The physical vulnerability of roads to debris flow

La vulnérabilité physique des routes aux coulées de boue

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ABSTRACT: The physical vulnerability of roads to debris flow is expressed through fragility functions that relate flow volume to damage probabilities. Fragility relations are essential components of quantitative risk assessments (QRA) and allow for the estimation of risk within a consequence-based framework. This paper describes fragility curves produced in order to provide the conditional probability for a road to be in, or to exceed, a certain damage state for a given debris flow volume. Preliminary assessments were undertaken by means of a detailed questionnaire. Fragility curves have been defined for three damage states for high speed (reported herein) and for low speed roads (to be reported later) in order to cover the typical characteristics of roads vulnerable to debris flow. The probability of any given damage state being met or exceeded by a debris flow of a given volume (10m^3 to 100,000m^3) was derived from the mean of the responses received. The development of the fragility curves is described and data issues discussed.

RÉSUMÉ : La vulnérabilité physique des routes aux coulées de boue s'exprime à travers des fonctions de fragilité qui mettent en rapport le débit volumique et les probabilités de dommages. Les relations de fragilité sont des composantes essentielles des évaluations quantitatives de risques (QRA) et permettent d'estimer le risque au sein d'un cadre basé sur les conséquences. Cet article décrit les courbes de fragilité produites afin d'indiquer la probabilité conditionnelle qu'une route se trouve, ou dépasse, un certain état d'endommagement pour un débit volumique donné de boue. Des évaluations préliminaires ont été réalisées au moyen d'un questionnaire détaillé. Des courbes de fragilité ont été définies pour les trois états d'endommagement pour les routes à grande vitesse (présentées dans ce document) et pour les routes à petite vitesse (qui feront l'objet d'un rapport ultérieur) afin de couvrir les caractéristiques typiques des routes vulnérables au coulées de boue. La probabilité d'atteinte ou de dépassement d'un état d'endommagement donné en présence d'une coulée de boue d'un volume donné (10m^3 à 100 000m^3) a été dérivée de la moyenne des réponses reçues. L'élaboration des courbes de fragilité est décrite et les problématiques liées aux données sont abordées.

KEYWORDS: Landslides, debris flows, hazard, risk, probability, fragility, QRA.

1 INTRODUCTION

Fragility curves are a graphical means of describing the physical vulnerability of elements at risk to a given hazard. They give the conditional probability of a particular element at risk to be in, or to exceed, a certain damage state as a result of a hazard of a particular type or intensity (Mavrouli & Corominas 2010). Fragility relationships are essential components of quantitative risk assessments (QRA) as they allow for the estimation of risk within a consequence-based framework.

For the purposes of this work the element at risk is a road and the hazard is debris flow. Damage probabilities have been assigned for specific debris flow volumes; these should not be confused witht he probability of event occurence. Fragility curves have been produced which indicate the probability of a debris flow of a given volume exceeding each of three damage states. To the best of the Authors' knowledge this is the first time that fragility curves have been developed for the effects of debris flow on roads. Fragility relationships are widely adopted in seismic 'expected loss' and risk assessments, being a valuable tool to explicitly assess the vulnerability of structures to earthquake hazard (Pitilakis et al. 2006).

While several possible approaches were available, including analytical and empirical ones, for the development of fragility curves, 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.

This paper describes the questionnaire sent to experts globally to collect data for the fragility curve development. It also describes the analysis and interpretation of the data collected, and its validation using real world examples.

2 METHODOLOGY

2.1 *Road characterisation*

Many different classifications of roads could be considered, covering numerous key factors such as construction type, stiffness, and traffic speed. However, in order to reduce the questionnaire to a reasonable size some simplification was needed. Primarily it was decided that, for the purposes of this exercise, all roads could be considered to be relatively stiff and brittle (the low strain stiffness of even an unbound pavement is such that it is likely to behave in a stiff, brittle manner). In order to further simplify the analysis roads have been divided into low and high speed roads, characterized as follows:

- High speed: speed limit between 80 and 110km/h and one or more running lane in each direction, most likely in conjunction with a hardstrip 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.

The gap between the speed limits of the two classes of road, reflects 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. The results reported here are for high speed roads.

2.2 *Damage states*

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 and range from the type of damage that is unlikely to significantly affect the passage of vehicles, at least on high speed roads, to that which causes longer term damage and restrictions to the speed and/or passage of traffic.

Respondents to the survey were requested to use their expert judgement to assess the probability of each damage state being exceeded (Table 2) for a given event size. Respondents were asked to use the qualitative descriptors 'Highly Improbable' and 'Extremely Likely' with caution, and only where an extensive, high quality dataset supports the classification.

Table 1. Damage state definition.

Damage State	High Speed Roads
P1 (Limited damage)	Encroachment limited to verge/hardstrip
P2 (Serious damage)	Blockage of hardstrip and one running lane
P3 (Destroyed)	Complete blockage of carriageway and/or repairable damage to surfacing

Table 2. Description of probabilities.

Qualitative Descriptor	Description	Value for Analysis
Highly improbable	Damage state almost certainly not exceeded, but cannot be ruled out	0.000001
Improbable (remote)	Damage state only exceeded in exceptional circumstances	0.00001
Very unlikely	Damage state will only be exceeded in very unusual circumstances	0.0001
Unlikely	Damage state may be exceeded, but would not be expected to occur under normal circumstances	0.001
Likely	Damage state expected to be exceeded under normal circumstances	0.01
Very likely	Damage state expected to be exceeded	0.1
Extremely likely	Damage state is almost certainly exceeded	1.0

3 RESULTS

The questionnaire was sent to 176 experts; 47 responses (27%) were received from 17 countries: UK (34%), Greece (23%), other European countries (26%), Asia (4%), Australasia (4%), North America (4%) and the Middle East (2%). The respondents' backgrounds were Academia (32%), the Commercial Sector (51%) and Government Bodies (17%).

4 ANALYSIS

4.1 *Preliminary fragility curves*

It is a relatively straightforward matter to construct preliminary fragility curves from the average of the probability responses at each volume, at each damage state and for both high speed roads and local roads as illustrated in Figure 1. These curves have the basic attributes of typical fragility curves. In broad terms these curves and the data that underpin pass the sense test. The curves generally show that landslides of a given volume are associated with higher probabilities of exceeding a certain damage state when they affect local roads than when they affect high speed roads, as would be expected. In addition, the curves for high speed roads generally show little effect at small landslide volumes, below a few hundred cubic metres.

It is noticeable that the mean probabilities do not reach unity for any of the curves. This implies that the damage states as defined can never be met or exceeded with complete certainty. However, this is an inevitable function of using the average of the responses, as the maximum possible response coincides with the desired termination point of each curve (a volume at which exceeding the given damage state is inevitable and the probability is unity). Further stages of analysis were undertaken to interrogate and better understand the data.

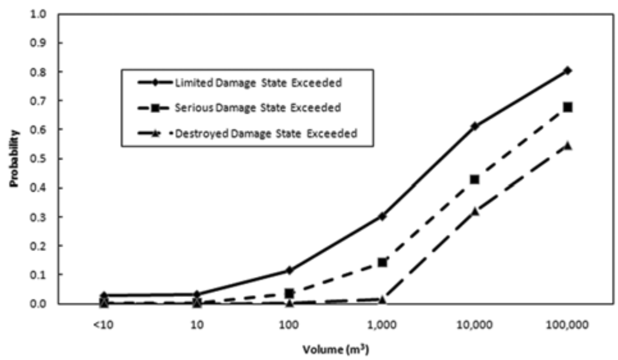

Figure 1. Preliminary fragility curves for high speed roads.

4.2 *Curve fitting*

Standard Excel^{TM} curves were fitted (third order polynomial for Limited Damage and fourth for Severe Damage and Destroyed states). This gave better separation of the individual curves than is shown in Figure 1, and there was greater contrast between the results for high speed and local roads (Pitilakis & Fotopoulou 2011). This technique allows a degree of extrapolation of the data to higher volumes/probabilities. However, over application of such extrapolation tends to distort the curves at lower volumes.

4.3 *Manual extrapolation*

The data presented in Figure 1 may be manually extrapolated by a further logarithmic cycle by visually judging the appropriate value of probability at 1,000,000m^3 in order to maintain the broad appearance and trend of the curves. It is noticeable that, even when the volume is increased to 1,000,000 m^3 in this way none of the fragility curves reach unity; only that for Limited Damage for local roads reaches a value of around 0.95.

4.4 *Weighting the data*

Clearly the experience of the respondents is a critical metric in terms of understanding, evaluating, analysing and interpreting these data. The respondents were asked to assess their experience on a scale of zero (no experience) to 10 (extensive experience). The scores of this self-assessment weight 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. It thus seems potentially appropriate to place a greater confidence in the responses received from those who reported that their level of experience was higher than the average and a number of approaches is possible.

Firstly, a weighting approach may be taken. However, care is needed to ensure that the sample is weighted rather than the individual responses; otherwise bias will be introduced into the results. (Weighting the individual responses will, depending upon the precise approach taken, either increase or decrease the individual probabilities contained within the questionnaires for those with higher expertise and the converse for those with lower levels of expertise. There is no logical justification for such a change and this should therefore be avoided.) Weighting the sample may be done as follows

$$p = \frac{\sum_{i=1}^{n} p_i E_i}{\sum_{i=1}^{n} E_i} \quad (1)$$

where p = weighted mean probability of a particular damage state being exceeded; p_i = the individual responses of the probability of a particular damage state being exceeded; E_i = the individual responses in terms of self-assessed experience; and n = the number of responses.

However, there does remain a question as to what a weighted average means and statistical advice (Sexton, pers. comm.) indicates that the results should be treated with a degree of caution.

This yields fragility curves with lower probabilities of given damage states being exceeded by a given event volume than those derived from the full data set (Figure 2). This may indicate that either those with less experience overestimate, or those with greater expertise underestimate, potential damages.

The second approach involves rejecting the data from those respondents reporting less experience, leaving only that from those who assessed themselves as more experienced in this area. Statistical advice (Sexton, Pers. Comm.) indicates that approximately only scores from the upper 25% of the available range should be examined. This implies that the analysis should be undertaken for those judging their experience level as eight or above (33% of respondents). However, plotting the data led to a rather confused picture and to the conclusion that the 16 responses corresponding to the 33% of respondents reporting their experience level to be eight or above were insufficient to present a coherent picture. As for the weighting approach the resulting fragility curves yield lower probabilities of given damage states being exceeded by a given volume of event than those derived from the full data set.

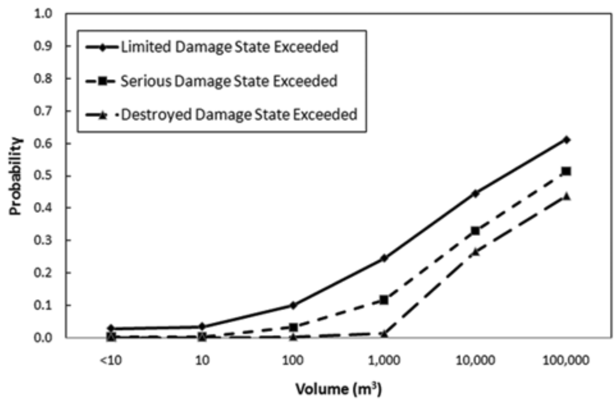

Figure 2. Weighted fragility curves: top, local roads; bottom, high speed roads.

5 INTERPRETATION

The curves illustrated in Figure 1 do not stretch between zero and unity. Even when manually extrapolated to a landslide volume of $1{,}000{,}000\text{m}^3$ the curves do not reach unity as would be expected if they had been derived from by modelling in which such an outcome would have been constrained.

Using the current approach it is inevitable that the mean probability of each damage state being reached or exceeded is less than unity unless all of the respondents return such a value. This then begs the question of how to account for such an inevitable, and seemingly contradictory, facet of the results. It is straightforward to 'force' the curves to reach to unity by a ratio approach (the forced probability at any value of landslide volume, $p_{\text{if}} = p_{\text{i}}.[1/p_{\text{n}}]$ where p_{i} is the mean probability and p_{n} is the mean probability at the maximum landslide volume).

In order to determine whether such an approach can be justified one must examine the more detailed responses of the respondents to the questionnaire and in particular the responses of those where a probability of unity was assigned to the combinations of landslide volume and damage state. These data illustrate, as might be anticipated, that the number of responses assigning a probability of unity increases markedly with landslide volume while decreasing with increased damage state severity. Most importantly, for high landslide volumes, the majority of respondents give unity for the likelihood of a given damage state being reached or exceeded, lending justification to 'forcing' the curves to reach unity.

As discussed, the preliminary fragility curves of Figure 1 can be forced to unity, and manually extrapolated to the next order of magnitude in terms of landslide volume (i.e. $1{,}000{,}000\text{m}^3$). The next logical step is to combine these two actions as illustrated in Figure 3. The curves illustrated therein conform to the 's'-shape generally perceived as being the correct form for fragility curves. Notwithstanding this, one would normally expect that the curves for different damage states would reach unity at different landslide volumes; that they do not is a function of the type of analysis undertaken and it seems reasonable, as none of the curves reach unity, to force them all to such a level at the highest volume considered.

Geographical variations and variations potentially caused by respondents' backgrounds (Academic, the Commercial Sector, and Governments) were investigated. It was concluded that the datasets were generally too small to draw definitive conclusions albeit that the data appeared to suggest that:

- Responses for the UK exhibited slightly higher probabilities for larger landslide volumes compared to those for the 'Rest of the World'.
- The responses for Academia exhibited slightly higher probabilities for larger landslide volumes compared to those for the Commercial Sector.

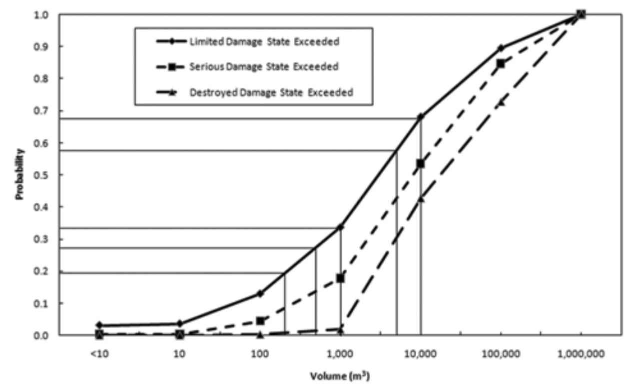

Figure 3. Fragility curves for high speed roads 'forced' to unity and manually extrapolated to the next order of magnitude of debris flow volume. Lines for Limited Damage at 200, 500, 1,000, 5,000 and $10{,}000\text{m}^3$ are also shown.

6 VALIDATION

The comments received from respondents generally supported the use of curves of the form illustrated in Figure 3 and events from Scotland in the UK and the Republic of Korea are considered here. Figure 4 illustrates hypothetically-shaped curves in which the numbers given relate to a $5{,}000\text{m}^3$ event on a high speed road (Figure 3). The probabilities (p) of the damage being equal to or greater than a given level are:

- Damage greater than or equal to 'Limited', $p = 0.6$.
- Damage greater than or equal to 'Serious', $p = 0.4$.
- Damage greater than or equal to 'Destroyed', $p = 0.3$.

The discrete, or conditional, damage state probabilities (i.e. the probabilities of the occurrence of a given damage state) are estimated from the probabilities given above:

- Probability of no damage = 1.0 - 0.6 = 0.4.
- Probability of 'Limited' damage = 0.6 – 0.4 = 0.2.
- Probability of 'Serious' damage = 0.4 – 0.3 = 0.1.
- Probability of 'Destroyed' damage state = 0.3.

Note that the conditional probability of the 'Destroyed' damage state is always equal to the probability of that state being exceeded. Vulnerability assessment using fragility curves is, of course, probabilistic in nature and the models used in their construction – in this case based upon expert judgment – have inherent uncertainties. Accordingly, the validation examples are not expected to precisely predict the observed damages.

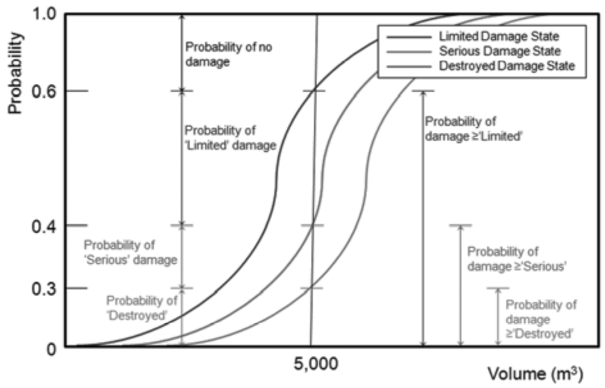

Figure 4. Hypothetical fragility curves: the numbers relate to a 5,000m^3 event on a high speed road (see Figure 3) and show conditional probabilities and those of a given event exceeding a damage state.

6.1 *A85 Glen Ogle, Scotland*

In August 2004 two debris flow events occurred at Glen Ogle blocking the A85 strategic road, culverts and other drainage features, and necessitated a full repair to the road pavement, safety barriers and parapets. 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, 2006, 2009). 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). These figures are believed to exclude material deposited on the road and it seems reasonable therefore to round these figures up to around 5,000m^3 and 10,000m^3. This illustrates the uncertainty when dealing with debris flow volumes between the amount mobilised and that deposited at road level.

Figure 4 shows how these event volumes plot on the fragility curves. 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). 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 being 0.4 seems to be broadly in line with observations in its immediate aftermath, affecting a road length of around 200m. Similarly the damage caused by the smaller event, although significantly less in terms of physical damage to the infrastructure, would also be classified as 'Destroyed' and this seems to broadly reflective the probability of 0.3 (Figure 4).

6.2 *Chuncheon National Highway, Republic of Korea*

Debris flows of around 500m^3 to 1,000m^3 were evident at the Chuncheon National Highway Tunnel Portals (Lee & Winter, 2010). 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) (Figure 4).

Only very minor damage was incurred and this reflects the small volumes and the combined conditional probabilities of 0.8 for no damage and of the 'Limited' damage. 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.

7 CONCLUSIONS

A survey of experts was conducted to develop of preliminary fragility curves for the effects of debris flows on roads.

Included in the questionnaire was the opportunity for the respondents to make 'free text' responses to defined questions. Their responses have been used, in part, to determine the form of analysis. Consequently the proposed fragility curves have been extrapolated to include events one order of magnitude greater than the largest considered in the questionnaire. In addition, this form of determining fragility curves renders it almost impossible for the probabilities to range from zero to unity; according the proposed fragility curves have been stretched to ensure such a spread.

The derived fragility curves have been compared to known events in Scotland (UK) and the Republic of Korea. In general the curves tend to give results that might be deemed 'sensible' with probabilities of around 0.3 to 0.8 being suggested for the known damage states. Exceptions to this occur when detailed site characteristics introduce complexities that are not, and could not be, accounted for in the analysis.

Notwithstanding this, the method of data acquisition and the perceived interpretations of the questionnaire for this first approach raise some interesting issues that will be explored in a later paper. Continued efforts are needed, potentially including the use of modelled and empirical data.

8 ACKNOWLEDGEMENTS

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