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Landslide hazards and risks to road users, road infrastructure and socio-economic activity

Risques de glissement de terrain et risques pour les usagers de la route, les infrastructures routières et l'activité socio-économique

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ABSTRACT: The assessment of landslide hazards and risks forms an essential precursor to landslide risk reduction. This is particularly the case when an authority is responsible for an infrastructure or building portfolio that may be affected by multiple hazards. In this paper semi-quantitative and quantitative assessments of landslide hazards and risks to road networks are considered in terms of the risks that affect road users (fatality), road infrastructure and the socio-economic activities that the network facilitates. A framework for risk acceptance is used to set the context, and the use of a semi-quantitative assessment to determine the sites of highest risk is described. These highest risk sites are subject to the first known quantitative risk assessments for road user fatalities as a result of debris flows. A novel approach is taken to assess the socio-economic risks and the use of fragility curves to articulate the vulnerability of road infrastructure, including the newly-developed approach involving systems of assets, is also described. The effects of climate change are considered alongside likely social and/or demographic change and a strategic approach to landslide risk reduction is presented.

RÉSUMÉ: L'évaluation des dangers et des risques de glissements de terrain constitue un précurseur essentiel de la réduction des risques de glissements de terrain. C'est particulièrement le cas lorsqu'une autorité est responsable d'une infrastructure ou d'un portefeuille de bâtiments pouvant être affectés par de multiples aléas. Dans ce document, les évaluations semi-quantitatives et quantitatives des risques de glissements de terrain et des risques pour les réseaux routiers sont considérées en termes de risques pour les usagers de la route (décès), les infrastructures routières et les activités socio-économiques que le réseau facilite. Un cadre d'acceptation des risques est utilisé pour définir le contexte et l'utilisation d'une évaluation semi-quantitative pour déterminer les sites les plus à risque est décrite. Ces sites présentant les risques les plus élevés font l'objet des premières évaluations quantitatives connues des risques de décès d'usagers de la route par suite de coulées de débris. Une nouvelle approche est adoptée pour évaluer les risques socio-économiques et l'utilisation de courbes de fragilité pour articuler la vulnérabilité des infrastructures routières, y compris l'approche récemment développée impliquant des systèmes d'actifs, est également décrite. Les effets du changement climatique sont pris en compte parallèlement aux évolutions sociales et / ou démographiques probables et une approche stratégique de la réduction des risques de glissements de terrain est présentée.

Keywords: Landslide; hazard; risk; infrastructure; fatality; economic

1 INTRODUCTION

Landslides have formed a major focus of study in the UK for geotechnical engineers, engineering geologists, geomorphologists and other relevant professions. A remarkably wide range of event type including large individual slides (e.g. Mam Tor), large landside complexes (e.g. Undercliff, Isle of Wight), rock falls and debris flows (both of which have significant impact on transport infrastructure) are encountered (e.g. Jones & Lee 1994; Cooper 2007; Bromhead & Winter 2019).

Fatalities due to landslides are, however, relatively rare. The spate of fatalities in south-west England during the period July 2012 to March 2013 (four deaths as a result of three separate landslides) was unusual and such losses, while undoubtedly tragic, are unusual in the context of the UK.

While the morphology of debris flow in Scotland and the Republic of Korea is markedly similar, the annual landslide fatality count is startlingly disparate with the Republic suffering an average of 36 fatalities per annum during the period 1970 to 2017 (Lee & Winter 2019). In this context it seems reasonable to suggest that the UK is generally a low risk environment with respect to landslides (Gibson et al. 2013). Notwithstanding this, significant challenges remain in terms of ensuring the protection and optimal use of assets, minimising risk to road users and ensuring that socio-economic risks are adequately addressed.

Rainfall-induced debris flow events often affect the Scottish strategic road network (Winter et al. 2006; Milne et al. 2009). The risks associated with such events range from damage to the physical infrastructure, through potential injury and fatality to road users, to socio-economic losses associated with the incidents, associated delay and diversion and, potentially, to the loss of business (e.g. Figure 1).

In this paper a framework for risk acceptance is used to set the context for the work undertaken to assess and articulate the risks to road users, the physical infrastructure, and to the socio-economic activities supported by the road network. Issues surrounding the impact of climate and global change are addressed before a strategic approach to landslide risk reduction is detailed.

Figure 1. Debris flow at the A83 Rest and be Thankful, Scotland, 28 October 2007.

2 RISK ACCEPTANCE

Landslide hazards are commonplace and affect many parts of the world and the associated risks affect many different cultures.

The elements at risk may include infrastructure (e.g. roads, rail), public service buildings (e.g. hospitals, schools), commercial property (e.g. shops, factories, offices) and residential property (e.g. blocks of flats and houses). Clearly these elements at risk will also include, to a variable degree, the risk to life and limb of the users and occupants of such facilities.

The type of element at risk and the vulnerability of those elements determines what might be described as a reasonable and proportionate response to a given risk profile. However, it can be difficult to compare such responses to different risk profiles in different parts of the world as the varied social (cultural) factors and economic circumstances can mean that the tolerance of the associated risk is very different indeed.

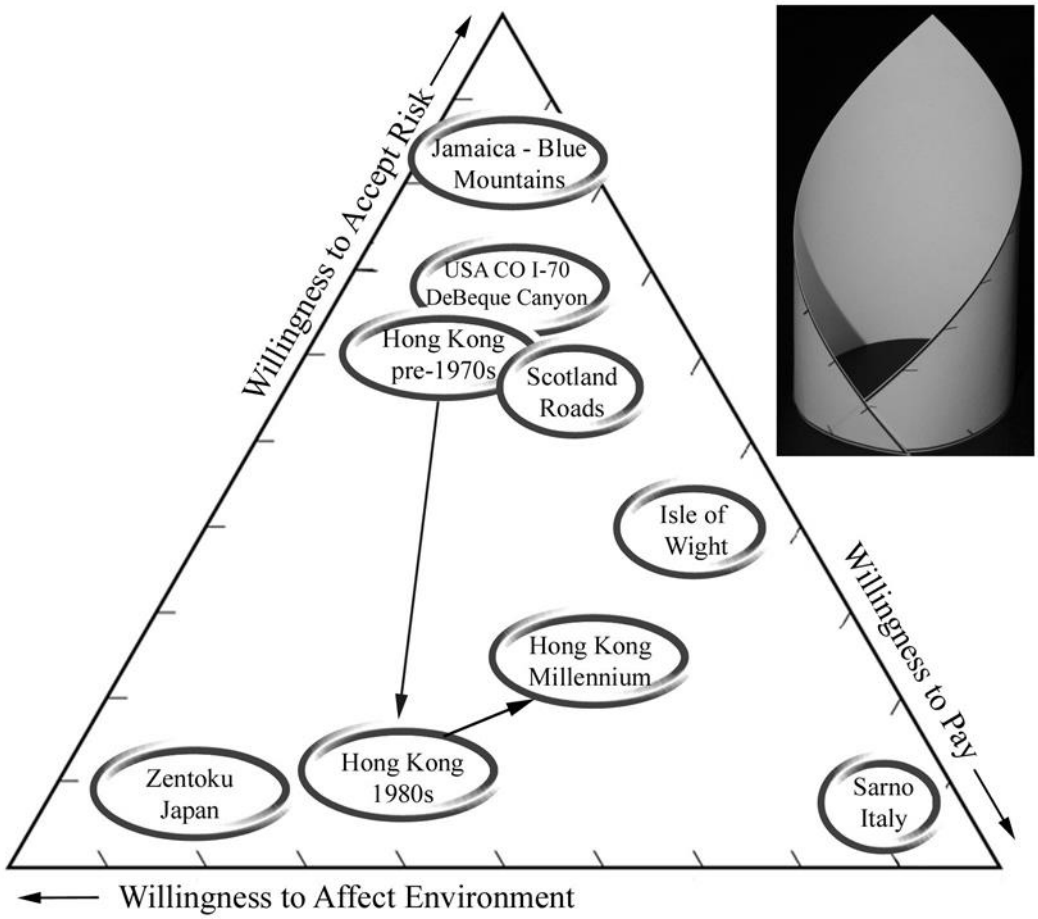

Figure 2. The 'Willingness Diagram' showing the different approaches to landslide risk in the UK and other parts of the World. Inset: The extreme bottom-left and bottom-right corners of the ternary diagram tend to converge and the diagram might more strictly be rendered as if wrapped around a cylinder about a vertical axis (from Winter & Bromhead 2012).

It seems clear (Winter et al. 2008; Winter & Bromhead 2012) that such varied approaches to landslide risk are driven not only by the willingness to accept or tolerate) risk, but also by the willingness (or ability) to pay to mitigate risk and the willingness to alter the environment in the process. These factors are interlinked using the ternary 'Willingness Diagram' (Figure 2).

In addition to this geographical variance in culture, the willingness diagram was applied to generic and conceptual approaches to landslide remediation (Section 8). This was not intended to highlight correct, or incorrect, approaches. Instead it reflects different approaches that are the result of a wide range of inputs to the decision-making process including engineering, geological, geomorphological, economic, data and information (particularly the availability of data in a usable format: e.g. GIS), sociological, political, policy-led and cultural factors.

3 SEMI-QUANTITATIVE RISK ASSESSMENT

Hazard and risk assessments can be carried out at a variety of scales and using qualitative, semi-quantitative and quantitative approaches.

Typically, although not exclusively, as assessments move from small-scale (e.g. global or continental) to medium-scale (e.g. national or regional) to large-scale (e.g. site or area) then the availability of quantitative information increases and more detailed assessments are possible. Thus, while small- to medium-scale assessments may typically be conducted in a semi-quantitative framework, large-scale assessments are more typically conducted quantitatively. In addition, it should be noted that even when regional quantitative risk assessments are undertaken (e.g. Redshaw et al. 2017) the nature and resolution of the data is such that the conclusions that can be drawn from the results will still be reflective of the regional nature of the assessment rather than of a quantitative assessment carried out at a larger scale with higher resolution data.

This should not negate the fact that, as Suzanne Lacasse so clearly articulated in her 2015 Rankine Lecture, that [even quantitative risk assessment] "is the systematic application of engineering judgement".

In this section, and in Section 4, semi-quantitative regional and site-scale fully-quantitative risk assessment (QRA), respectively, are described.

The semi-quantitative regional risk assessment was undertaken as the major component of the Scottish Road Network Landslide Study (Winter et al. 2005; 2009; 2013a) that was instigated in direct response to the debris flow events that adversely affected the trunk (strategic) road network in Scotland in August 2004 (Winter et al. 2006; Winter 2019).

The study had the overall purpose of ensuring that the hazards posed by debris flows were systematically assessed and ranked and this was intended to allow all sites to be effectively prioritized for potential action within available budgets (see also Section 8) (Winter et al. 2005).

The hazard and risk assessment Winter et al. (2009) comprised three phases:

- a pan-Scotland, GIS-based, assessment of debris flow susceptibility;
- a desk-/computer-based interpretation of the susceptibility and ground-truthing (to gather field data to either complement or dispute the desk-based data) to determine hazard; and
- a desk-based exposure analysis, primarily focusing upon life and limb risks, but also accounting for socio-economic impacts (traffic levels, and the existence and complexity of the diversionary route were used).

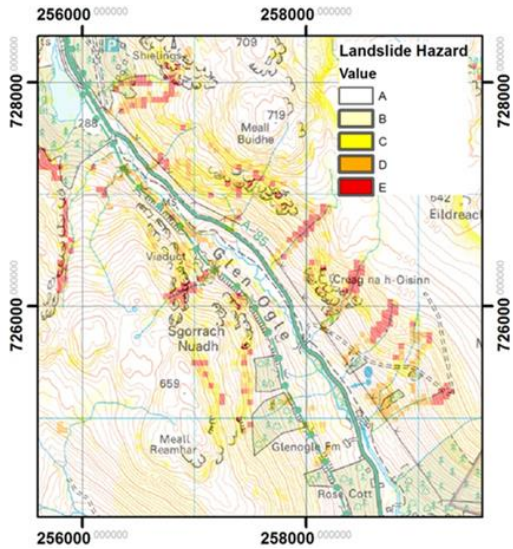

Figure 3. Results of the GIS-based susceptibility assessment for Glen Ogle (from Winter et al. 2009; 2013a). (Base mapping Ordnance Survey 1:50,000 © Crown Copyright. All rights reserved Scottish Government 100046668, 2011.)

These successive stages were used to determine the locations of sites of highest hazard ranking (risk) (Winter et al. 2009; 2013a). The results of the first stage susceptibility analysis for the A85 at Glen Ogle, one of the sites adversely affected in August 2004, are

illustrated in Figure 3. This provides a clear basis for the evaluation of hazard at road level and thus to the determination of risk. Figure 4 illustrates an example of the hazards identified at road level with a ranked priority (red being highest, followed by orange, brown and yellow being the lowest but not illustrated here).

Taking the Cruden & Varnes (1996) definition of risk 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.

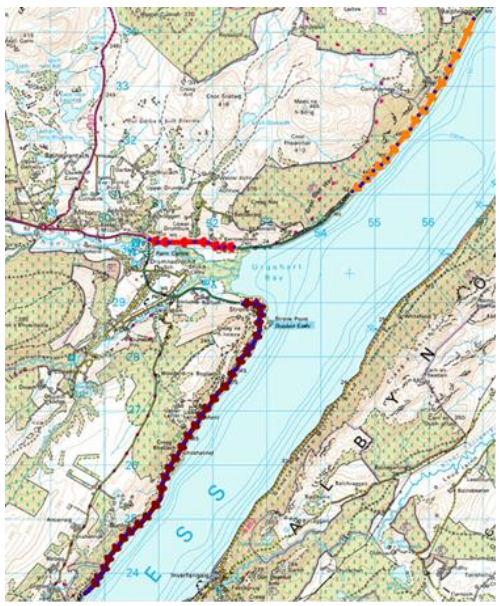

Figure 4. Hazard sections at A82 Loch Ness. Showing lengths categorised, from top to bottom, as Priority 3 (A82-03, orange), Priority 1 (A82-04, red) and Priority 2 (A82-05, brown) (from Winter et a/. 2009; 2013a). (Base mapping Ordnance Survey 1:50,000 © Crown Copyright. All rights reserved Scottish Government 100046668, 2011.)

It is possible to simplify the eq. (1) as the presence of the elements at risk (a road) is binary (it is either present or not) and treat E×V as a weighted function that considers exposure both in terms of the number of vehicles per day and an evaluation of the potential consequences of a closure and the resulting difficulty and, in some cases, absence of diversionary routes. Clearly this structure, as described by Winter et al. (2013), contains elements of life and limb risk and also socio-economic risk.

The results of the semi-quantitative regional risk assessment are shown in Figure 5 with the 66 sites with the highest semi-quantitative scores overlain on a map of Scotland. The results were also tabulated but the intention was to isolate the highest risk sites rather than to provide a league table.

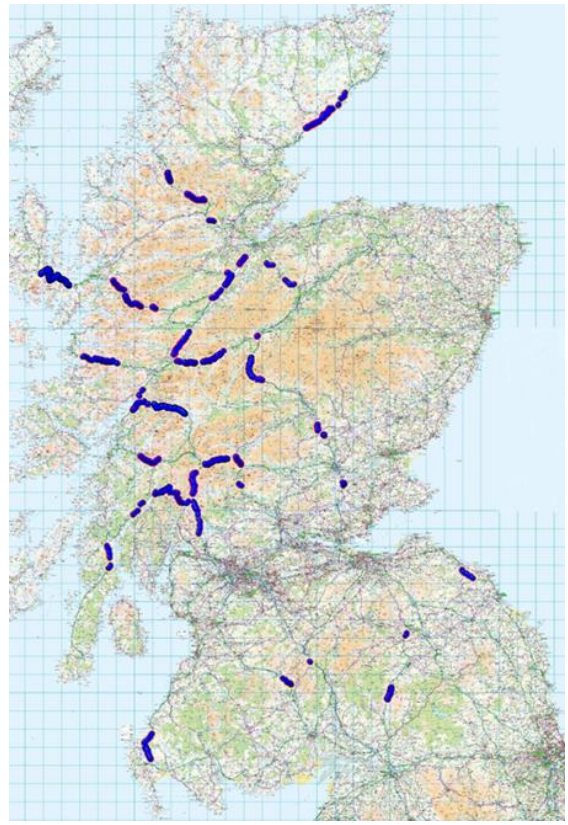

Figure 5. The 66 sites with a hazard ranking (risk) score of 100 or greater (from Winter et al. 2009; 2013a). (Base mapping © Crown Copyright. All rights reserved Scottish Government 100046668, 2011.)

This relatively rapid form of assessment was an effective means of determining the highest

risk sites in Scotland (approximately 78,000 km^2), an area comparable with other extensive assessments (e.g. Castellanos Abella & Van Westen 2007; Dio et al. 2010). Assessments have also been undertaken at the continental scale (e.g. Jaedicke et al. 2014) to inform planning policy at the highest national/trans-national level.

This knowledge can be used to determine those sites that should be targeted for further study and more refined risk assessment (Sections 4, 5 and 6) as well as for landslide risk reduction measures (Section 8).

4 QUANTITATIVE RISK ASSESSMENT

One important benefit of a robust regional assessment is that it allows a more detailed and targeted assessment of sites that pose the highest risks. Typically this involves the use of quantitative risk assessment (QRA) techniques (Corominas et al. 2014). The methodology for QRA for debris flow risk to road users is described by Wong & Winter (2018) in what is believed to be the first full, formal quantitative risk assessment. The methodology was initially applied to the A83 Rest and be Thankful site and a subsequent assessment of the A85 Glen Ogle site was conducted (Winter 2018).

The results from the two sites represent a high frequency-low magnitude site (A83) and a low frequency-high magnitude site (A85).

The form of equation used corresponds to that presented by Lee & Jones (2016) as follows:

$$Risk = P(Event) \times P(Hit|Event) \times P(Damage|Hit) \times C \quad (2)$$

where *P(Event)* is a measure of the expected likelihood of a landslide event per annum,

P(Hit|Event) is the annual probability of a vehicle 'hit' given that a landslide event occurs which involves both spatial and temporal probabilities of affecting the elements at risk,

P(Damage|Hit) is the annual probability of damage given that a 'hit' has occurred, as a measure of chance between 0 and 1, and

C is the consequences as a result of the landslide event.

For the purposes of this work 'Damage' was taken to represent the fatality of one or more road users and effectively encompasses the concepts of both 'Damage' and 'Consequences' (i.e. $P(Fatality|Hit)\times C$).

Two scenarios were considered, that of a vehicle being hit by a debris flow that reaches the road (A) and that of a vehicle hitting a debris flow that has already reached the road (B).

The results for the A83 (Figure 6) demonstrate that for numbers of fatalities N = 1 and 2 lie in the 'Unacceptable' zone with the remaining values being in the 'As Low As Reasonably Practicable (ALARP)' zone. In contrast, those for the A85 (Figure 7) generally lie in the 'Broadly Acceptable' zone with N = 1 and 2 lying in the ALARP zone.

No account of landslide risk reduction measures is made in Figures 6 or 7. This is particularly important at the A83 site, at which a strategic approach has been taken to the reduction of landslide risk (Winter 2014a; 2016a: see also Section 8) including educational leaflets, wig-wag warning signs (Winter et al. 2013b; Winter & Shearer 2017) and the provision of debris flow nets.

The QRA was conducted prior to October 2014 and at that time additional debris flow nets and catch pits were planned along with significant planting of the hillside to improve stability (Winter & Corby 2012; Winter 2016b). Additional nets and catch pits have since been installed and the planting programme is progressing through the planning stages.

This work articulated the effect on societal risk of the landslide risk reduction measures that were in place as of October 2014 and not those measures installed subsequently.

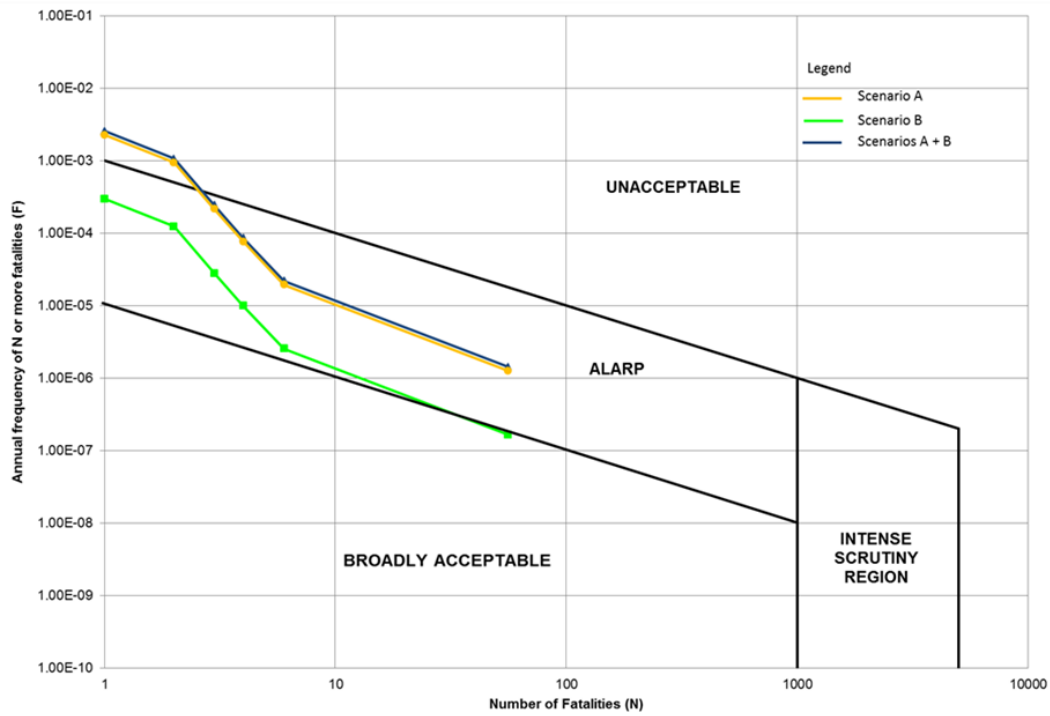

Figure 6. F-N curves based on the Wong et al. (2004) approach for the A83, before mitigation measures (compare to Figure 8).

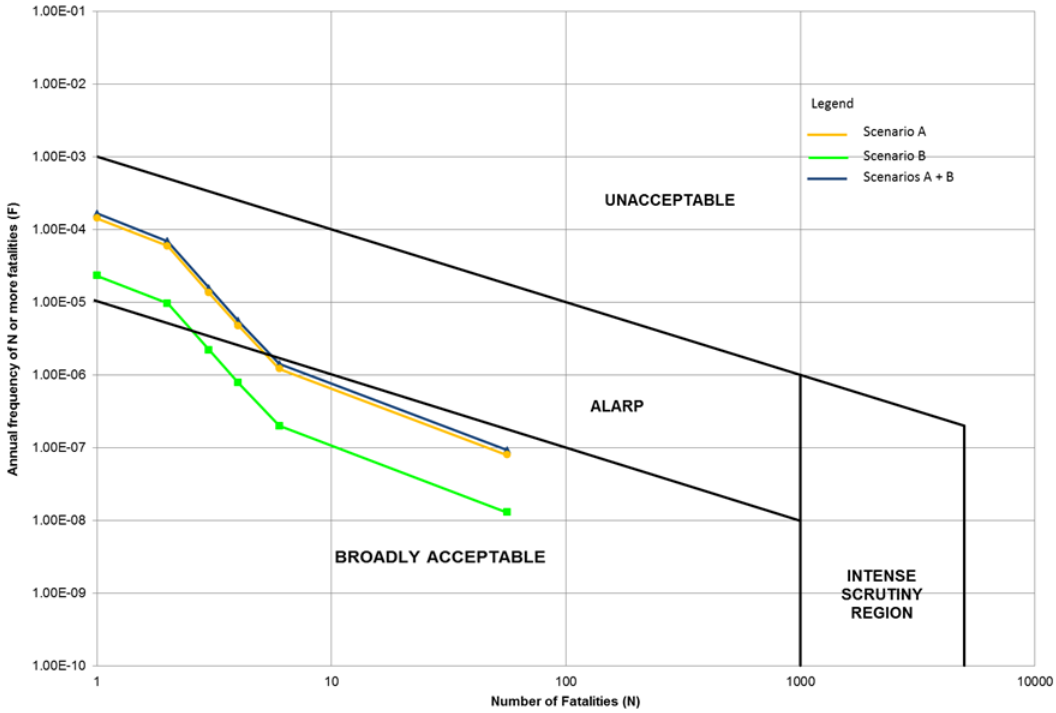

Figure 7. F-N curves based on the Wong et al. (2004) approach for the A85.

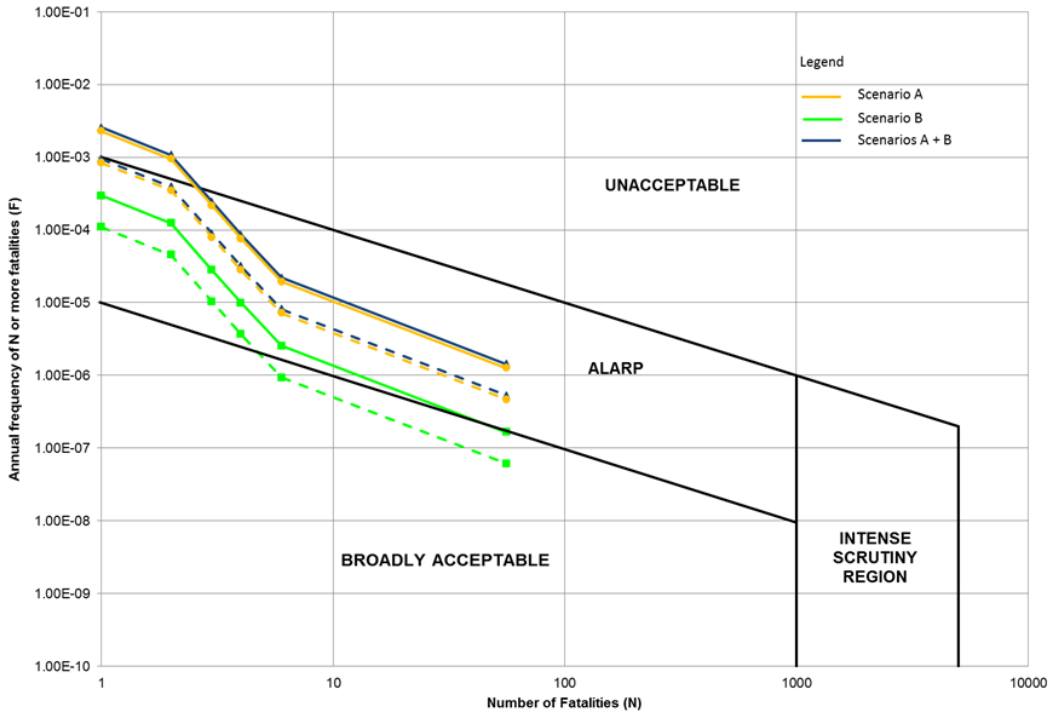

Figure 8. F-N curve showing the risk reduction for the A83 due to the mitigation measures extant as of October 2014 based on the Wong et al. (2004) approach. The dashed lines represent the risk after the mitigation measures are taken into account. Note that the line for Scenarios A and B combined is partly obscured by that for Scenario A.

This was achieved by the use of an event tree diagram and carefully considering (and testing) the contribution to hazard reduction and that each element of the strategic programme made and then calculating the revised risk levels in terms of F-N (Figure 8).

This process was made possible by the detailed evaluation of the wig-wag signs (Winter et al. 2013b) and events that had occurred and tested the efficacy of the debris flow nets. As can be seen in Figure 8, taking account of the landslide risk reduction measures brings the risk back to the ALARP zone for all values of N.

For the F-N (societal/fatality) calculations a notional vehicle speed of 50 mile/h was assigned for the analysis of societal risk. This was considered to be typical of passenger vehicle speeds experienced at the sites (regardless of the speed limit) and is conservative for goods vehicles subject to a lower speed limit.

Wong & Winter (2018) and Winter (2018) also presented results for personal individual risk (PIR), the annual probability of an individual becoming a fatality during a single trip through a site (Lee & Jones 2014). The calculation of such data is an essential precursor and input to the more detailed calculations for the F-N diagrams presented in Figures 6 to 8 and these in turn rely on the calculation of the potential loss of life (PLL). PLL essentially extrapolates PIR based on the amount and type of traffic that uses the site. Thus, rather than being the risk of an individual becoming a fatality at a given site, it is the risk of any individual, taken from those using the route, becoming a fatality; the PLL, and F-N, thus represents a risk to society rather than to the individual.

In the case of PIR the lower of national or posted speed limits were used which are 60

mile/h (97 km/h) at the A83 and 50 mile/h (80 km/h) for passenger vehicles. The results correspond to annual probabilities of fatality of 1.583E-09 at the A83 and 1.147E-10 at the A85, respectively.

The PIR can also be extrapolated to give an annual risk level for both commuters and logistics truck drivers. The national or posted speed limit was used for commuters while the national speed limit for goods vehicles over 7.5 tonnes (maximum laden weight) in Scotland of 40 mile/h (except for the A9 Perth to Inverness) was used for logistics truck drivers.

The annual probability of fatality for commuters at the A83 site was 7.440E-07 and 1.922E-06 for logistics truck drivers; at the A85 site it was 5.391E-08 for commuters and 1.248E-07 for logistics truck drivers. These figures were based on commuters making daily return trips through a site on five days per week for 47 weeks a years, and for logistics truck drivers, making two daily return trips through a site on five days per week for 47 weeks a year.

QRA is an undoubtedly powerful tool to analyse, understand and present the effects of landslides on society. Additionally it can be used to articulate the effects of landslide risk reduction measures as is the case at the A83.

The form of equation used for the QRA (eq. 2) can be directly related to that used for the semi-quantitative regional risk assessment (eq. 1) with hazard (H) in eq. (1) being represented by $P(Event)$ in eq. (2), elements at risk represented by $P(Hit|Event)$ and vulnerability being represented by $P(Damage|Hit)\times C$ (or $P(Fatility|Hit)\times C$). While direct numerical comparisons are not possible the consistency of process does lend confidence to the overall approach, especially when, given the nature of the risks, such work is so often subject to political, media and public scrutiny.

Notwithstanding this the QRA process is, of course, considerably more time-consuming on a site-by-site basis, than the semi-quantitative assessment, and demands significant resources. The associated costs mean that it is not generally possible, or appropriate, to apply QRA to a large number of sites and targeting of the highest risk sites necessary. This means that the existence of a semi-quantitative, regional assessment is an essential precursor to QRA. In addition, a sound knowledge of the infrastructure and its users is required, more so even than for the semi-quantitative regional assessment, in addition to high level knowledge of the physical processes (in this case debris flow).

5 SOCIO-ECONOMIC RISK

The social and economic impacts of landslides are both significant and complex. Roads in Scotland, for example, provide vital communication links to remote communities.

Loss of life and major injuries associated with rainfall-induced landslide events is thankfully rare in Scotland, the real impacts are economic and social. Severance of the access of these communities to services and markets as a result of, for example, a landslide or flooding, has significant economic and social consequences. At an individual level opportunities related to employment, education, health, welfare and social activities may be lost or restricted.

Landslides can occur at almost any time of year, although summer (July and August) and winter landslide seasons (October/November to January) have been identified (Winter et al. 2005; 2009). The Scottish landscape has a high economic value and the most important peak in tourist activity coincides with the summer landslide season.

The qualitative economic impacts of such landslide events include:

- the loss of utility of parts of the road network,
- the need to make often extensive detours in order to reach a destination, and
- the severance of access to and from relatively remote communities for services and markets for goods; employment, health and

educational opportunities; and social activities.

The economic impacts of a landslide event that closes a road, or other form of linear infrastructure were summarized by Winter & Bromhead (2012), in three categories, as follows:

- Direct economic impacts.
- Direct consequential economic impacts.
- Indirect consequential economic impacts.

Direct economic impacts: The direct costs of clean-up and repair/replacement of lost/damaged infrastructure in the broadest sense and the costs of search and rescue. These should be relatively easy to obtain or estimate for any given event, provided that this is done soon after it occurs.

Direct consequential economic impacts: These generally relate to 'disruption to infrastructure' and relate to loss of utility. For example, the costs of closing a road (or implementing single-lane working with traffic lights) for a given period with a given diversion, are relatively simple to estimate using well-established models. The costs of fatal/non-fatal casualties and accidents may also be included here and may be taken (on a societal basis) directly from published figures. While these are set out for the costs of road traffic accidents, or indeed rail accidents, there seems to be no particular reason why they should be radically different to those related to a landslide as both are likely to include the recovery of casualties from vehicles. Indeed, for events in which large numbers of casualties may be expected to occur, data relating to railway accidents may be more appropriate.

Indirect consequential economic impacts: Often landslide events affect access to remote rural areas with economies that are based upon transport-dependent activities, and thus the vulnerability can be extensive and is determined by the transport network rather than the event itself. These impacts include those due to the dependence upon the transport network for incoming and/or outgoing goods, and for the transport of staff and visitors as well as any associated longer term impacts. If a given route is closed for a long period then how does that affect confidence in, and the ongoing viability, and credibility, of local businesses. Manufacturing and agriculture (e.g. forestry in western Scotland) are a concern as access to markets is constrained, the costs of access are increased and business profits are affected and short-term to long-term viability may be adversely affected. Perhaps of even more concern are the impacts on tourist (and other service economies) businesses. It is important to understand how the reluctance of visitors to travel to and within 'landslide areas' is affected after an event that has received publicity and/or caused casualties and how a period of inaccessibility (reduced or complete) affects the short and long-term travel patterns to an area for tourist services. Such costs form a fundamental element of the overall economic impact of such events on society. They are thus important to governments as they should affect the case for the assignation of budgets to landslide risk mitigation and remediation activities. However, these are also the most difficult costs to determine as they are generally widely dispersed both geographically and socially. Additionally, in an environment in which compensation might be anticipated, albeit often erroneously, those that have the best data, the businesses affected by such events, are also those that anticipate such compensatory events.

The above primarily relates to the economic impacts that affect linear infrastructure, particularly roads, Alimohammadlou et al. (2013) describe landslide losses in a more generic sense whilst including many of the elements described in the foregoing.

A similar scheme was presented by Benson (2012) in respect of disaster losses and considered the following:

- Direct losses: Relate to human life and injury and physical damage to productive and social assets.
- Indirect losses: Refer to disruptions to the flow of goods and services stemming from the direct losses.
- Secondary effects: Concern the impacts on socio-economic imbalances and the functioning and performance of an economy.

While closely correlated with the Winter & Bromhead (2012) scheme, these have a broader disaster impact focus than the landslide impacts on a road network.

There is a variety of approaches to determining the economic (and social) risks posed by landslides. Typically these quantify the direct economic losses (e.g. Highland 2006) and occasionally some aspects of direct consequential and/or indirect consequential losses (e.g. Schuster & Highland 2007; Highland 2012). Bespoke methods designed to address a particular set of circumstances are also used to estimate the indirect consequential economic impacts of landslides (MacLeod et al. 2005; Anon. 2013).

Klose et al. (2015) in contrast collected local direct and direct consequential costs for a series and extrapolated these to an entire road network on the basis of a susceptibility survey and infrastructure exposure model, while Eidsvig et al. (2014) used an indicator-based methodology to assess the relative socio-economic vulnerability of communities to landslides at local to regional scale.

The approach developed by Winter & Bromhead (2012) has been used to articulate socio-economic costs of both landslide and flood events that have affected the road network in Scotland. Published and unpublished records were interrogated to obtain direct economic impacts, software used to model delays at roadworks was used to obtain direct consequential economic impacts and questionnaire surveys were used to obtain cost and, perhaps more importantly, qualitative information on the indirect consequential impacts (Winter et al. 2016). Winter et al. (2018) describe the development and application of the methodology, and the results and their interpretation in detail.

The results indicate a range of total direct economic impact costs of between approximately £400k and £1,700k (2012 prices) for four Scottish landslide events from 2004 to 2014. The corresponding direct consequential costs were between around £180k and £1,400k. Daily costs are presented by Winter et al. (2018), however, the variation in the type of full and partial closure for different events, and their change over time for specific events as repair and remediation work is undertaken defies a simple presentation.

Unsurprisingly the daily direct consequential economic impacts are largely dependent upon traffic levels while the total costs depend upon the traffic and the duration of the disruption. The methods for direct and direct consequential economic impacts have also been applied to flood events that affect the road network; the events generally affect more developed peri-urban parts of Scotland and their rather short duration, transient nature meant that the direct costs were small but the direct consequential costs (c. £3,200k) much greater than for any of the landslide sites considered (Winter et al. 2016).

Surveys of businesses in the areas of events provided cost information that could be interpreted in a number of ways and therefore gave a very wide range of potential results. They did, however, provide useful qualitative information (Winter et al. 2018). For events of lesser impact, descriptors that relate to the hazard are used: ‘landslide’, ‘flooding’ and other words that describe the event itself are also to the fore (Figure 9).

In contrast responses to events of greater impact and or repetition such as at the A83 (Figure 10), at which a significant number of events and consequent closures have occurred

over the past 20 years, tend to relate to the effects, risks, or impacts, that derive from the event.

Figure 9. Word map of responses from survey respondents: A85 Glen Ogle, 18 August 2004.

Figure 10. Word map of responses from survey respondents: A83 Rest and be Thankful, 28 October 2014.

In this case the most frequently used word was ‘road’, with words such as ‘closed’, ‘staff’, ‘visitors’, ‘due’, ‘access’, ‘tourism’, ‘minor’ and ‘island’ also coming to the fore. These latter responses seemingly describe the consequences of the hazard, or the economic risks associated with the hazard, rather than the hazard itself, implying a greater economic impact or, at least, a greater awareness of the economic impact.

5.1 Vulnerability Shadow

The vulnerability shadow (Winter & Bromhead 2012) is closely linked to economic impacts and determines their extent and overall magnitude. The vulnerability shadow is a largely qualitative means of expressing the areal extent of the impact of hazards such as landslides and floods (Winter 2014b). It is thus a measure of the area over which the effects of the risks associated with the hazard are experienced. The magnitude of the vulnerability will not be constant in the area affected and may, as a first level approximation, be expected to decrease with distance from the hazard event.

The vulnerability shadow cast can be extensive and its geographical extent can be determined by the transport network, including closures and diversionary routes, rather than the relatively small footprint of the event itself. In the case of the A83 landslide event at the Rest and be Thankful in 2007, the event itself was of the order of around 400m^3 with a footprint that closed a few tens of metres of the length of the road (Winter 2014b).

In Scotland the vulnerability shadow has been evaluated using knowledge of the local transport networks and the socio-economic activity associated with the network that has been built up over a period of 30 years. This includes an holistic evaluation of major nodes, origins and destinations and includes both experience and knowledge gleaned from formal surveys (e.g. Winter et al. 2013a). The vulnerability shadow was thus estimated (Figure 11) to be of the order of 2,800km^2 (total area approximately 3,500km^2, 20% allowed for areas of sea).

The area has a population density of approximately 13 people/km^2 (www.argyll-bute.gov.uk) and the event thus had the potential to have had an economic impact upon up to approximately 36,400 people in Argyll & Bute, plus any transient (e.g. tourist) population.

It is instructive to make some simple comparisons with Hong Kong SAR, which has an average population density of around 6,500 people/km^2 (www.gov.hk). This dictates a much greater transport network density. Thus, and purely for the sake of comparison, in order to have an economic impact on the same number of people the vulnerability shadow cast need only be approximately 5.6km^2 (2km by 2.8km, for example).

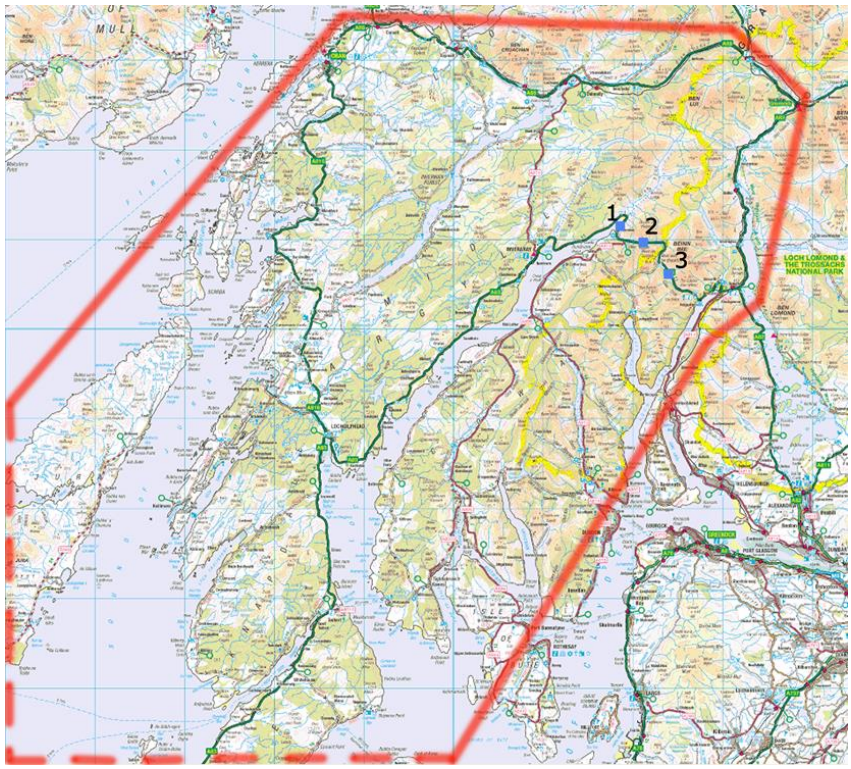

Figure 11. A relatively small debris flow event (blue square '3') closed the A83 at the Rest and be Thankful on 28 October 2007; the vulnerability shadow that was cast (bounded in red) was extensive (Winter 2014a; 2014b). The 2004 events at Cairndow ('1') and Glen Kinglas ('2') are also shown. (Image based on OS 1:250,000 mapping. © Crown Copyright. All rights reserved Scottish Government 100020540, 2018.)

It is not suggested that the economic impacts would be similar for events with vulnerability shadows of these diverse sizes in Argyll & Bute and Hong Kong. However, it is clear that the low density/dispersed network in Argyll & Bute dictates a large vulnerability shadow while the much more dense/less dispersed network in Hong Kong means that vulnerability shadows will be small, with the exception of events that affect critical infrastructure corridors, as more alternative routes will exist and will be more proximal to the event (Winter 2014b).

A landslide on the B1 route in the Blue Mountains of Jamaica (Figure 12) effectively severed the local coffee production industry from the most direct route to the international market for this high value product. As such a single landslide event placed severe constraints on the economy of the Blue Mountains. Again, while the footprint of the actual event was relatively small, the vulnerability shadow was projected over a much greater area creating tangible economic and social losses.

The economic impact and the vulnerability shadow are concepts that apply equally to other discrete climate-driven events that have the potential to close parts of the road network such as flood events. Like landslides, such flood events are generally thought to be likely to increase in frequency as a result of climate change (Galbraith et al. 2005; Anon. 2011a; Winter et al. 2005; 2010a; 2010b; Winter & Shearer 2013) (see also Section 7). However, it is clear that for some events it is the hazard itself and not the transport network and, more pointedly, its density that determines the location, shape and extent (morphology) of the vulnerability shadow. However, it is important

to recognise that the morphology of the vulnerability shadow related to other types of event (e.g. glacial lake outburst floods), may be determined by the nature of the hazard itself.

Figure 12. Landslide on the B1 road at Section in Portland Parish, Jamaica. This event severed much of the local coffee production industry from the ports used to ship the product to market. (This picture is a photo-collage and some distortion is inevitable.)

An example in which the hazard determines the vulnerability shadow is the Seti River debris flow in Nepal (Figure 13). On 5 May 2012 the event caused significant erosion and deposition in the river channel over a distance of around 40km. The event was initially thought to have resulted from a failed landslide dam. However, subsequent inspection of satellite imagery and aerial photography (Petley & Stark 2012; Petley 2014), and more detailed site inspection and investigation (Dahal & Bhandary 2013) led to the conclusion that the event was a debris flow initiated by part of a 22Mm^3 rock avalanche originating on the slopes of Annapurna IV and entering the upper stream channel at high speed. An estimated 71 people lost their lives at Kharapani, some 20km north of Pokhara. The vulnerability shadow was constrained by the dimensions of the hazard flow within the stream channel, extending beyond these bounds only where infrastructure was damaged, including the footbridge at Kharapani.

Figure 13. Residents of Kharapani located on the platform in the middle distance on the Seti River, Nepal, were among fatalities from the 5 May 2012 debris flow event. The abutment of the suspended footbridge is on the platform.

Similarly, it is entirely possible that the event itself and the transport network may define the vulnerability shadow during different phases of an event. The Zhouqu debris flow disaster (Gansu Province, PR China) occurred at around midnight on 8 August 2010 and claimed the lives of around 1,750 people (Dijkstra et al. 2014; Winter 2019). The vulnerability shadow was initially constrained by the hazard as the debris flow swept through the gorge and the town below (Figure 14). Approximately at the base of the picture, but just out of shot, is the main road that links Zhouqu to the rest of China. As the road was also blocked by the event, the vulnerability shadow spread in both directions along the valley and was thus considerably more extensive than it might otherwise have been if the debris flow run-out had been shorter. Thus, in this case, the morphology of the vulnerability shadow was determined by both the hazard, in the initial phase of transport and deposition, and the transport network (the road), in the latter phase as the run-out zone was reached.

The vulnerability shadow has proven to be a useful and effective means of assessing (semi-quantitatively), presenting and articulating the areal extent of socio-economic landslide (Winter et al. 2016; 2018) and flood hazards (Winter et

al. 2016; 2018; Milne et al. 2016) as exemplified in Figure 11. Indeed, this approach has been extended by Winter et al. (2018), using Figure 11, to enable specific areas within the wider vulnerability shadow to be identified and the economic impact on each area assessed individually.

Figure 14. The channel in which the 8 August 2010 Zhouqu debris flow occurred (Gansu Province, PR China) (from Winter 2019). The road and river that pass through the valley are located just below the bottom of the picture.

6 INFRASTRUCTURE RISK

In the previous sections the primary focus has been the risk to road users and the socio-economic risks. In this section the focus is on the risk to the physical infrastructure elements.

The physical vulnerability of roads to debris flow may be expressed through fragility functions that relate flow volume to damage probabilities. Fragility curves have been produced that indicate the probability of a debris flow of a given volume exceeding each of three damage states. Typically, damage to roads resulting from debris flow may include one or more of the following:

- Debris covering the carriageway, preventing vehicle movements.
- Damage to the carriageway surfacing materials.
- Blockages and other types of damage to the drainage system.
- Damage to vehicle restraint systems.
- Damage to support structures including slopes and retaining walls downhill from the road.

The vulnerability to debris flow for impacted buildings has been expressed using fragility curves and/or probabilities of exceedance of damage states (Haugen & Kaynia 2008; Jakob et al. 2012; Quan Luna et al. 2011; Papathoma-Khöle et al. 2012), while Winter et al. (2014) developed fragility curves for the effects of debris flow on road infrastructure. While several possible approaches were available for the development of fragility curves, including analytical approaches, it was decided that expert engineering judgement should be used due to a lack of a comprehensive empirical dataset as well as the complex nature of the problem

All roads were considered to be relatively stiff and brittle (the low strain stiffness of even an unbound pavement, for example, may be typically up to around one gigapascal) in comparison to most debris materials. In order to further simplify the analysis, roads were divided into low- and high-speed roads, characterized as follows:

- High-speed roads: speed limit between 80 and 110km/h and one or more running lane in each direction, very often in conjunction with a hard strip or hard shoulder.
- Local (or low-speed) roads: speed limit typically <50km/h on a single-carriageway (one lane for each traffic direction) or single-track. This category is intended to encompass both paved (bituminous, unreinforced or reinforced concrete) and unpaved constructions.

Clearly there is a gap between the speed limits of the two classes of road, reflecting the transition between local roads and high-speed roads, which is by no means geographically

consistent. This reflects reality – in some countries and regions certain road geometries are more closely aligned with the definition of local roads, and in others they are more closely aligned with the definition of high-speed roads. Speed limit is not, and should not be, the only determinant of the category of road. In most instances, the category that a particular geometry and speed limit combination will belong to is relatively self-evident, but extending the speed limits between 50 and 80km/h in the category descriptions could lead to uncertainty and potential incorrect categorisation.

Table 1. Damage state definitions

Damage state	High-speed roads	Local (low-speed) roads
P1 (Limited damage)	Encroachment limited to verge/hard strip	Partial blockage of carriageway
P2 (Serious damage)	Blockage of hard strip and one running lane	Complete blockage of carriageway and/or damage to ancillaries
P3 (Destroyed)	Complete blockage of carriageway and/or repairable damage to surfacing	Complete blockage of carriageway and/or damage to surfacing. For unpaved roads the surfacing may remain damaged but passable at reduced speeds post clean-up

Representative damage states associated with the consequences of a debris flow of a given volume intersecting a road were defined. The damage states considered in the questionnaire are defined in Table 1. The damage states range from 'limited damage' which, for high speed roads, is unlikely to significantly affect the passage of vehicles, through 'serious damage', to 'destroyed' involving complete blockage and damage to the road itself that for, high-speed roads at least, will almost certainly need to be repaired prior to reopening to traffic without restrictions on speed.

The survey was conducted amongst 176 debris flow experts, with a 27% response rate and responses from 17 countries. These represented most parts of the world, but with a significant majority of 83% being received from Europe. The responses were split between those representing academia (32%), the commercial sector (51%) and government bodies (17%).

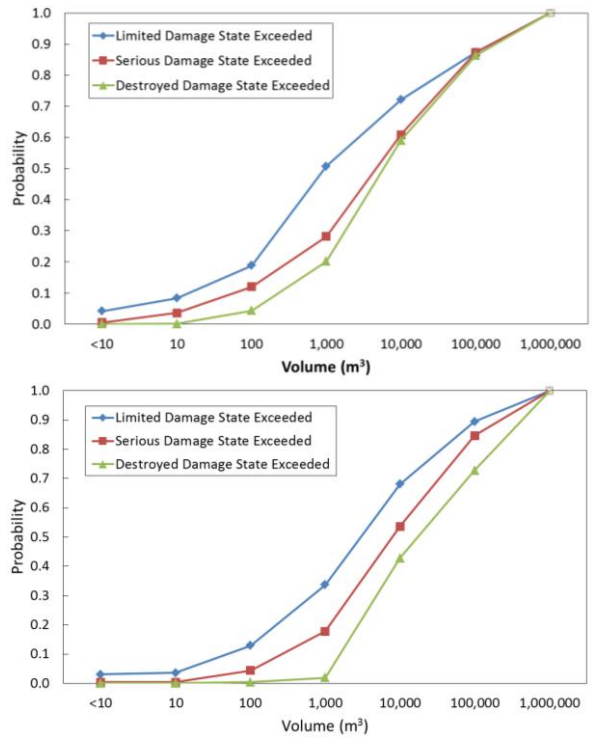

Figure 15. Fragility curves: top, local roads; bottom, high-speed roads.

The data collection, analysis and interpretation is described in detail by Winter et al. (2014) and the resulting curves are illustrated in Figure 15 while Figure 16 explains the probabilities inherent within the fragility curves, in particular the probability of a given damage state being exceeded and the conditional probabilities of a given damage state.

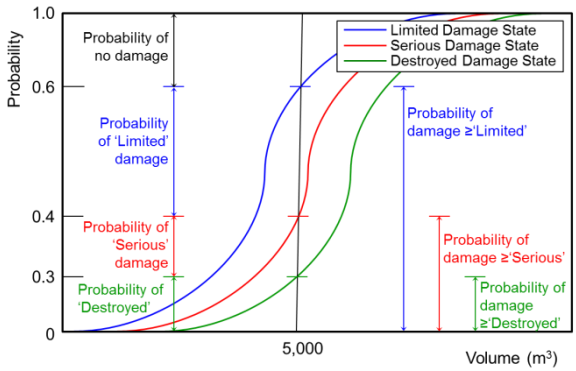

Figure 16 Hypothetical fragility curve illustrating a 5,000m³ event on a high-speed road (Figure 15), illustrating the probabilities of a given damage state being exceeded and the conditional probabilities for damage states.

The experience of the respondents is a critical metric in terms of the data set, and respondents were asked to assess their experience on a scale of zero to 10. The scores of this self-assessment were weighted towards the higher end of the range, as might be expected from a sample of respondents who were selected for their known expertise in this area. As also might be expected, the confidence of respondents for low-volume events is markedly higher than for high-volume events, reflecting the higher frequency, and therefore experience, of low-volume events and the data indicated that for low-volume events, the confidence in the responses is high while for high-volume events (100,000m^3) confidence is lower.

The results were tested against events from Scotland (Winter et al. 2006; 2009) and the Republic of Korea (Lee & Winter 2010; 2019). The results from determining the probabilities of a given damage state given the volumes of the events that occurred were found to be broadly consistent with field observations; two examples of the validation work follow.

6.1 A85 Glen Ogle, Scotland

In August 2004, two debris flow events occurred at Glen Ogle (Figure 17). These blocked the A85 strategic road, culverts and other drainage features, and necessitated a full repair to the road pavement, safety barriers and parapets (Winter et al. 2005; 2006). Some 20 vehicles were trapped by the events and 57 people were airlifted to safety; one vehicle was swept away in the latter stages of the event (Winter et al. 2005). The smaller southerly and larger northerly events were estimated to have deposited around 3,200m^3 and 8,500m^3 in their respective debris lobes, having been triggered by smaller translational slides of around 285m^3 and 280m^3 (Milne et al. 2009). The depositional figures are believed not to include material deposited on the road, and it seems reasonable therefore to round these figures up to around 5,000m^3 and 10,000m^3.

Figure 17. The larger northerly of the two August 2004 debris flows at A85 Glen Ogle.

For the smaller (5,000m^3) event, the conditional probabilities for no damage, limited, serious and destroyed damage states are 0.4, 0.2 (0.6), 0.1 (0.4) and 0.3 (0.3) (the probabilities of the damage states being met or exceeded are given in parentheses); for the larger (10,000m^3) event, the conditional probabilities are around 0.3, 0.15 (0.7), 0.15 (0.55) and 0.4 (0.4), in both cases for a high-speed road. Certainly the damage caused by the larger event would have been described as destroyed using the scheme considered here, and the probability of this state, 0.4, seems to be broadly in line with observations made in its immediate aftermath, albeit affecting a road length of around 200m. Similarly, the damage caused by the smaller event, although somewhat less in terms of physical damage to the infrastructure, would also be classified as destroyed and this seems to be broadly reflective of the probability of 0.3 returned from Figure 15.

6.2 Seoul to Chuncheon National Highway Tunnel Portals, Republic of Korea

Landslide deposits at the Chuncheon National Highway tunnel portals (Figure 18) were 500m^3 to 1,000m^3. For an event of this volume (1,000m^3) the conditional probabilities of the damage states no damage, limited, serious, and destroyed are 0.7, 0.1 (0.3), 0.18 (0.2), and 0.02 (0.02), for a high-speed road.

Only very minor damage was incurred at the Seoul to Chuncheon National Highway tunnel portals, and this reflects the small volumes; the probability of either limited damage or no damage (the combined conditional probabilities) is 0.8 (Figure 18). The road was not open at the time of the event, and there is every possibility of both further and larger events that have the potential to meet or exceed higher damage states.

6.3 Systems of Assets

The concept of fragility also lends itself to being based on the results of modelling and in that sense has been widely applied including damage related to both highway and railway embankments and cut slopes (Argyroudis & Kaynia 2015), cantilever retaining walls (Argyroudis et al. 2013) and to the settlement of bridges (Peduto et al. 2018). The first two of the foregoing examples reflect, to a large degree, the genesis of fragility curves as a tool to understand the severity and potential damage due to seismic activity.

Figure 18. Debris flow site from July 2009 above tunnel portals on the Seoul to Chuncheon National Highway in the Republic of Korea: (top) source area; and (bottom) view from the source area looking out over the tunnel portals.

Infrastructure assets comprise Systems of Assets (SoA) – a combination of interdependent assets exposed not to one, but to multiple hazards, depending on the environment within which these reside (Argyroudis et al. 2018). This multi-element, multi-hazard approach presents a

far more realistic, real-world, approach to understanding and assessing the behaviour and the fragility of assets and SoAs subjected to one or a sequence of similar or disparate hazards.

7 CLIMATE CHANGE AND RESILIENCE

In terms of the potential variability in climate changes, and the subsequent impacts, the statement widely attributed to Donald Rumsfeld, the former US Secretary of Defence at a Defence Department briefing in 2002, is pertinent (Winter et al. 2010b):

"There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know."

Whatever the merits of the language used – Rumsfeld's statement won the 2003 *Foot in Mouth Award* from the Plain English Campaign and was also hailed as an example of found poetry – the sentiment, if not the precise wordings, has been around for considerably longer. (It arguably has its roots in Socrates' statement "I know that I know nothing", which is often interpreted as a reflection on the confidence levels, and uncertainty inherent, implicit within knowledge and information.) It does, however, provide a useful conceptual and temporal framework for past, current and future climate and the associated potential changes. This may be framed as follows:

- Known knowns: These include historic and recent climate trends, their relation to current patterns and the fact of climate change (the sequence of greenhouse gas emissions, global warming, and climate change and instability).
- Known unknowns: The precise degree and nature of climate change and some of its impacts, particularly in the light of the variability in climate change forecasts and likely instability in year-on-year climate patterns. These impacts might, for example, include the reaction of vulnerable human populations to both climate change and instability.
- Unknown unknowns: The nature of some other impacts of climate change, although as these are genuinely unknown unknowns these will really have to wait until our knowledge is more complete – that these are unknowns is after all the point. Possibly the real value of this element of the framework is as a reminder that there will always be issues that arrive unexpectedly out of leftfield.

Knowns and unknowns fit well within many geological and geotechnical frameworks with the challenge being to move backwards on the scale from unknown unknowns, through known unknowns to known knowns reducing the risk in the process.

It is also important to bear in mind that one person's known known may be another's known unknown or even unknown unknown; knowns and unknowns may be dependent upon professionalism, specialism, awareness and other factors. This emphasises the need for effective and ongoing communication both within and between the professions.

An integrated data approach was taken to an evaluation of landslide hazard and risk in the light of global change, including climate change by Winter & Shearer (2013; 2014). Data sets describing recent trends (1914 to 2004) in the climate of Scotland (Barnett et al. 2006a; 2006b), current meteorological synoptic data from the national Meteorological Office, and both deterministic climate change forecasts (UKCOP02: Hulme et al. 2002) and probabilistic forecasts (UKCP09: Jenkins et al. 2009; Anon. 2011a; 2011b) were all considered in order to give an holistic view of the potential change in hazard frequency and intensity.

In broad terms the data presented a picture that tended to suggest that landslide frequency and magnitude would increase in Scotland in the future, at least in the winter months. The picture for the summer months was considerably more complex, but one likely outcome was that while the frequency of events would decrease their magnitude, when they do occur, may increase. These conclusions were broadly consistent with those from earlier parts of the work on climate change and the effects on Scotland's road network (Winter et al. 2005).

A consideration of the consequent risks to road users from landslides and climate change concluded that while the effects of climate change were most likely to increase the hazard, increases in the elements at risk and their vulnerability are likely to increase in line with road traffic (and rail passenger) growth. The risk to road users was thus considered likely to increase as a result of both climate change and traffic growth.

A study of the hazards and risks associated with coastal flooding (Milne et al. 2016) concluded that the hazard frequency was likely to increase by a factor of up to around 2.5 between the present and 2100. The economic impacts were also evaluated using the methodology set out by Winter et al. (2016; 2018) and inevitably this demonstrated increased economic impacts on the same scale. However, when projected traffic growth was factored in, this increase in the elements at risk and their vulnerability, produced a much greater impact at around 19 times the present day impacts and around eight times those forecast due to the changing hazard alone.

The conclusion that changes in elements at risk and their vulnerabilities play a key role, and often one that is dominant, driven by social and/or demographic change, is extremely important. Clearly a focus on hazards, with the elements at risk and their vulnerabilities, being treated almost as an afterthought is neither adequate nor acceptable. However, this clearly-demonstrated potential for these oft-neglected components to dominate the risk outcome demonstrates rather graphically that, as interesting as the hazards may be to us as ground engineering professionals and/or geoscientists, it is essential that we engage with other disciplines to adequately assess the elements at risk and their vulnerabilities in order to produce effective risk assessments.

The outcomes of such risk assessments must be balanced against, and be used in the consideration of, opportunities to reduce risk by means of new and renewed infrastructure, albeit this is not a panacea for all ills due to a lack of affordability. In this sense it is essential that resilience of existing and new infrastructure is considered and enhanced where possible.

In terms of resilience, the frequency of events is extremely important relative to the recovery time for an event, and in the coastal flooding case study examined by Milne et al. (2016) for example, the recovery time was around 6.5 weeks (the time from the event occurring to the road being fully open again). This was significantly less than the event frequency allowing full recovery of system resilience between events in that case. However, where the event frequency is less than the recovery time full system resilience may not be recovered before a subsequent event reduces the resilience of the road system further. In such cases the road system resilience is not restored sufficiently before the next event occurs and this can lead to a decrease in system resilience (increase in system vulnerability) over time as illustrated in Figure 19.

Figure 19 is, of course, a simplification of the real situation. For example, in order to keep the diagram relatively straighforward each event is shown at the same magnitude and the frequency is also constant for each of the two scenarios illustrated.

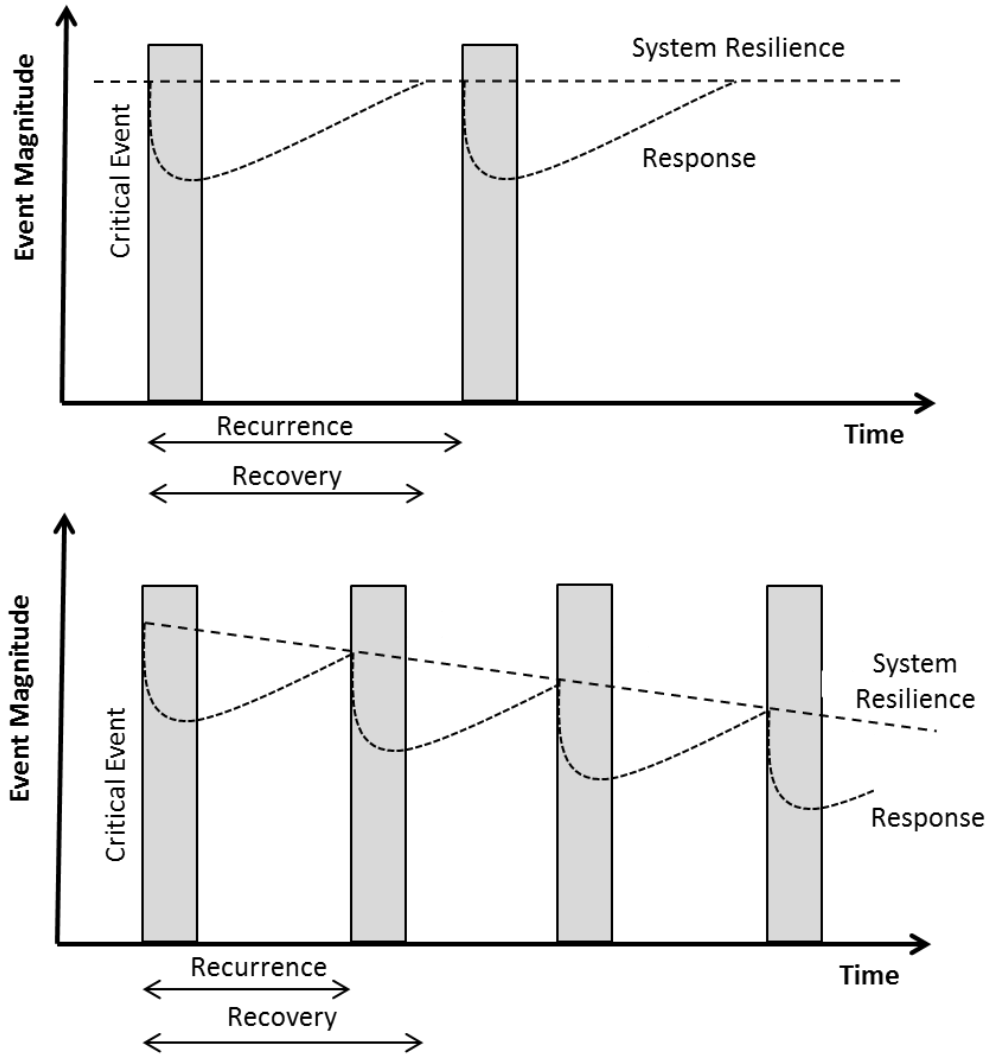

Figure 19. A simplified, conceptual illustration of the effects of repeated hazard events on infrastructure system resilience. Top (sustained resilience): When the event recurrence period is greater than the recovery period then the system resilience, of a road for example, will be retained (i.e. full system resilience recovery is possible between events). Bottom (unsustained resilience): However, if the recovery period is greater than the recurrence period there will be a decrease in system resilience over time (equally this might be considered to be an increase in system vulnerability) (from Milne et al. 2016, adapted from a diagram representing system vulnerability by Dijkstra & Dixon, 2010).

There is also a number of possible responses to the impacts of repeated hazard events on infrastructure and, while these include repeated repair, which is broadly that illustrated in Figure 19, other responses might include repair of the infrastructure in such a way as to build in greater resilience than was previously available or, indeed, to allow resilience to gradually decline as shown in the lower half of Figure 19, which over time may effectively correspond to a controlled abandonment of the infrastructure.

8 LANDSLIDE RISK REDUCTION

The primary purpose of landslide risk assessment is to enable decisions on risk reduction and, in particular, the prioritization of multiple sites that could potentially be subject to risk reduction through management and/or mitigation in the light of defined budgets.

Bromhead (1997) presented a simple, logical and philosophically consistent framework within which to describe the physical treatment of landslides, providing a useful framework for the interpretation of the detailed methods described by VanDine (1996) and Couture & VanDine (2004) for example. Winter et al. (2005; 2009) developed an approach to landslide risk reduction that accounted for management actions to reduce the vulnerability of mobile (road user) elements at risk as well as mitigation actions that reduced either the hazard or the vulnerability of the static elements at risk (infrastructure).

Winter & Bromhead (2012) brought many of these elements together in the willingness diagram (see Section 2) for both both generic forms of landslide risk reduction (Figure 20) and conceptual, approaches to landslide risk reduction (Figure 21).

Further development work was reported by Winter (2014a) to articulate a strategic approach to landslide risk reduction. This incorporates a classification scheme for landslide management and mitigation and provides a common lexicon (or group of words) that can be used to describe goals, outcomes, approaches and processes related to risk reduction, and to allow a clear and sequential focus thereon.

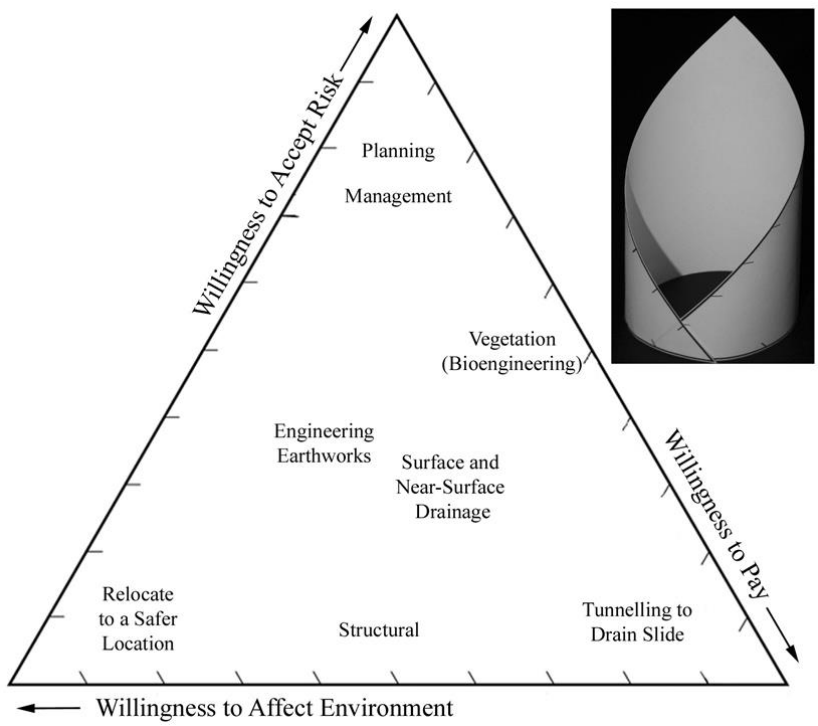

Figure 20. The 'Willingness Diagram' comparing different generic forms of landslide risk reduction. Inset: The extreme bottom-left and bottom-right corners of the ternary diagram tend to converge and the diagram might more strictly be rendered as if wrapped around a cylinder about a vertical axis.

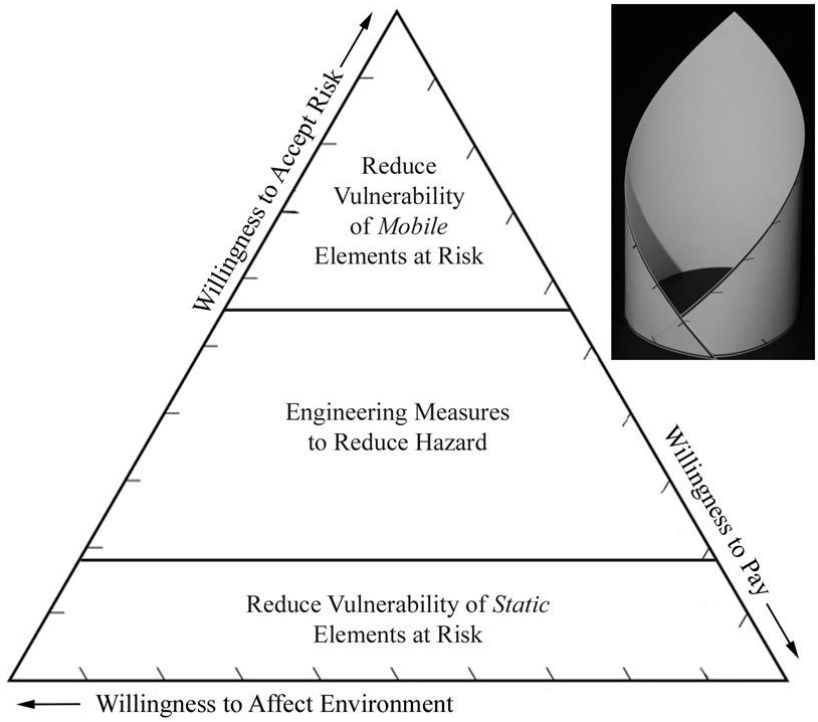

Figure 21. The 'Willingness Diagram' showing conceptual approaches to landslide remediation. Inset: The extreme bottom-left and bottom-right corners of the ternary diagram tend to converge and the diagram might more strictly be rendered as if wrapped around a cylinder about a vertical axis.

To reduce landslide risk to acceptable levels, either the potential exposure or losses (vulnerability) that are likely to arise as a result of an event, and/or the magnitude of the hazard must be addressed. Thus management strategies involve exposure reduction outcomes and mitigation strategies involve hazard reduction outcomes (Figure 22). Further, it is important that those funding such works, including infrastructure owners and local governments, are able to focus clearly on goals of, the outcomes from, and the approaches to such activities rather than the details of individual processes and techniques.

The strategic approach encourages a top-down approach to the selection of management and mitigation processes (specific measures and remedial options). It is intended to aid a focus on the primary goal of landslide risk reduction, the secondary desired outcome(s) and the tertiary generic approach to achieving that outcome rather than, initially at least, the specific measure or options (the process or processes) used to achieve that outcome.

The focus on the secondary desired outcome from risk reduction thus relates to the reduction of the exposure, or vulnerability, of the at-risk infrastructure and people (and their associated socio-economic activities) and/or reduction of the hazard itself. Hazard reduction may be achieved either directly or by reducing the vulnerability of the physical elements at risk. In a road environment the people at risk are road users, whereas in an urban setting they are residents and business people. The tertiary focus is then on the approach(es) to be used to achieve the desired outcome before specific measures and remedial options are considered. By this means a more strategic top-down approach is encouraged rather than a bottom-up approach.

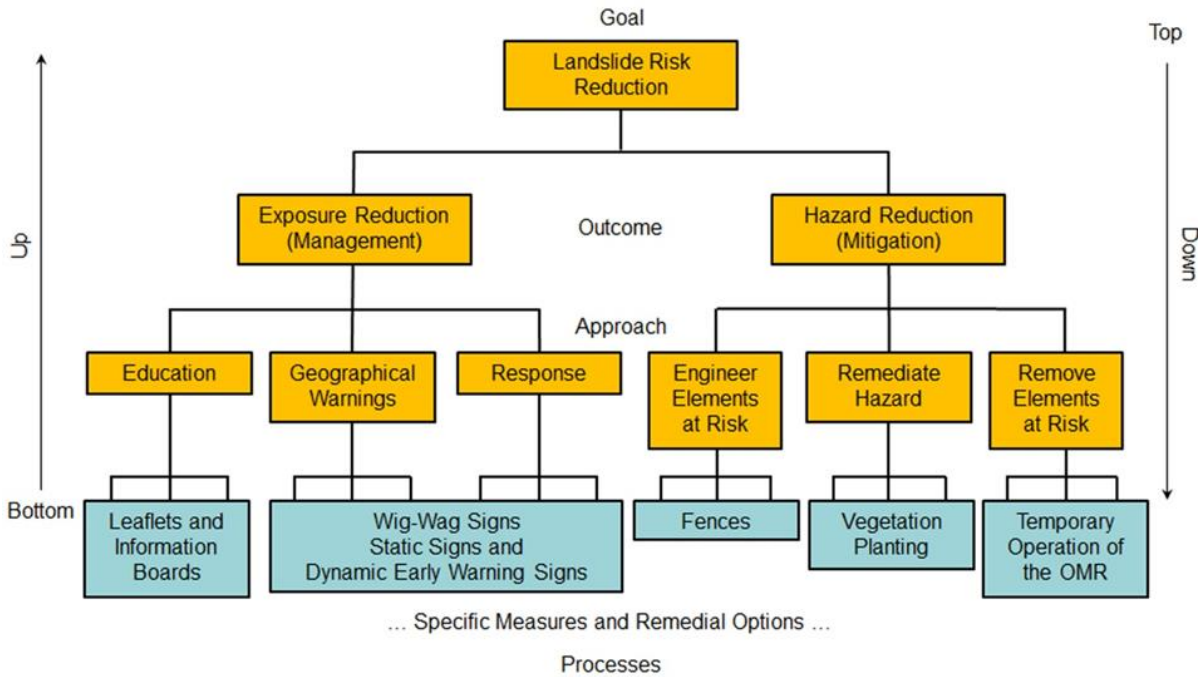

Figure 22. Classification for landslide management and mitigation to enable a strategic approach to risk reduction. The blue boxes illustrated the application of the strategic approach at the A83 Rest and be Thankful.

This approach also provides the aforementioned common lexicon for the description and discussion of landslide risk reduction strategies, which is especially useful in a multi-agency environment. It also renders a multi-faceted (holistic) approach more viable and easier to articulate while helping to ensure that the responses to the hazard and risks in play are appropriate. This approach should be especially useful for infrastructure owners and operators who must deal with multiple landslide, and other, risks, that are distributed across large networks. Such an approach promotes a considered decision-making process that takes account of both costs and benefits. It also encourages careful consideration of the right solution for each location and risk profile, potentially making best use of often limited resources.

The following sections and Figure 22 describe the strategic approach and include limited details of the application of the approach at the A83 Rest and be Thankful site in Scotland (Winter 2016a).

8.1 Exposure Reduction (Management)

Exposure reduction can take three basic forms:

- Education (and information).
- Geographical (non-temporal) warnings.
- Response (including temporal, or early, warnings).

Typically education in its broadest sense may form a key part of an information strategy. It may comprise leaflets, or other forms of communication, that are distributed in both electronic and hardcopy form. The hardcopy also may be available at rest areas for road risks and in retail outlets for urban risks. In addition, information boards may be provided in scenic rest areas, where they can be easily accessed by the public (as well as electronically). The interpretive goals embedded within the communications strategy are critical to success.

These should be specific to the setting and desired outcomes, but may for example consider the development of the landscape (including geological, geomorphological and anthropogenic processes) and set the landslide hazard and risk within that overall picture.

Geographical warning signs may be used in a variety of environments, to demonstrate the presence of landslide hazards. In a road environment they usually follow the standard warning sign form and include a graphic representing rock fall.

The responsive reduction of exposure lends itself to the use of a simple three-part management tool: Detection, Notification and Action (or DNA), providing a simple framework for management responses:

- Detection of either the occurrence of an event (e.g. monitoring, observation: Sparkes et al. 2017; 2018; Winter et al. 2017) or by the forecast of precursor conditions (e.g. rainfall: Winter et al. 2007; 2010b; 2019).
- Notification of the likely/actual occurrence of events to the authorities (e.g. in a roads environment the Police, the road. administration and the road operator).
- Action that reduces the exposure of the elements at risk to the hazard. Again, in a roads environment, this could include media announcements, the activation of geographical signs that also have a temporal aspect (e.g. flashing lights) (e.g. Winter et al. 2013b; Winter & Shearer 2017: Figure 23), the use of variable message signs, 'landslide patrols' in marked vehicles, road closures, and traffic.

8.2 Hazard Reduction (Mitigation)

The challenge with hazard reduction in Scotland often is to identify locations of sufficiently high risk to warrant spending significant sums of money on engineering works. The costs associated with installing extensive remedial works over very long lengths of road may be both unaffordable and unjustifiable and even at discrete locations the costs can be significant. Moreover the environmental impact of such engineering works should not be underestimated. Such works often have a lasting visual impact and, potentially, impact upon the surrounding environment. Such works should be limited to locations where their worth can be clearly demonstrated.

Figure 23. Temporal 'wig-wag' landslide warning signs.

In addition, actions such as ensuring that channels, gullies and other drainage features are clear and operating effectively are important in terms of hazard reduction. This requires that the maintenance regime is both routinely effective and also responsive to periods of high rainfall, flood and slope movement. Planned maintenance and construction should take the opportunity to limit hazards by incorporating suitable measures including higher capacity/better forms of drainage, or debris traps into the design. Critical review of the alignment of culverts (etc.) normally should be carried out as part of any planned maintenance or construction activities.

Beyond such relatively low cost/low impact options three categories of hazard reduction measures may be considered:

- Works to engineer, or protect the elements at risk.

- Remediation of the hazard to reduce failure probability.
- Removal, or evacuation, of the elements at risk.

There are many means of engineering or protecting the elements at risk and this approach accepts that debris flows will occur and makes provision to protect the road, thus limiting the amount of material reaching the elements at risk.

The potential structural forms for protection from debris flow include shelters, barriers and fences (Figure 24), basins, check dams and baffles. Flexible fences absorb the kinetic energy of the debris flow, thus reducing the forces that the structure must accommodate. These systems have been shown to work well, particularly for the arrest of rock fall, but all such systems require maintenance after an impact.

Figure 24. A83 Rest and be Thankful flexible debris fence.

Debris basins are formed as large decant structures, incorporating a downstream barrier that retains debris but allows water to pass. They may be used in association with lined debris channels to move material downslope where potential storage areas on the hillside are limited; lined channels may be used in isolation if storage is limited on the hillside or available only at the foot of the slope. Rigid barriers such as check dams and baffles may slow and partially arrest flows within a defined channel, and on hillsides may protect larger areas where open hillside flows are a hazard and/or channelised flows may breach the stream course. VanDine (1996) gives design and use guidance for check dams and baffles, including low cost earth mounds. Rigid barriers and debris basins 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 (Versace 2007), at a cost estimated at between €20M and €30M.

The remediation of landslide hazards to reduce the probability of failure may involve alteration of the slope profile by either cut or fill, improvement of the material strength (most often by decreasing pore water pressures), or providing force systems to counteract the tendency to move (Bromhead 1997).

The engineering options available to prevent debris flow depend upon the specific circumstances. Debris flows can be triggered from relatively small source areas, within very large areas of susceptible ground, 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 generic link between debris flows and intense rainfall is well-established and effective runoff management can reduce the potential for debris flow initiation. However, in many circumstances on-hill drainage improvement may have limited impact due to the small scale of many debris flow events. In other locations and situations positive action to improve drainage might well have a more 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.

The planting of appropriate vegetation can also contribute to the reduction of instability (Coppin & Richards 2007). Notwithstanding this, the positive effects of such measures can be difficult to quantify but include canopy interception of rainfall and subsequent evaporation, increased root water uptake, and transpiration via leaf cover, and root reinforcement. In addition, the life cycle of the vegetation planted must be considered as, depending upon the species, the climate and other conditions relevant to growth there may be a considerable period before the effects provide a meaningful positive effect on stability. In addition, future deforestation, or harvesting, must also be considered as this is widely recognised as a potential contributor to instability. Such measures do not provide instant solutions and may not always be effective in the long term, especially if commercial forestry is practised. The species planted must be appropriate to the local environment – the planting of non-native species is not allowed in most countries for example. However, the successful application of local knowledge and species can prove successful and a major planting exercise is planned as part of the long-term strategy for the A83 Rest and be Thankful site (Winter & Corby 2012).

Finally, the option of removing the elements at risk from the geographical location of the hazard remains. Typically in an urban or per-urban environment this might involve the abandonment of a settlement (Coppola et al. 2009) or in a transport context the realignment of an infrastructure route, either permanently or on a temporary basis.

It should, of course, be noted that decisions to adopt such extreme options are not taken in isolation. Road realignment might be undertaken as part of a road administration's route improvement activities in order to upgrade both the alignment and the layout of junctions, in particular to reduce road traffic collision risk, and to ensure compliance with current design standards. In cases where the debris flow risk is high and other factors indicate that some degree of reconstruction is required, road realignment may be a viable option. While road realignment has been undertaken in response to landslide activity in Scotland, it was also in response to a genuine need for realignment of the route to increase safety and to ensure compliance with current design standards.

More unusually the Old Military Road in Glen Croe (Figure 25), which is located downslope and therefore somewhat more distant from the hazards at the Rest and be Thankful, has been reopened as an emergency diversion route for periods during which the A83 strategic road is not available; during such periods an alternating, one-way convoy scheme is implemented.

Figure 25. A83 Rest and be Thankful Old Military Road and traffic convoys during a period when the A83 was closed to traffic due to a debris flow, the A83 is to the left-centre and the Old Military Road to the right-centre of the image.

9 SUMMARY AND CONCLUSIONS

In this paper a framework for risk acceptance is used to set the context for a review of the assessment of landslide hazard and risk from the regional scale (small-scale and semi-quantitative) to the site-based scale (large-scale and quantitative).

A regional, semi-quantitative assessment has been used as the basis for further work to assess

the risks related to road users (fatalities), the infrastructure and to the socio-economic activities that the road network supports and facilitates at a larger-scale.

The A83 QRA is believed to be the first full, formal quantitative risk assessment for debris flow risk to road users.

The economic impact assessment uses a bespoke methodology developed to account for all aspects of such economic impacts at specific sites and has been applied to flood events as well as to landslides. The concept of the vulnerability shadow is particularly important to developing a full understanding of such localised events that can have impacts over a significant geographic area.

The use of fragility curves to articulate the vulnerability of physical infrastructure to debris flow is described as it relates to both high-speed and low-speed roads in Scotland and the Republic of Korea. Its potential application to systems of assets, rather than component assets, is set-out in brief.

Climate change is clearly an important consideration when dealing with processes, such as debris flow, that are driven by meteorological events such as rainfall. The understanding of climate impacts is set within the Rumsfeldian context of known knowns, known unknowns and unknown unknowns, which provides a useful framework for articulating the various challenges associated with both climate change and broader issues surrounding global change.

An integrated data approach taken to an evaluation of landslide hazard and risk in the light of global change, including climate change, clearly demonstrates that the elements at risk and their vulnerability are at least as important as the hazard assessment; this conclusion is also supported by the details of the QRA at both the A83 and A85 sites.

The discussion of landslide hazard and risk assessment and of climate change is supported by information derived from assessments of flood (pluvial and coastal). The assessment of the changing economic risk over time clearly demonstrates the potential for the elements at risk and their vulnerability, driven by social and/or demographic change, to be the dominant factors in determining the level of risk rather than: the hazard. The implications of this are clear, a focus on hazards with the elements at risk and their vulnerabilities being treated almost as an afterthought is neither adequate nor acceptable; it is essential that we, as geoprofessionals, engage with other disciplines to adequately assess the elements at risk and their vulnerabilities in order to produce and collaborative effective risk assessments.

Resilience is considered in the context of climate change and the relations between event frequency (recurrence), the time required for recovery and the rate of that recovery are highlighted graphically.

Landslide risk reduction is addressed from a conceptual point of view and a strategic approach is described that offers a logical classification system and encourages a top-down approach to such activities. This helps to avoid a bottom-up approach that can encourage the sometimes inappropriate use of what has worked in the past. The strategic approach provides a common lexicon that can aid clarity of communication in multi-agency risk reduction environments. The application of this approach is demonstrated using the A83 Rest and be Thankful site as an example.

As a profession it is clear that we have some way to go in terms of integrating our approach to landslide hazard assessment with an acceptable form of landslide risk assessment. However, the progress made in the last 15 years should provide encouragement that, with adequate funding and a willingness to engage and collaborate with other professions, this is eminently achievable.

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