view including instability, biodiversity and aesthetics.

The work undertaken by Forestry Commission (Raynor and Nicoll, 2012) on the south-west facing slopes of Beinn Luibhean in Glen Croe considers the site conditions using the well-established Ecological Site Classification, decision support system. This allows factors important to the establishment of vegetation and trees to be taken into account in the design of a planting scheme. The factors that are taken into account are as follows:

- Accumulated temperature 5°C, day degrees. This is the annual sum of the hourly average temperatures that exceed 5°C, divided by 24 to give the 'day degrees' (the equivalent value summed for days). The value at the mid-slope, 450m contour, 741°C which is at the lower end of the scale on which native broadleaf species may be readily established.
- Moisture deficit in mm. This is an indication of the dryness of the growing season (as opposed to the wetness) and is defined as the difference between potential evaporation and rainfall. The range of values from the site is 69mm to -82mm, the negative values indicating that precipitation exceeds potential evaporation. These values indicate that drought rooting conditions are unlikely to be encountered.
- Exposure (Direct Aspect Method of Scoring, DAMS) which indicates the potential for restriction on plant growth due to desiccation, physical damage due to wind-induced uprooting (windthrow). The values obtained range from 13.3 to 28.4 with a mid-slope value of 19.2. The values indicate that exposure will hinder the establishment of trees and shrubs above an elevation of around 450m.
- The Conrad index of continentality indicates an oceanic climate with warm, moist summers and cool, wet winters with no meaningful variation across the site (as might be expected) with no hindrance to vegetation establishment from that cause.

The Forestry Commission work also considers the geology, soils, drainage patterns, the extant vegetation and the potential for muirburn at the site.

A number of conclusions are drawn by Raynor and Nicoll (2012) and also from discussions between the Authors and the Forestry Commission Scotland. These are set out below as the Authors' views, experiences, assessments and conclusions. These are as follows:

1. Continuous cover forestry with conifers is not appropriate at the site. This is in part due to the exposure, the potential for windthrow and the need for future more intensive management.
2. A mix of native broadleaf tree and shrub species would be appropriate. This would give a mix of root spread and depth, including potentially to bedrock, maximising the root reinforcement effect. Coppicing would need to be practiced, where appropriate, in order to ensure that the height of the planting did not become such as to present a windthrow hazard, whilst maintaining a strong root system.
3. This type of woodland planting above the 450m contour is unlikely to be successful and is therefore not appropriate. However, additional planting of a different nature/species mix (smaller woody shrub species such as Sea Buckthorne and Montane Willow) may be established on the upper fringes, above 450m (Sinclair and Bennell, 2012)
4. Establishment of the vegetation up to the 450m contour such that a significant contribution to stability is made is likely to take at least 15 years with 30 years being more likely where climatic conditions are most severe. The range provided reflects the inherent imprecision regarding the length of time that it will take to fully establish the desired vegetation to the degree that it contributes to the effective mitigation of future debris flows. Not only is it ordinarily difficult to give a definitive figure but the exposed nature and steep profile of the slope (with the inherent potential for landslide events occurring during the establishment phase) adds to that uncertainty. It is likely that differential establishment will occur on the slope with some planting areas becoming effective sooner than others. This will be affected by the depth of soil cover above bedrock as well as microclimatic variations across the slope.
5. In order to optimise the benefits of the planting this should be in an interconnected association of 10m square blocks.
6. Planted areas should be fenced to prevent livestock and deer from entering and damaging the planting.
7. Additional measures should be taken to keep livestock and deer from entering the area and forming new paths around the fenced boundaries, potentially leading to further instability.
8. Limited self-seeding of the areas outside the notional 10m square planting blocks and above the 450m contour is likely to take place as the vegetation below establishes, potentially commencing at around 15 to 20 years after planting.
9. It is additionally proposed that willow pole planting (Hiller and MacNeil, 2001; Steel et al., 2004) is undertaken in the sides of gulley in order to provide additional stability in these all-important areas.

The work by Sinclair and Bennell (2012) is broadly confirmatory of Raynor and Nicoll's work adding some detailed pointers related to ensuring the best conditions for vegetation establishment. In particular, it was suggested that a programme of bracken control be undertaken, albeit noting that a period of 24 hours of dry weather is required following spraying and that supplementary fertiliser be applied to selected plantings in order to accelerate early growth.

What is clear is that, in the context of both the nature of the planting and the time that will be required for it to establish and become effective, the use of vegetation alone does not constitute an effective counter measure against landslide activity at this location. Its use should be as part of a broader strategy, including land management measures such as stock control, and also engineering measures to control debris flow. Such engineering measures form part of the work being undertaken in parallel by Jacobs (Anon., 2012).

5 Summary and Conclusions

In recent years a number of debris flow events have closed the A83 trunk road in the vicinity of the Rest and be Thankful. The damage caused has been both difficult and costly to repair, and the associated closures have caused traffic delays with attendant socio-economic impacts.

This report examines the merits of a number of ecological and related landslide mitigation options for the south-west facing slopes of Beinn Luibhean in Glen Croe above the A83 trunk road. The use of explosives is not considered to be an appropriate approach to increasing the stability at this location.

Setting aside the detailed engineering options and the wider options, such as realignment, that are being addressed by Jacobs (Anon., 2012), it is clear that there is no easy, let alone single, solution for the slope above the A83 road at this location. Any approach to reducing instability at this location is likely to form part of a strategy, comprising of a package of measures, designed to address such instability and the effects thereof in the short, medium and long term.

Vegetation planting as an aid to stability is discussed in detail and both the positive effects and the potential dis-benefits are recognised. It is consider that vegetation planting could form part of the overall stability management strategy at this location. However, the type of planting should be low-height broadleaf trees and shrubs and not continuous cover conifer plantation. An outline scheme for planting, developed by Forestry Commission Scotland and others in collaboration with the Authors, is briefly described. The potential for the scheme to reduce instability is in the long-term and it must be considered as part of a broader strategy that incorporates other aspects of land management, including stock control, and appropriate engineering measures.

Issues related to the potential for livestock to aid or detract from stability are discussed. It is considered that livestock have a negative effect on stability. They will also have a detrimental effect upon recently planted vegetation. It is recommended that if a planting scheme is undertaken then livestock, including deer, should be excluded from the planted area and the wider hillside area.

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