LANDSLIDE HAZARD AND RISK ASSESSMENT, AND MANAGEMENT AND MITIGATION FOR THE SCOTTISH ROAD NETWORK

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ABSTRACT

A series of rainfall-induced debris flow events in August 2004 intersected the Scottish strategic road network and at Glen Ogle 57 people were airlifted to safety. While there were no major injuries the social and economic impacts were severe, in particular the severance of access to and from relatively remote communities. The need to acknowledge such natural processes and act accordingly was recognized. A study was commissioned with the overall purpose of ensuring that the hazards posed by debris flows were systematically assessed and ranked allowing sites to be effectively prioritized within available budgets. The methodology used to undertake a pan-Scotland, GIS-based, assessment of debris flow susceptibility is described as is the approach taken to interpret the resulting imagery in order to establish those sections of road alignment subject to hazards. The hazard scores assigned using this approach were subsequently modified in light of the results of site-specific inspections. The ranking of hazards based upon the potential exposure of road users to debris flow hazards and the potential socio-economic impacts is also described and a map illustrates the locations of the highest hazard ranking sites. The approach to management and mitigation is primarily based upon exposure reduction initially reacting to the occurrence of events but with a longer term objective to be able to forecast periods during which debris flow is more likely on the basis of rainfall. Hazard reduction is also envisaged involving engineering measures. However, such environmentally-intrusive, high cost measures are likely to be relatively few and need to be justified in the context of wider budgetary and programme constraints.

1. INTRODUCTION

The widely-reported Scottish debris flow events of August 2004 were caused by rainfall substantially in excess of the norm, with some areas experiencing over 300% of the 30-year monthly average and storm intensities of up to 150mm/hour. A small number of these intersected the trunk (strategic) road network and in Glen Ogle (Figure 1) 57 people were airlifted to safety. While there were no major injuries the social and economic impacts were severe, in particular the severance of access to and from relatively remote communities had a substantive and negative impact on the local population [1].

Figure 1 – Debris flow at A83 Glen Ogle on 18 August 2004.

The need to acknowledge such natural processes and act accordingly was recognised by Transport Scotland, the Government agency responsible for the trunk road network, and a study was commissioned. The overall purpose of the study was to ensure that the hazards posed by debris flows were systematically assessed and ranked and that a management and mitigation strategy was developed and implemented for the Scottish trunk road network. The purpose of the ranking system is to allow the future effects of debris flow events to be appropriately managed and mitigated as budgets permit, thus ensuring that the exposure of road users to the consequences of future debris flows is minimized [2].

The methodology used to undertake a pan-Scotland, GIS-based, assessment of debris flow hazards (more strictly susceptibility) is described as is the approach taken to interpret the '2.5 dimensional' GIS-based assessment in order to establish those sections of road alignment subject to hazards. The hazard scores assigned using this approach were subsequently modified in the light of the results of site-specific inspections [3]. The ranking of hazards, to give an analogue for risk, based upon the potential exposure of road users to debris flow hazards and the potential socio-economic impacts is also described and a map illustrates the locations of the highest hazard ranking sites.

The overall approach to management and mitigation is described and some early examples of implementation are described.

Typically the debris flows encountered in Scotland (e.g. Figure 2) are characterised by a small translational sliding failure within soft wet ground on a hillside. When the material from such failures intersects with an existing stream channel the failed material is entrained into the water and accumulates further debris by erosional means before depositing the material as the slope slackens, typically where infrastructure such a roads may be located [3, 4]. This scenario is typical also of other regions of the World [e.g. 4].

2. SUSCEPTIBILITY

The susceptibility assessment was carried out within a GIS environment and considered the following main characteristics:

- Availability of debris material.
- Hydrogeological conditions.
- Land use.
- Proximity of stream channels.
- Slope angle.

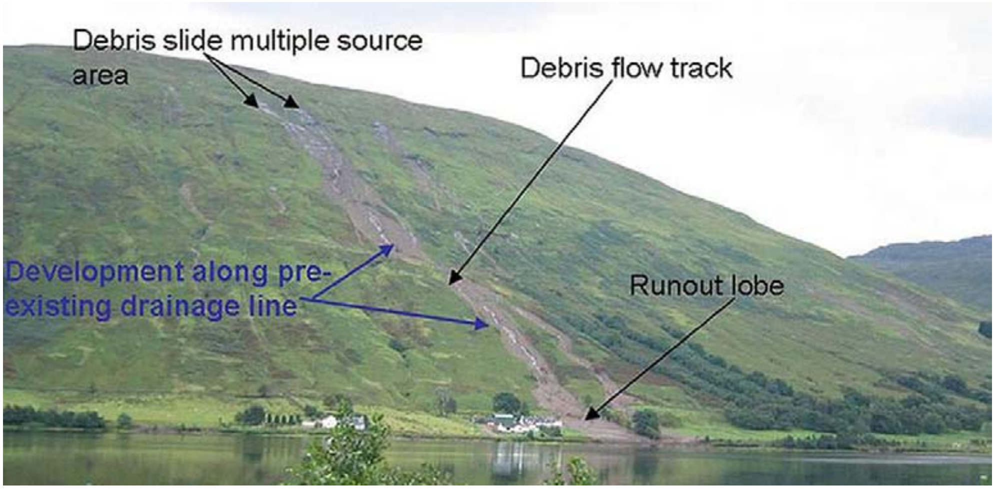

Figure 2 – Morphology of a typical Scottish debris flow: A83 Cairndow August 2004.

Lithologies represented by polygons in the British Geological Survey (BGS) DiGMapGB-50 product were interpreted against a scale that indicated the degree to which the bedrock or superficial unit at surface would provide non-cohesive granular material as a source of debris. The ROCK_D (BGS Rock Description code) attribute of each polygon was reinterpreted in terms of potential mobilization by water as a debris flow in both the fresh unweathered and the weathered regolith states. In addition an analytical method was developed to determine likely zones of peat accumulation, in the absence of a consistent and reliable data-set, as such materials are known to be capable of triggering debris flow.

Again lithologies were interpreted on the basis of their permeability and thus the ability of water to remain within the deposit and develop pore water pressures to a level where the shear strength is sufficiently reduced to initiate failure.

Centre of Ecology and Hydrology data (CEH Landcover 2000 data) was interpreted to give an indication of the likely effect of landcover on the debris flow potential at a given location. Factors such as the ability of the vegetation to reduce infiltration and reduce soil moisture, as well as the effects of root reinforcement of the ground were taken into account.

The majority of debris flows that are sufficiently persistent to reach any form of infrastructure in Scotland are associated with stream channels. Proximity to water courses was thus seen as an important determining factor and their locations were automatically generated from NEXTMap digital terrain models using hydrological modelling techniques.

Slope angle has a self-evident effect upon slope instability and the potential for debris flow to be triggered. In general the higher the slope the greater the potential, although as slope angles become greater allowance must be made for the diminishing availability of debris.

Each of the above data sets was scored from one to 10 with input from both those working directly on the GIS assessment and the working group panel set-up to oversee their work. The working group comprised geologists, engineers and infrastructure owners all of whom had extensive experience of debris flow in the context of the Scottish trunk road network.

The resulting scores for each of the above five variables were weighted in order to better reflect their individual importance to the development of conditions potentially leading to the triggering of debris flow. Although it is extremely difficult to understand, in detail, the precise interaction between each of the factors described, the working group generated a series of weighting factors. These were based upon the knowledge and experience of members of the working group involved in the investigation and management of debris flows in Scotland. Different scenarios were modelled interactively for discrete geographical areas in working group meetings in order that real-world examples could be used to validate the model results [5]. As a result of the very long runtimes of the pan-Scotland GIS data the project team decided that no account of whether potentially susceptible materials were on, above or below a slope would be taken. As a result some effectively flat areas, of no practical debris flow susceptibility such as the Stirling Carse were highlighted in the assessment. The results are represented in Figure 3.

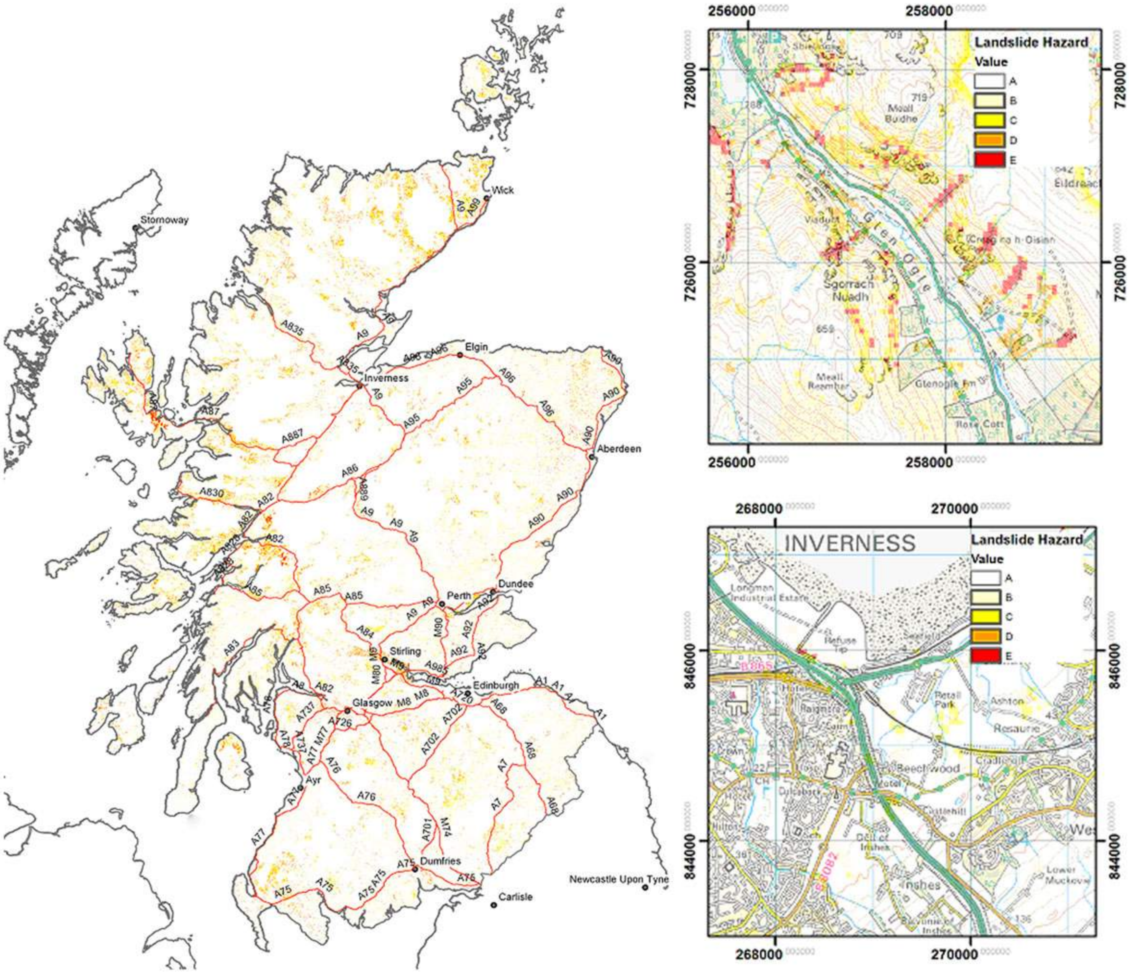

Figure 3 – Results of the GIS-based susceptibility assessment: (left) the results for Scotland; (top-right) results for Glen Ogle, a known site of susceptibility; (bottom-right) results for Inverness a known area of limited susceptibility.

3. HAZARD ASSESSMENT

The hazard assessment comprised an interpretation of the GIS-based susceptibility assessment to determine road lengths likely to be affected by debris flow, followed by initially selective site-specific inspections using walkover techniques. The GIS assessment was pan-Scotland, covering the entire road network while the interpretation focused on the trunk road network.

3.1. GIS Interpretation

The GIS interpretation was undertaken using the imagery from the GIS-based assessment, national Ordnance Survey mapping at 1:50,000 scale and low resolution aerial photography. The interpretative process was thus focused upon the morphology of the ground between areas of potential susceptibility and roads. Slope angles, the presence of stream channels that might aid the passage of debris and any potential barriers to flow were, amongst other factors, considered. Consequently the interpretation may be summarised as a semi-quantitative/qualitative determination of potential debris flow tracks and run-out zones to determine whether they intersect with the trunk road asset. The interpretative work was carried out by a single team in order to ensure consistency of approach and was split into two stages, as follows:

- A coarse sift to separate out those sites requiring further consideration (‘Main Study’) from those for which no further action was required (‘Other (None)’) and for which action would only be required if major upgrade works, typically a realignment of the road within the existing corridor, were planned (‘Opportunistic’) (Table 1). The sites for which no further action was required were largely flat areas of land highlighted in the susceptibility assessment (see Section 2) and were not consideration further.
- In the second stage the Main Study sites were separated into four main categories in order to assign a hazard score and also to indicate those for which further site-specific assessment (see Section 3.2) was most pressing. Two atypical sites were highlighted for ‘Separate Assessment’; these are characterized by steep talus slopes and have been intensively studied in the past which lends itself to a much more focused and targeted approach being taken as part of the follow-up to this study. The results of this second phase are summarized in Table 2.

Table 1 – Results of the first phase of interpretation of the GIS assessment. The trunk road network is approximately 3,200km in length.

	Route Lengths Assessed (km)	Percentage of Route Lengths Assessed (%)	Percentage of Network (%)
Other (None)	619	37	19
Opportunistic	458	27	14
Main Study	607	36	19
Total	1,684	100	53

Table 2 – Results of the second phase of interpretation of the GIS assessment.

	Route Lengths Assessed (km)	Percentage of Main Study Route Lengths (%)	Percentage of Route Lengths Assessed (%) (see Table 1)	Percentage of Network (%)	Initial Hazard Score
Priority 1	135	22	8	4	80
Priority 2	154	25	9	5	60
Priority 3	160	26	9	5	40
Priority 4	112	19	7	4	20
Separate Assessment	46	8	3	1	80
Total	607	100	36	19	-

3.2. Site-specific studies

The site specific studies were intended to validate the hazards derived from the interpretation of the GIS-based assessment, to provide an interpretation of data not available during that process and to provide an interpretation at a more detailed scale than could otherwise be provided. The work was divided into three stages as follows:

- Desk study: These activities were intended to be carried out prior to embarking upon site-based activities and included familiarisation with the location from national mapping and the results of the GIS-based assessment. In addition newly-available information in the form of high resolution aerial photography was incorporated into the assessment.
- Preliminary site inspection: This was intended to allow a provisional, but necessarily limited, view of the site setting. This was achieved by a drive-through of the length of road in question, with the inspector as a passenger, stopping as necessary to observe

and note features from road level. Photographs were taken to illustrate features and decisions made.

- Detailed site inspection: This process essentially completed the hazard assessment process by relating the information considered thus far (which was either image/data-based or a physical view from a remote location) to the ground itself. In practice the detailed site inspection comprised a walkover from road level and excursions up slope (or down where necessary) as required, but typically every 0.5km to 1.0km.

Primarily this stage of the work was intended to adjust the scores already obtained. At each stage hazard scores were assigned in the categories of water, instability, slope/topography and vegetation and land-use. These scores were additive / subtractive to those already obtained from the interpretation of the GIS-based assessment and thus built upon the work already carried out.

The selection of sites for more detailed site-specific work was based on the priorities set out in Table 2 but also taking account of the initially limited availability of high resolution aerial photography, the value of which is illustrated in Figure 4. In addition, there were insufficient resources available to undertake all of the work planned in the first year. The Priority 1 and 2 sites for which aerial photography was available at the time broadly coincided with the budget available and these studies were undertaken during 2007. The scores for sites not studied were adjusted by means of an averaging process [3]. Further batches of sites have since been since studied during 2008 and 2009 such that only a very small number remain outstanding due to the remaining unavailability of high resolution aerial photography. Further study of the two sites identified for Separate Assessment is ongoing during 2010 and 2011.

4. HAZARD RANKING

The risk to life and limb to which road users may be subject from debris flow hazards was identified at the outset of this project by Transport Scotland's senior management as the primary concern, with socio-economic impacts being secondary (but nonetheless important). In this work the common definition of risk [6] was used, as follows:

$$R = H \times E \times V \qquad (1)$$

Where *R* is the risk,
H is the hazard,
E denotes the elements at risk, and
V is the vulnerability of the elements at risk to the hazard.

The hazard was determined as described in Section 3. The elements at risk, namely the road and the associated road users, are either present or not at a given plan location and therefore corresponds to unity where a road is present and zero where a road is not present. The vulnerability equates to risk to life and limb of road users and the socio-economic impacts, including diversionary effects, of temporary closures due to landslides.

This allows a simplification of Equation (1) and for the purposes of this study it may be rewritten as:

$$R_H = H \times E_X \qquad (2)$$

Where R_H is the Hazard Ranking, so described as it is recognised that the work reported does not consider all aspects of risk, and
E_X represents the vulnerability of road users to life and limb risks and the potential socio-economic impacts, referred to as 'exposure' herein.

Figure 4 – Aerial photographs (north to the top) showing the Glen Ogle debris flows of August 2004 showing key features (Licensed to Transport Scotland for PGA, through Next Perspectives™): Left; 4km by 3km (12 tiles), National Grid Reference (NGR) of SW corner NN 560 250 or 2560 7250; Right; 1km by 1km (single tile), NGR of SW corner NN 570 260 or 2570 7260.

KEY:
1. Northerly debris flow: (a) potential source area(s), (b) debris track, (c) runout/debris fan and (d) subsequent carriageway repair;
2. Southerly debris flow: (a) potential source area(s), (b) debris track, (c) runout/debris fan and (d) subsequent carriageway repair;
3. Historic rock falls; and
4. Other debris flows assumed to have occurred in August 2004.

Traffic levels effectively represent life and limb exposure. While sightlines and other factors that influence visibility of the road ahead could be used to refine the exposure of life and limb [e.g. 7], to a large extent traffic flows relate to the type of road alignment in place, and thus to sightline lengths, and the route lengths considered meant that a straightforward approach was more suitable. Similarly, the socio-economic aspects of exposure may be represented not only by the traffic flow, in terms of severance and amount of traffic delayed, and also by the existence, length and quality of any diversion necessary in terms of the extent of additional travel.

As with the different elements that make up the hazard assessment, the different elements of exposure must also be added together in order to achieve an overall score. Relevant categories were determined and scores then assigned for both traffic flow and diversionary aspects of exposure for each site. The scores for these individual factors were then weighted to reflect their relative importance and then summed to produce the overall exposure score.

The traffic categories used by Transport Scotland reflect the traffic flows over the entire network. The lowest flow category comprises those roads with an Annual Average 2-way 24-hour Daily Flow (AADF) of less than 10,000 vehicles per day. It was apparent at the outset of the work to define the traffic flow scores that this lowest category would cover a large proportion of the hazardous sites identified and would not allow effective differentiation between them. A decision was therefore made to use alternative categories. These new categories and their associated exposure scores (E_{XT}) were defined as follows:

- AADF ≤ 2,500 vehicles per day, E_{XT} = 1.0.
- 2,500 < AADF ≤ 7,500 vehicles per day, E_{XT} = 1.5.
- 7,500 < AADF ≤ 25,000 vehicles per day, E_{XT} = 2.0.
- AADF > 25,000 vehicles per day, E_{XT}= 2.5.

The diversion scores (E_{XD}) were based upon an evaluation of the potential consequences of a closure at each site. Where the diversion was short and effective (e.g. by other trunk and/or 'A'-road) then the consequences were defined as 'Limited'. Where the diversion was long, by difficult means (e.g. 'C', 'D' and/or unclassified road) or does not exist (in practical terms) the consequences were defined as 'More significant'. 'Significant' represents the middle ground between these two extremes and the diversion scores were defined as follows:

- Limited, E_{XD} = 0.
- Significant, E_{XD} = 1.
- More significant, E_{XD} = 2.

For any given site, weightings were then applied to the two exposure scores. The two weighted scores were then added together to give a total score for exposure. The weightings applied reflect the paramount importance of reducing the exposure to risks related to life and limb of the travelling public, and for this reason the traffic score was weighted more heavily than the largely disruption-focused diversion score. It should however be noted that the traffic score does itself include significant elements that relate to the potential disruption to road users.

The final exposure score is thus given by:

$$E_X = (E_{XT} \times 1.0) + (E_{XD} \times 0.5) \qquad (3)$$

Accordingly, Equation (2) may thus be rewritten as follows:

$$R_H = H \times [(E_{XT} \times 1.0) + (E_{XD} \times 0.5)] \qquad (4)$$

The overall hazard ranking scores were thus able to be computed. The final hazard ranking scores and the process by which they were obtained are set-out in much greater detail than is possible herein elsewhere [3]. In discussion with the end user of the work it was decided that those 66 sites with the highest hazard rankings, a score in excess of 100 (Figure 5), should be subject to management and mitigation activities.

5. MANAGEMENT AND MITIGATION

The foregoing process culminates in a decision on whether the hazard ranking, in the context of the safe operation of the road network at any location, is acceptable or not. At those locations where the hazard ranking is deemed unacceptable, some form of mitigative action is required. To reduce the hazard ranking (or risk) to the road user to acceptable levels, either the magnitude of the hazard and/or the potential exposure or losses that are likely to arise as a result of any debris flow, must be reduced.

The reduction of the exposure of road users forms the main focus of the work here. In this case the debris flow event is taken as a given and either the number of people exposed to the hazard must be reduced, for example by closure of the road, or warning must be given to exercise caution at appropriate times and places. To reduce the hazard itself, physical intervention is required but in many cases the options will be of higher cost and more intrusive. It is anticipated that relatively few locations will justify expenditure to this degree.

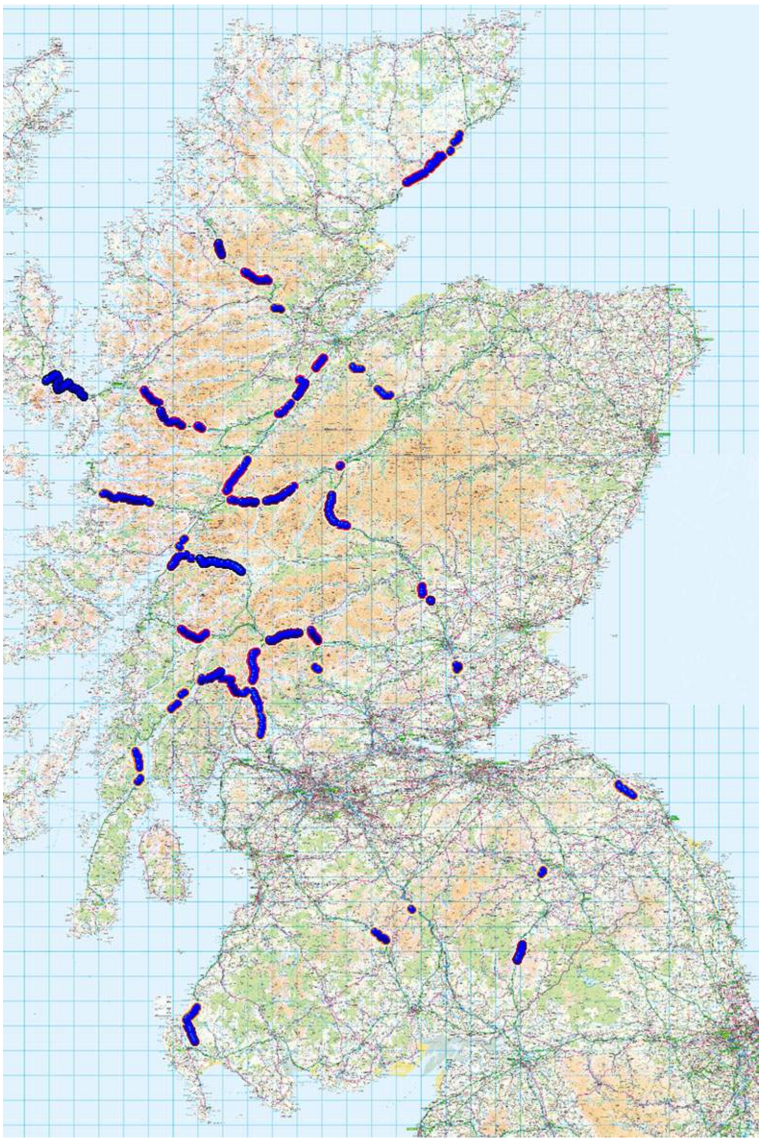

Figure 5 – The 66 sites with a hazard ranking score of 100 or greater. (Base mapping © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

5.1. Exposure reduction

The reduction of exposure lends itself to the use of a simple and memorable three-part management tool [2], as follows:

- *Detection:* The identification of either the occurrence of an event (e.g. by instrumentation/monitoring or observation) or by the measurement and/or forecast of precursor conditions (e.g. rainfall).
- *Notification:* The notification of the likely/actual occurrence of an event to the authorities including the Police, Traffic Scotland, Transport Scotland and the Operating Company.
- *Action:* The proactive process by which intervention reduces the exposure of the road user to the hazard, by for example road closure or traffic diversion. This also includes the dissemination of hazard(s) and exposure information by for example signs, media announcements and 'landslide patrols' in marked vehicles.

At present this DNA approach to mitigation must be reactive to debris flow events. There may be a case for reacting to extremely heavy rainfall events. However, a caveat to this is the need to consider carefully at what levels the triggers should be set, insofar as the relation between rainfall and landslides/debris flows in Scotland is by no means fully understood.

In the longer-term, the detection of precursor triggering conditions (i.e. rainfall) may enable both the *Notification* and *Action* phases to be taken in anticipation of the occurrence of major events. However, to do this an extensively enhanced rainfall detection network will be required across Scotland. Once this is in place it is fully expected that it will require some considerable time and effort to ensure that sufficient data has been obtained and analysed so as to be able to introduce a reliable warning system. Even then atypical events, which are not the subject of warnings, and false alarms are to be expected. A programme of public and media education and awareness-raising is likely to be desirable to minimise any potential adverse reaction to such scenarios [8].

5.1.1. Detection

The movement of slope material can be monitored in real time and the results used as a management tool. Monitoring instruments such as tilt meters and acoustic sensors can record movement from potential debris flow or positioned such that notification is received if debris reaches or gets close to a road (e.g. trip wires). However, it must be appreciated that the seeding area for debris flows can be very large and can be located high on the hillside. This introduces difficulty in pinpointing optimum locations for monitoring installations and uncertainty as to whether the debris will reach the road.

Whether such a system would be sufficient in isolation, and in the context of a road, is questionable. However, in conjunction with rainfall forecasts and possibly the deployment of operatives, the likelihood of road users being affected by debris flow events could be reduced significantly. Any instrumentation would most likely need to be electronic with remote reading of data sent back to a central control point and a wide range of options is available [2]. The selection of appropriate instrumentation is a site-specific activity and requires detailed evaluation of a number of factors, not least physical access and availability of telecommunications.

An alternative approach is to use operatives to detect debris flow events by introducing “landslide patrols” during periods of high rainfall. It is essential that such operatives are trained in what to look for and that patrols should operate in pairs for safety reasons. Given the wide range of locations at which debris flow activity may be experienced this might prove to be a more practical alternative, the costs of instrumenting and monitoring extensive lengths of slope being potentially prohibitive. In addition, the value of observations made by the general public should not be underestimated, especially given the proliferation and ubiquity of mobile telecommunications.

5.1.2. Notification

In the immediate aftermath of the occurrence of a debris flow event, notification must reach the Police, the Operating Company and the infrastructure owner. The decision must then be made rapidly as to what action is to be taken (see below). The nature of debris flows is such that in most cases the road will be blocked and therefore closed to all intents and purposes. It is, however, important that such closures are formalised at safe locations distant from further potential events.

It is important to note that if landslide patrols, comprising trained personnel, are used as part of the *Detection* process then the functions of that role must also be extended to ensure that the proper authorities are notified promptly. It should also be noted that the effectiveness of such patrols for detection will be extremely limited in other than full daylight. It may well be that such patrols have more value in rendering assistance to the public in the aftermath of an event than in actually spotting an impending flow.

5.1.3. Action

In terms of positive action that may be taken after a debris flow then by far the most important is the closure of the road length (or lengths) affected and the implementation of appropriate pre-planned diversion routes. However, it is important to note that closing the road in the area immediately adjacent to the event is not an adequate response. Debris flow propensity is generally believed to affect long lengths of hillside and an evaluation of the vulnerable area must be performed in order to ensure that an appropriate length of road is closed. Closure might be achieved by operating barriers such as the snow barriers present on some of Scotland's roads.

In all cases re-opening of the road, or its return to normal operation, must only occur after a thorough inspection of the road and the adjacent slopes has been undertaken to ensure that the likelihood of further debris flow events is at an acceptable level. Current practice is to undertake ground-based inspections only when the adverse weather has abated and only to reopen the road once such inspections indicate that the residual hazard and exposure are at an acceptable level.

In terms of implementation, work has been undertaken to implement static signing at sites of highest hazard ranking (as illustrated in Figure 5) indicating start (and length) and end points of the hazardous lengths of road and with repeater signs where necessary. The existing, and developing variable message sign (VMS) network, is being used at times of higher risk. In addition a trial is underway of wig-wag signs at the Rest and be Thankful site on the A83. These include the static sign with the addition have a secondary sub-plate; amber lights flash on and off at times of higher risk as determined form rainfall forecasts (Figure 6).

There has been in addition considerable effort has been expended in raising the awareness of landslide issues amongst both relevant professionals, including road operators, and the public. This has taken the form of public lectures and talks, media appearances and the development of an advisory leaflet which may be accessed from the Transport Scotland website. In addition a programme to develop information signs for rest areas, lay-bys and National Park Gateways is under development. These signs are intended to set the issues surrounding landslide hazards in a balanced context. Such information includes a description of the geological and geomorphological setting of the area and highlights landslides as one of the inevitable consequences of that setting.

5.2. Hazard reduction

The challenge with hazard reduction is in identifying locations that are of sufficiently high hazard ranking to warrant spending significant sums of money on engineering works. The costs associated with installing remedial works over long lengths of road are almost certainly both unaffordable and unjustifiable. Moreover the environmental impact of such engineering work should not be underestimated, having a lasting visual impact at the least and potentially more serious impacts. It is considered that such works should be limited to locations where their worth can be proven.

In addition, simple measures such as ensuring that channels and gullies are kept open can be effective in terms of hazard reduction. This requires that the maintenance regime is fully effective both in routine terms and also in response to periods of high rainfall, flood and slope movement. It is also important that maintenance and construction projects currently in design take the opportunity to limit any hazards by incorporating, where suitable, measures such as higher capacity or better forms of drainage, or debris traps. In particular, critical review of the alignment of culverts and other conduits close to the road should be carried out as part of any planned maintenance or construction activities.

Figure 6 – Landslide wig-wag sign.

Typically, the reduction in hazard will entail physical engineering works to change the nature of a slope or road to reduce the potential for either initiation and/or the potential for a debris flow to reach the road once initiated. Debris flows are dynamic in nature and are quite often initiated some distance above the road; when they reach the road they are relatively fast moving high energy flows. The energy of these systems has a significant impact on the nature of the engineering works that can be used to reduce the hazard to the road and its users. Hence, there are three broad approaches to the selection of hazard reduction works.

5.2.1. Road protection

In this case it is accepted that debris flows will occur and provision is made to protect the road. Potential structural forms include debris basins formed by large decant structures with a downstream barrier, and lined debris channels which may be used in association with debris basins or as an alternative where potential storage areas on the hillside are limited. In the latter case their purpose is to effectively move material to alternate, lower-lying, storage areas. Figure 7 illustrates examples from British Columbia in Canada. While such large scale debris basins may not be viable in Scotland for reasons including the smaller scale landscape along with aesthetic and other environmental considerations, where cyclical hazards are identified as having a short return period, smaller scale structures may be appropriate.

Debris flow shelters can be used to form canopies over sections of road to afford protection from debris. Such structures are usually formed from reinforced concrete and flow energy is often dissipated by placing a depth of granular material on the roof on which the debris flow lands. In situations where the energy is anticipated to be very high, modifications can be made to debris flow shelters to allow the debris flows to pass over the top of the structure. This is done by shaping the top of roof of the shelter such that the falling material passes over the structure without dissipating its energy. This shaping or profiling involves constructing a ‘ski-jump’-type reinforced concrete structure.

Figure 7 – Examples of a debris basin (left) and lined debris channel (right) form British Columbia in Canada.

Barriers and fences also have a role to play in retaining debris flow. Fences are often designed to be flexible so that the kinetic energy of the debris flow is dissipated over a short period of time, thus reducing the forces that the structure must accommodate. These systems have been shown to work well. Such fences do however require maintenance after the impact of a debris flow. As part of ongoing work at the A83 Rest and be Thankful site, defined as one of the higher risk sites on the Scottish trunk road network, fully flexible barriers have been installed (Figure 8). Notwithstanding this it is clear from Figure 8 that even relatively large fences blend into the landscape effectively.

Figure 8 – A83 Rest and be Thankful debris fence: close-up (left) and distant views (right).

Less flexible barriers may also be used to trap or divert debris flow and may be formed using stiffer components, including gabion baskets. However, more common are check dams and baffles which are used to slow and partially arrest flow within a defined channel.

Barriers may also be constructed across hillsides in order to protect larger areas where open hillside flows are a risk and/or channelised flows may breach the stream course.

The use of check dams and baffles is described along with design guidance for such structures [9], wherein the use of low cost earth mounds that act as impediments to debris flow is also related. However, one of the main issues with the use of such structures, low cost or otherwise, is that they are effective in slowing and arresting flow primarily in the debris fan area. The situation in Scotland is that most, if not all, of the roads potentially affected by debris flow are located in either the high energy transport zone or the upper reaches of the debris fan. Roads located on debris fans frequently run close to a loch side and therefore the opportunity for the use of these types of measure tends to be limited.

Rigid barriers were built as debris flow defence structures at Sarno to the east of Naples in Italy following the events of May 1998 in which 159 people were killed [10]. At Sarno itself a series of debris basins has been constructed with capacities up to around 200,000m^3. Rigid barriers in the form of combination reinforced concrete barrier-and-trench structures extend across the foot of the hills for up to a kilometre either side of the basin; check dams have also been constructed in the main stream channels [10]. The works have been the subject of extensive landscaping and sports fields and other facilities such as cycle tracks (e.g. Figure 9) have been incorporated. The cost of the works, including the ancillary works, has been estimated at between €20M and €30M [11].

Figure 9 – Debris basin with a peripheral cycle track at Sarno in Italy.

An Austrian Standard for the ‘Design of [debris flow] structural mitigation measures’ is currently in draft and is based upon the requirements of Eurocode 1 [12]. This and other documents [9, 13] provide useful information for the design of such structures.

5.2.2. Debris flow prevention

The engineering solutions applicable to the prevention of debris flow depend greatly upon individual circumstances. Debris flows can be triggered from relatively large source areas and be initiated high on the hillside above the road. There may be particular conditions where conventional remedial works and/or a combination of techniques such as gravity retaining structures, anchoring or soil nailing may be appropriate. However, in general terms the cases where these are both practicable and economically viable are likely to be limited.

The link between debris flows and intense rainfall has been established previously in this document. As a result, effective runoff management can reduce the potential for debris flow initiation. In the circumstances of the debris flows that occurred in the summer of 2004, it is considered that on-hill drainage improvement would have had little impact because of the scale of the events. In other locations and situations positive action to improve drainage might well have a beneficial effect. Such measures could include improving channel flow and forming drainage around the crest of certain slopes to take water away in a controlled manner.

5.2.3. Road realignment

Road realignment is undertaken as part of Transport Scotland's route improvement activities in order to improve the road in terms of both alignment and junction layout, in particular to reduce accidents and to ensure compliance with current design standards. In cases where the debris flow hazard ranking is high and other factors indicate that some degree of reconstruction is required, road realignment may be a viable option. This type of expedient has historically been used on the Scottish rail network, for instance at Stromeferry, Penmanshiel and Dolphinston, where hazards have been sufficiently significant to justify the high cost of such realignments.

CONCLUSIONS

This paper reports on the approach taken to a regional study of hazards and risks from debris flow as they affect the Scottish road network.

The initial susceptibility assessment was carried out in a GIS environment and used well-established data sets. The process of translating susceptibility into hazard required a much more hands-on approach in order to determine the lengths of road which might potentially be reached by mobilized susceptible materials. In addition, and in order to adequately define the hazard, the use of on-the-ground site assessments was deemed essential, as was the use of high resolution aerial photography which was not available during the earlier stages of the study. Both activities proved their worth by allowing the identification of features which were not evident during the earlier phases of the work.

The primary vulnerability was considered to be the exposure of road users to life and limb risks although social and economic issues were also considered. These issues were captured by means of traffic flow data and an assessment of the potential for traffic diversion.

The approach to management and mitigation of the risks associated with debris flow is also described. In the main this focuses on exposure reduction by means of the DNA (detection, notification, action) approach. This involves relatively low cost and environmentally less intrusive measures such as signing and education. While this approach is currently responsive to events in the longer term a proactive approach based upon the relation between rainfall and debris flow events in Scotland is anticipated. Higher cost, more environmentally intrusive options for hazard reduction are described. Notwithstanding the examples described, it is considered that there is limited scope for such works on the Scottish trunk road network.

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