2006 ECI Conference on Geohazards
Lillehammer, Norway
Editors: Farrokh Nadim, Rudolf Pöttler, Herbert Einstein, Herbert Klapperich, and Steven Kramer

Year 2006 *Paper* 24

A First-Order Second-Moment Framework for Probabilistic Estimation of Vulnerability to Landslides

Marco Uzielli[*] S. Duzgun[†]
B. V. Vangelsten[‡]

[*]International Centre for Geohazards, Norwegian Geotechnical Institute
[†]Geodetic and Geographic Information Technologies Middle East Technical University
[‡]Norwegian Geotechnical Institute

A First-Order Second-Moment Framework for Probabilistic Estimation of Vulnerability to Landslides

Abstract

The object of the present paper, which synthesises a broader research effort by ICG (2006a), is the development of a probabilistic framework for the quantitative estimation of the vulnerability of the built environment to landslides. The method draws inspiration from an existing 3-dimensional qualitative framework proposed earlier by ICG (2005). As vulnerability is directly included in quantitative risk analysis (QRA), it would be beneficial to convert the conceptual framework to a quantitative perspective. It should be recognised that, in real investigations, the input parameters and the models used in vulnerability assessment are necessarily vague and imprecise, and are subjective to some degree. Thus, strong emphasis should be placed towards a consistent processing of uncertainty. A first-order second-moment (FOSM) framework, which is capable of addressing and processing uncertainties in input variables and models to provide estimates of the uncertainty in vulnerability, is proposed. Results of the proposed methodology may serve as a more rational basis for vulnerability input to QRA. The basic framework of the proposed procedure can be exported to risk analyses related to other natural hazards.

A First-Order Second-Moment Framework for Probabilistic Estimation of Vulnerability to Landslides

M. Uzielli[1], Ş. Düzgün[2] and B.V. Vangelsten[3]

[1]International Centre for Geohazards, Norwegian Geotechnical Institute, P.O. Box 3930, Ullevaal Stadion, N-0806, Oslo, Norway; PH +47-22021011; email: muz@ngi.no
[22]Geodetic and Geographic Information Technologies Middle East Technical University, 06531, Ankara, Turkey; email: duzgun@metu.edu.tr
[3]Norwegian Geotechnical Institute, P.O. Box 3930, Ullevaal Stadion, N-0806, Oslo, Norway; PH +47-22023009; email: bvv@ngi.no

Abstract

The object of the present paper, which synthesises a broader research effort by ICG (2006a), is the development of a probabilistic framework for the quantitative estimation of the vulnerability of the built environment to landslides. The method draws inspiration from an existing 3-dimensional qualitative framework proposed earlier by ICG (2005).

As vulnerability is directly included in quantitative risk analysis (QRA), it would be beneficial to convert the conceptual framework to a quantitative perspective. It should be recognised that, in real investigations, the input parameters and the models used in vulnerability assessment are necessarily vague and imprecise, and are subjective to some degree. Thus, strong emphasis should be placed towards a consistent processing of uncertainty.

A first-order second-moment (FOSM) framework, which is capable of addressing and processing uncertainties in input variables and models to provide estimates of the uncertainty in vulnerability, is proposed. Results of the proposed methodology may serve as a more rational basis for vulnerability input to QRA. The basic framework of the proposed procedure can be exported to risk analyses related to other natural hazards.

Introductory overview and reference definition of vulnerability

Landslide risk analysis is inherently complex. The greater difficulties in achieving reliable results for landslides in comparison to other natural hazards (such as earthquakes and floods) have been highlighted in the geohazards literature (e.g. Glade 2003). Such difficulties are due essentially to the complexity in modelling landslide hazard, intensity and landslide vulnerability. Glade (2003) identified several prominent factors contributing to such complexity: lack of accurate data for reliable hazard analysis; the strongly site-specific nature of landslide phenomena; the difficulty in determining the spatial extent of landslide hazard; the quantitative heterogeneity of vulnerability of different elements at risk for qualitatively similar landslide mechanisms; and temporal non-stationarity in hazard and vulnerability.

It is generally accepted that quantitative risk analysis (QRA) for natural hazards is to be preferred over qualitative analysis whenever possible, as it allows for a more explicitly objective output and an improved basis for communication between the various categories involved in technical and political decision-making. The necessity of quantifying uncertainties in existing landslide risk analysis methodologies has been emphasised (e.g. Glade 2003, ICG 2004). To allow for a more consistent integration between the analysts and the planners, the development of uncertainty-aware approaches is warranted.

In conformity with the ISSMGE Glossary of Risk Assessment Terms (e.g. http://www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf), vulnerability is defined here as "the degree of expected loss in an element or system in relation to a specific hazard." Consequently, vulnerability ranges from 0 (no loss expected) to 1 (total loss expected). This definition implies that the *physical* perspective of vulnerability is considered as opposed to the *social* perspective. ICG (2004) provided an extensive review of the various existing perspective of vulnerability assessment.

Source framework and the transition to a quantitative perspective

ICG (2005) proposed a 3-dimensional framework for the qualitative characterisation of vulnerability of the built environment to landslides. The three conceptual dimensions are represented by magnitude (M), scale of investigation (S) and elements at risk (E). As can be seen in Figure 1, landslide vulnerability takes a value on the vulnerability cube depending on the magnitude of the landslide, scale of investigation and type of element at risk.

In the source framework, vulnerability estimation is complicated by the fact that E, M and S are correlated. In addition, there exists autocorrelation in E and M; moreover, ICG (2005) highlighted the fact that E, M and S are non-stationary in time. As shown in Figure 1, depending on the time of occurrence of a landslide and the spatial extent of the landslide and elements at risk, vulnerability can take different values.

The risk assessment literature is pervaded by terminological redundancies and ambiguities, and definitions (even for the basic components of risk assessment itself) are seldom univocally accepted. ICG (2006a) suggested that, in a quantitative perspective, *exposure* [defined by Lee & Jones (2004) as "the *proportion* of each category of elements at risk expected to be affected by the landslide event"] be used in place of "elements at risk", the latter defined as "the *maximum potential value* of all vulnerable elements belonging to one category." Also, "intensity" should replace "magnitude" as the former is more directly related to damage.

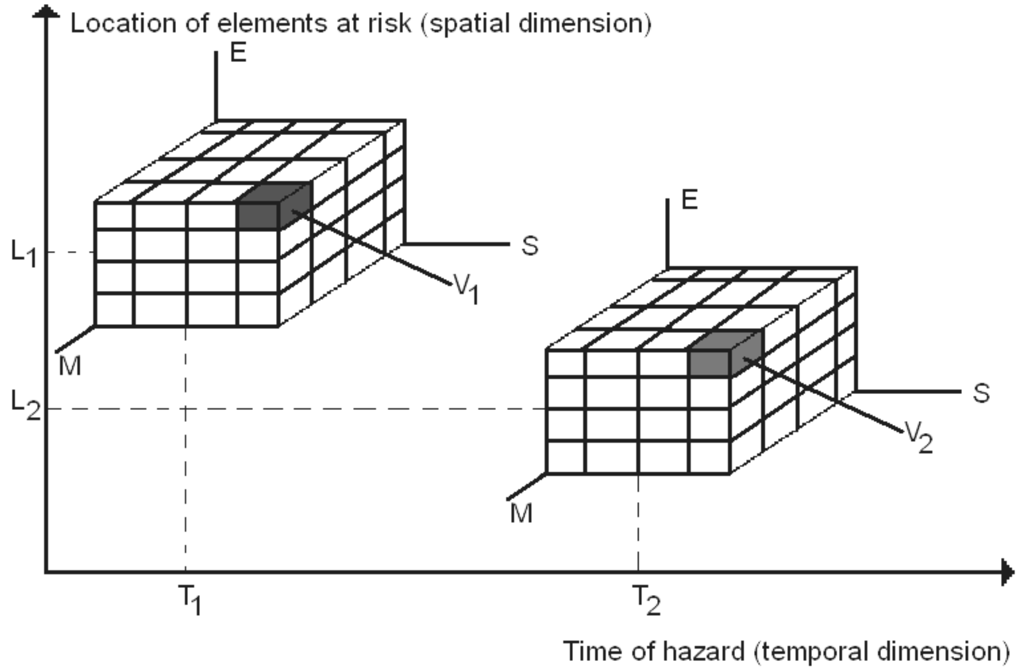

Figure 1. Visual representation of the qualitative 3-D vulnerability model and spatio-temporal variability in vulnerability

Here, *vulnerability* is defined quantitatively as the product of the random variates *intensity* and *exposure*. As discussed in ICG (2006a), utilisation of the latter terms in place of *magnitude* and *elements at risk* results in the elimination of correlations between vulnerability factors, thereby simplifying the calculation procedure.

Uncertainty: basic definitions

One of the main conceptual ambitions of the framework is the explicit consideration of uncertainty. More specifically, uncertainties in landslide intensity and elements at risk are addressed, as well as the uncertainty arising from the scale of investigation.

Total uncertainty can be subdivided broadly into aleatory and epistemic uncertainty. In the context of vulnerability assessment, aleatory uncertainty results from the variability in intensity- and exposure-related parameters in the reference area of interest. It is to be expected, for instance, that the velocity, volume and depth of a sliding mass acting on any vulnerable element would not be spatially homogeneous. Intuitively, it may be understood that the degree of heterogeneity (and, consequently, the magnitude of aleatory uncertainty) are related to the scale of investigation at which the analysis is performed.

Epistemic uncertainty is conceptually related to the limitations which are inherent to the measurement and estimation of runout parameters (e.g. velocity, volume, depth of a landslide), and to the derivation of intensity parameters from the outputs of runout analysis itself. It is composed essentially of measurement uncertainty, statistical estimation uncertainty and transformation uncertainty. Statistical estimation error results from bias in sample statistics due to limited numerosity in samples of measured parameters. Measurement uncertainty results from equipment, operator/procedural and random measurement effects. Transformation uncertainty is due to the approximations and simplifications inherent in empirical, semi-empirical, experimental or theoretical models used to relate measured quantities to intensity and exposure parameters.

The absolute and relative magnitudes of aleatory and epistemic uncertainty are markedly case-specific. A substantial difference should be emphasised: while epistemic uncertainty can be reduced by increasing the amount of data, aleatory uncertainty may remain unchanged, or even increase, with additional data. Aleatory and epistemic uncertainties, as is generally the case, are assumed to be mutually uncorrelated. A detailed insight into the components of uncertainty as defined above is provided in ICG (2006b).

FOSM vulnerability modelling

Probabilistic quantification of vulnerability is attempted by means of an approach relying on first-order second-moment (FOSM) approximation of uncertainty (e.g. Melchers 1999). The basis of FOSM lies in the statement that satisfactory estimates of the parameters of a distribution (which may be unknown) may be given by first-order approximations of Taylor series expansions of second-moment parameters (e.g. mean and variance) of a random variable calculated from samples. The FOSM framework addresses and processes uncertainties in input variables to provide estimates of the uncertainty in vulnerability.

It should be remarked that a strictly objective estimation of vulnerability to landslides is not feasible at present. It is to be expected that there will always be a degree of subjectivity in the quantification of parameters and in the formulation of models. While it would be advantageous to rely on a conspicuous bulk of measurements and reliable models, the importance of engineering judgement and expertise should not be downplayed. In any case, it is deemed worthy to propose a methodology which may address the problem in a quantitative, uncertainty-aware perspective.

In operational terms, FOSM analysis requires at least the definition of a central value and a measure of dispersion (e.g. variance, coefficient of variation). Here, the central value is termed *nominal value*. Nominal values, which represent the “most appropriate” value of a parameter for a specific type of analysis, may be assigned objectively or subjectively, depending on the amount and quality of available knowledge, experience and/or data. As the procedure operates at an areal level rather than at element-level, nominal values could, for instance, be related to statistical means.

In the present framework, uncertainty is represented by coefficients of variation (COV). In its most general definition, the COV of a set of values is given by the ratio between its standard deviation and its expected value. COVs can be assigned objectively, on the basis of: (a) available quantitative knowledge and/or data; or (b) subjectively, for instance on the basis of the “rule of thumb” provided by Harr (1987), by which "coefficients of variation below 10% are thought to be low, between 15% and 30% moderate, and greater than 30%, high." Sets of literature values of coefficients of variation for parameters pertinent to civil and geotechnical engineering are provided, for instance, by Harr (1987) and Phoon & Kulhawy (1999).

Second-moment modelling of exposure

The exposure of a category of elements at risk [Z_j] is calculated (or assigned) by the user in the range [0,1] on the basis of subjective or objective knowledge. Conceptually, it may be thought of as a "degree of presence and/or density" of elements in the spatial extension under investigation. A general model for the nominal value of exposure is proposed:

$$Z_j = 1 - \prod_{k=1}^{n_j} \left(1 - \rho_{j,k}\right) \tag{1}$$

in which $\rho_{j,k}$ are representative (e.g. average, weighted average or other) values for the $n_j \geq 1$ *exposure factors* [each defined in the range 0-1] contributing to the definition of category exposure. ICG (2006) provided a description of the main exposure factors for each category. From the previous definitions, it is seen that Z_j is also defined in the range [0,1].

The aleatory uncertainty in elements at risk is related to the homogeneity of category exposure inside the reference area. The conceptual link to the scale of investigation is evident, as a spatially extended area would probably display a larger variety of exposure for a given category of elements at risk.

To account for the aleatory uncertainty in category exposure, the COV of aleatory uncertainty of category exposure is defined:

$$COV_{aZ_j}^2 = \sum_{k=1}^{n_j} COV_{a\rho_{j,k}}^2 \tag{2}$$

in which $COV_{a\rho_{j,k}}$ is representative of the aleatory uncertainty in the *k*-th exposure factor. Similarly, the COV of epistemic uncertainty of category exposure is:

$$COV_{eZ_j}^2 = \sum_{k=1}^{n_j} COV_{e\rho_{j,k}}^2 \tag{3}$$

in which $COV_{e\rho_{j,k}}$ is representative of the epistemic uncertainty in the *k*-th exposure factor. It is assumed that epistemic and aleatory uncertainties are mutually uncorrelated for each exposure factor, and that exposure factors are mutually uncorrelated. Models for the calculation of the exposure for the several categories of elements at risk have been proposed by ICG (2006a). Other exposure models may be used, provided they are consistent with the framework's requirements.

Second-moment modelling of intensity

While there is no general consensus in the literature on a quantitative landslide intensity parameter (Hungr 1997), research efforts have related landslide-induced damage to kinetic energy of landslides and/or to their spatial features (e.g. volume, area, depth).

Epistemic uncertainty in the kinetic intensity component is due to uncertainty in nominal velocity (i.e. measurement error), in the (statistical) estimation error in the definition of the nominal value, and in the uncertainty inherent to the proposed model. Aleatory uncertainty in kinetic intensity results from the spatial variability of runout velocity in the area under investigation, and is accounted for in the model through the scale of investigation. On the basis of the above, it is recognised that there is no correlation between the epistemic and the aleatory uncertainties in kinetic intensity.

The spatial intensity component accounts for the magnitude of spatial impact, and may be defined as a spatial impact ratio. Epistemic uncertainty in spatial intensity is due to uncertainties in measurement of dimensional parameters of the reference landslide and of the built environment. As explained in ICG (2006a), there is no aleatory uncertainty in spatial intensity. To characterize the intensity parameter in the second-moment sense, first-order second-moment approximation of the product of random variates (e.g. Melchers 1999) is used for the calculation of the nominal value and the coefficients of variation of epistemic and aleatory uncertainty of intensity for the *j*-th category:

$$W_{n,j} = W_{nK,j} \cdot W_{nS,j} \tag{4}$$

$$COV^2_{eW,j} = COV^2_{eW_K,j} + COV^2_{eW_S,j} + COV^2_{eW_K,j} \cdot COV^2_{eW_S,j} \tag{5}$$

$$COV_{aW,j} = COV_{aW_K,j} \tag{6}$$

in which $W_{nK,j}$ and $W_{nS,j}$ are the nominal values of the kinetic and spatial intensity components, respectively; $COV_{eW_K,j}$ is the COV of epistemic uncertainty in kinetic intensity; $COV_{eW_S,j}$ is the COV of epistemic uncertainty in spatial intensity; and $COV_{aW_K,j}$ is the COV of aleatory uncertainty in kinetic intensity.

ICG (2006a) proposed models for kinetic and (category-specific) spatial intensity. However, any kinetic and spatial intensity parameters may be used, provided they are compatible with the proposed framework.

Scale of investigation

Scale of investigation is related to aleatory uncertainty (i.e. essentially to the spatial variability in the area of interest) in vulnerability factors. For each category, a COV of category homogeneity [$COV_{S,j}$] can be assigned to account for the degree of spatial homogeneity of W_j and Z_j in the reference vulnerable system:

$$COV_{S,j}^2 = COV_{aW,j}^2 + COV_{aZ,j}^2 \tag{7}$$

in which $COV_{aZ,j}^2$ and $COV_{aW,j}^2$ are representative of the aleatory uncertainties in Z_j and W_j, respectively, and are calculated as detailed in Eq. (2) and Eq. (6), respectively.

Second-moment vulnerability approximation

The vulnerability of the *j*-th category is expressed in the second-moment sense. From FOSM approximation of the product of independent variates, the nominal value and the COV of vulnerability are given by, respectively:

$$V_{n,j} = W_{n,j} \cdot Z_{n,j} \tag{8}$$

$$COV^2(V_j) = \left(1 + COV_{eZ,j}^2\right)\left(1 + COV_{eW,j}^2\right)\left(1 + COV_{S,j}^2\right) - 1 \tag{9}$$

It may be seen that the scale of investigation only appears in Eq. (9), i.e. in the quantification of the *uncertainty* in the estimate of nominal vulnerability.

Conclusions

This paper has summarised some of the main phases of a methodology proposed by ICG (2006a) for the second-moment estimation of vulnerability of the built environment to landslides. Synthetic insights were provided for basic definitions, first-order second-moment approximation and uncertainty categories; a qualitative source framework by ICG (2005) was briefly reviewed. Approaches for second-moment modelling of vulnerability factors (i.e. intensity, exposure, scale of investigation) were illustrated, as well as first-order second-moment estimation of vulnerability.

Application of the proposed framework to case-studies (ICG 2006c) confirmed the relevance of uncertainties in the estimation of vulnerability to landslides.

More reliable models, as well as the availability of more objective data regarding the damaging effects of landslides, could improve the methodology's capability to provide rational assessment of epistemic uncertainty in vulnerability estimation without requiring modification of the probabilistic framework presented herein.

References

Glade, T. (2003). “Vulnerability assessment in landslide risk analysis.” *Die Erde*, 134, 121-138.

Harr, M.E. (1987). *Reliability-based design in civil engineering*. Mc Graw – Hill, New York, NY.

Hungr, O. (1997). *Some methods of landslide intensity mapping.* Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, 19-21 February 1997, Balkema, Rotterdam, pp. 215-226.

ICG - International Centre for Geohazards (2004). *Risk and vulnerability for geohazards – Vulnerability in relation to risk management of natural hazards.* ICG Report 2004-2-3, Oslo.

ICG - International Centre for Geohazards (2005). *Risk assessment for earthquakes and landslides – Generalised Integrated Risk Assessment Framework.* ICG Report 2005-3-1, Oslo.

ICG - International Centre for Geohazards (2006a). *Vulnerability and risk assessment for geohazards. First-order second-moment probabilistic estimation of vulnerability to landslides.* ICG Report 2006-2-7, Oslo.

ICG - International Centre for Geohazards (2006b). *Vulnerability and risk assessment for geohazards. A general framework for second-moment uncertainty modelling.* ICG Report 2006-2-3, Oslo.

ICG - International Centre for Geohazards (2006c). *Vulnerability and risk assessment for geohazards. Slopes in clays: case study.* ICG Report 2006-2-1, Oslo.

Lee, E.M. and Jones, K.C. (2004). *Landslide risk assessment*. Thomas Telford, London.

Melchers, R.E. (1999). *Structural reliability – Analysis and prediction* (2nd Edition). John Wiley & Sons, Chichester.

Phoon, K.-K. and Kulhawy, F.H. (1999a). “Characterisation of geotechnical variability.” *Canadian Geotechnical Journal*, 36, 612-624.