Quantification of Engineering Geological Parameters

GIS-based Slope Instability Hazard and Risk Assessment

By Niek Rengers, Marco Huisman, Robert Hack and Jan Rupke

The identification, analysis, as well as mapping of geo-dynamical phenomena have always been considered to be of great importance in engineering geology. Much time and effort in particular has been devoted to the mapping of the occurrences of slope instability and to describe the relevant processes and triggering mechanisms.

The United Nations International Decade of Natural Disaster Reduction (IDNDR 1990 - 2000) has focused on the important influence of natural disasters on the security of the world's population and on its impact on the economical development of (specially) the poor countries. One of the main conclusions of the IDNDR was that geo-phenomena leading to natural disasters should be approached in a more exact way leading to quantitative concepts such as "hazard", "vulnerability" and "risk". Such a more quantitative approach allows for the development of "risk scenarios", that yield quantitative information on the spatial and temporal distribution of risk levels. This kind of information is absolutely indispensable for the selection of the most appropriate construction sites and for the definition of the most effective "risk reduction" activities.

Hazard, vulnerability and risk

Widely used internationally are the following definitions of hazard, vulnerability and risk in the context of natural hazards (12):

"Hazard" is defined as the "probability of occurrence of a potentially damaging phenomenon in a specified period of time within a given area". A slope instability hazard zonation (map) thus gives a spatial (for a given area) and temporal (for a defined period of for example 50 or 100 years) quantification of the probability of occurrence of a slope instability phenomenon. Such a hazard map yields much more information than just an "occurrence map" of the slope instability phenomena.

An important problem encountered in the preparation of slope instability hazard maps is the quantification of the temporal aspect. For this reason slope instability hazard zonation (maps) usually show only zones of equal hazard level where the probability of occurrence is defined in qualitative terms such as "high", "intermediate" and "low".

"Vulnerability" describes the expected degree of loss of the population, built-up structure or other infrastructure, as well as the loss of economical potential of an area, due to the occurrence of a natural hazard of a certain type and magnitude. The vulnerability is quantified in numbers between 0 and 1 (or as a percentage) to indicate which fraction of the population or of the "value" of the infrastructure is lost when the identified hazardous phenomenon occurs.

"Risk" is the (temporal and spatial) probability of quantified losses. Risk can be determined separately for population, for infrastructure, as well as for economic activity, and separately for various types of natural hazards (earthquakes, flooding, volcanism, slope instability). A complete inventory of the various types of risks in an area (risk scenario) makes visible in a quantitative way which parts of the population, the infrastructure, or the economic activity are most endangered.

With properly developed slope instability risk scenarios, risk reduction measures can be se-

Quantifizierung ingenieurgeologischer Parameter in Hanginstabilitäts- und Risikobewertung auf GIS-Basis

Die Arbeit behandelt die Konzepte von Risikoabschätzung und Vulnerabilität von Naturgefahren. Die Anwendung solcher Konzepte, die sehr wichtig für die Entwicklung von Risiko-Szenarien für Massenbewegungen sind, ist nur möglich, wenn die auslösenden Parameter für Massenbewegungen in Raum und Zeit in einer stärker quantitativ orientierten Art definiert werden können. Dies wird mit drei Beispielen von Massenbewegungs-Parametern illustriert, die deutliche räumliche und zeitliche Variationen aufweisen: Grundwasser und Porenwasserdruck, bebeninduzierte Bodenbewegungen und Abnahme der Festigkeitsparameter infolge von Verwitterung.

The paper describes the concepts of hazard, vulnerability and risk of natural hazards. The use of these concepts, which is important for the development of landslide risk scenarios, is only possible when the parameters which lead to landsliding can be defined temporally and spatially in a more quantitative way. This is illustrated with three examples of parameters of landsliding that show important spatial and temporal variation: groundwater level and pressure, earthquake induced ground motion, and degradation of strength parameters due to weathering.

lected, such as slope stability improvement measures (support, drainage) along road alignments, or relocation of population or structures.

A risk scenario allows the population at a local level to take decisions as to where the available money as well as other efforts or measures can be applied most effectively to reduce the identified risks in the most effective way. An important conclusion of the foregoing is that quantitative information on the parameters governing the hazardous processes is indispensable for effective risk reduction.

Quantification of parameters used for the spatial and temporal modelling in GIS

The quantitative determination of slope instability hazard and specifically its temporal aspect can only be achieved in a process of indirect hazard mapping, in which the most relevant parameters in the instability process are separately quantified and combined in GIS in an algorithm.

Recent research developments in spatial and temporal deterministic modelling of slope instability, have concentrated on the quantification of a number of the key parameters such as slope hydrology, ground motion due to seismic events, and the deterioration of geotechnical parameters due to weathering.

Geo Information Systems (GIS) are powerful spatial database software packages, that allow for the handling and integration of (geographically defined) spatial data from various origins (e.g. topography, geology, land use, hydrology) which is necessary in indirect hazard mapping. For more information on the use of GIS for landslide hazard analysis (13, 14).

Spatial modelling with GIS can be based on statistical and on deterministic modelling methods. Statistical methods are based on the analysis of the interrelationships between landscape factors (input as factor maps) with the observed occurrence of slope instability phenomena. Spatial extrapolation possibilities are limited to areas where landsliding processes are described with the same algorithm for the integration of factor maps. Temporal extrapolation (prediction) is possible only as long as extreme events are present in the data set used for the analysis. Deterministic methods are based on the use of slope stability calculation formulas with the input of terrain form, groundwater and seismic conditions as well as geotechnical parameters that are determined in the field or in the laboratory. These parameters can show spatial as well as temporal variations and both variations have to be defined quantitatively in the modelling in order to arrive at a true quantitative hazard assessment.

The concept of temporal and spatial variation of three predominant parameters for slope instability will be discussed shortly:

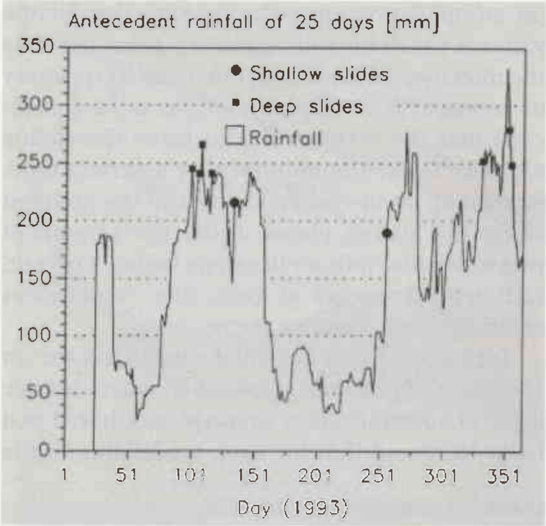

Fig. 1 Antecedent rainfall of 25 days and deep landslide events in 1993 as a function of time in a study area near Manizales (Colombia), after (11).

Bild 1 *Vorausgegangener Niederschlag der letzten 25 Tage und tiefe Hangrutschereignisse im Jahr 1993 als Funktion der Zeit in einem Untersuchungsgebiet nahe Manizales (Kolumbien), nach (11).*

- level and pressure of groundwater,
- frequency/intensity characteristics of earthquake induced ground motion,
- weathering of rock and soil mass parameters.

Level and pressure of groundwater

It has long been observed that landslide activity is strongly influenced by rainfall. This relationship is based on the concept that slope instability is triggered by water that infiltrates into the sliding mass and reaches the sliding plane to build up an uplift pressure. The time needed for the water to reach the sliding plane is determined by the thickness of the sliding mass and its (primary or secondary) permeability. It has to be considered that the water will also leave the sliding plane by underground flow after a certain time, depending on the permeability and the gradient along the sliding plane. Thus, the amount of rainwater that falls on the slope within a certain well-defined period of time (the "antecedent rainfall") is the decisive factor.

Terlien (11) has modelled this in GIS for an area near Manizales in Colombia, where a thick layer of volcanic ashes overlays weathered bed rock. He found that for deep landsliding of the complete ash cover over the weathered bedrock the antecedent rainfall of periods of 25 days was critical and that for shallow landsliding within the ash cover a period of antecedent rainfall of only 1 or 2 days was critical (Figure 1).

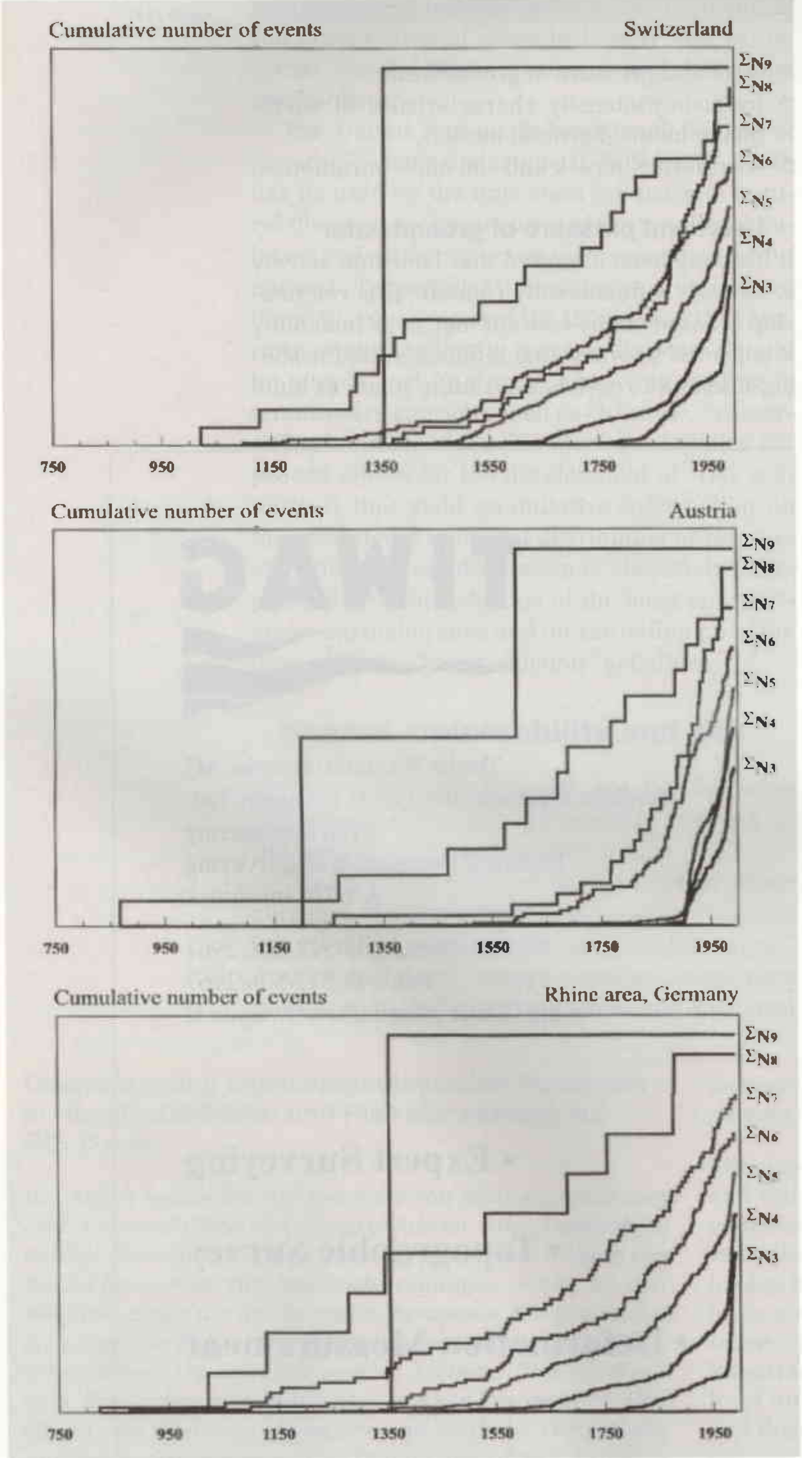

Fig. 2 Representation of the temporal course of the frequency of earthquakes for single intensity classes in Switzerland, Austria and the Rhine area in Germany. (N_9 = number of events ≥ 9 and <10).

Bild 2 *Darstellung der Erdbebenhäufigkeiten für einzelne Intensitätsklassen in der Schweiz, in Österreich und im Rheintal in Deutschland. ($N9$ = Anzahl der Ereignisse ≥ 9 und < 10.).*

As a result of this more precise quantification of the relationship between rainfall and landslide activity, the local monitoring of (antecedent) rainfall can be used to give early warnings for the occurrence of landsliding in that area. But as well this knowledge can be used to predict from long time range observations of rainfall characteristics, how often the critical amount of (antecedent) rainfall that will trigger landsliding will occur in the future (recurrence interval).

Earthquake induced ground motion

Another factor known to be triggering landslides is ground motion due to seismic events (earthquakes). Vertical as well as horizontal acceleration influence the resisting and driving forces of a potential sliding body. At higher values of the intensity of the ground motion this may lead to triggering of a landslide which would normally remain stable.

There is still much to be done in deterministic spatial (GIS-) modelling, to quantify the influence of seismicity on the occurrence of landsliding, but the quantification of the seismic hazard is the topic of extensive research work in many areas in the world.

Gruenthal et al. (4) have analysed the temporal and spatial patterns of ground motion records over long periods of time in Germany, Austria and Switzerland. They have subdivided this area in regions and have presented intensity/frequency graphs for each of these regions (Figure 2). This intensity/frequency information can be used to better quantify the influence of seismicity as a triggering factor for landsliding hazard.

The combination of adverse conditions of groundwater and seismicity will even further reduce the stability of a slope. The likelihood of the coincidence of both factors at the same time is certainly not very high, but can be determined quantitatively. This again is important for the determination of the hazard of occurrence of large scale landsliding, which is unlikely to occur without the coincidence of both factors.

Quantification of weathering and degradation of rock and soil masses

Many economically hazardous and potentially life-threatening mass movements in man-made as well as natural slopes are caused by degradation of soil and rock under the influence of erosion and weathering (6). Whereas in general the temporal behaviour of the civil engineering structure can be predicted for its envisaged engineering lifetime (in general 50 to 100 years), the degradation of soil and rock within this lifetime is only partially understood and generally relations are not quantified (1, 2, 7).

The understanding and quantification of degradation of soil and rock masses, and its impact on slope stability, is required for sustainable development in civil and environmental engineering, but is also needed by insurance and civil engineering companies to predict and to limit future economic and environmental risks due to civil engineering and infrastructure works. In a research programme of ITC (International Institute for Aerospace Survey and Earth Sciences, Delft, the Netherlands) an attempt is made to quantify the state of weathering of a rock or soil mass, as well as the further degradation of soil and rock quality over a period of 50 to 100 years. As a part of this research a slope stability study was carried out at a road construction project along the CN-420 road near Tarragona, Spain. One of the road cuts made during this project is presented here as an example of quantifying variable weathering and the stability of two slopes on a project scale.

The geology of the area around the project site is rather complicated from an engineering point of view. The road alignment runs through Carboniferous partially metamorphosed sedimentary rocks, with a low friction angle on the discontinuity planes (about 32-35°), and several intrusive dykes. Three lithologies are distinguished in the cuts:

- pizarra gris (a grey slate),
- arenisca gris (a grey metamorphosed sandstone), and
- the porfido granitico (a grey-white to yellow granodiorite).

It is to be noted that within these units the degree of weathering changes dramatically from one location to another. Both the carboniferous rocks and the intrusives may occur as fresh to slightly weathered material as well as completely weathered material or residual soil, and this

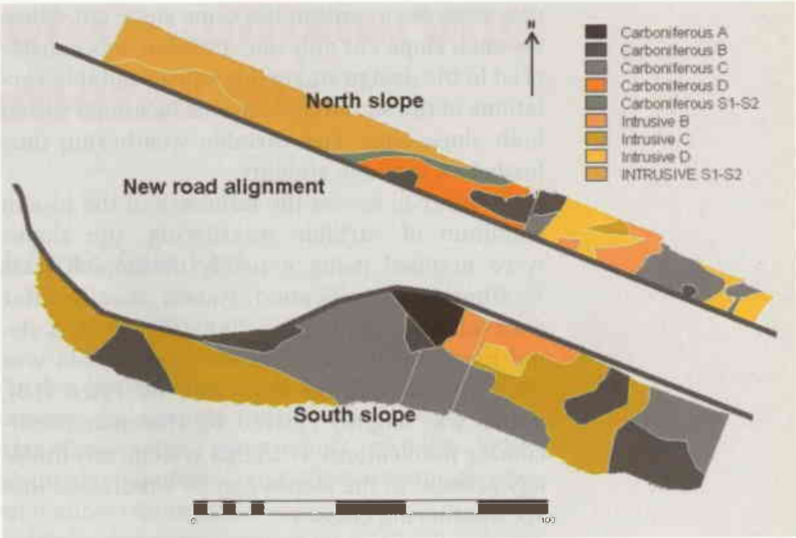

Fig. 3 The division of road cuts into units based on lithology and weathering. The coloured parts are the cuts on either side of this alignment. Scale in metres (3).

Bild 3 *Die Einteilung von Straßenanschnitten in Homogenitätsbereiche basierend auf Lithologie und Verwitterungszustand. Die farbigen Bereiche sind die Anschnitte auf beiden Seiten der Trasse, Maßstab in Metern (3).*

may even occur within the same slope cut. Since for each slope cut only one gradient was considered in the design stage, this causes notable variations of the stability at various locations within both slope cuts. The variable weathering thus leads to a variable stability.

In order to assess the influence of the in-situ condition of variable weathering, the slopes were mapped using a newly developed mass weathering classification system shortly after excavation, in September 2000 (Figure 3). A visual mass weathering classification system was used similar to that suggested by Price (10), which was slightly revised by Huisman (forthcoming publication). With this system, any lithology present in the slopes can be subdivided into six weathering classes:

A effectively unweathered,
B slightly weathered,
C significantly weathered,
D severely weathered,
S1 geotechnical soil (without relict discontinuities),
S2 *geotechnical soil* (with relict discontinuities).

This visual classification then leads to the subdivision of the cuts into zones, each described by a combination of lithology and a weathering class ("unit"). In general, all combination units present in a slope were accessible for testing at some point or another and the gathered data was also assigned to any inaccessible zones with the same combination of weathering degree and lithology. This zonation introduced a simplification, but that was accepted as an efficient way of quantifying the spatial variation of the strength characteristics of a large slope cut. Rock mass classifications were made with the SSPC system (5), which provided discontinuity orientations and strength characteristics.

The slope geometry was put in a GIS (ILWIS 2.23) together with the outline of the identified units and the strength data. Figure 3 is a map showing a top view of the studied road cut with the identified lithologies and weathering classes. In the GIS model, slope failure analysis is done for both planar and wedge failure.

Planar failure is assessed using standard equations for this factor of safety (8) and involves data such as the dip and dip direction of the discontinuities, the slope orientation and gradient, as well as the friction angles on the discontinuity planes.

For wedge failure the GIS model first determines whether or not there are intersecting discontinuities that fulfil the condition of a daylighting line of intersection in the free slope face, based on the discontinuity orientations and dips measured in the field. The method as described by Low (9) is used to calculate the factor of safety.

This approach leads to a value for the factor of safety for each pixel of the model. In this way, quantitative stability maps can be made. Another possibility that this model presents is to calculate critical slope heights and gradients at a given orientation and therefore it is applicable in the design stage of a project as well. This, however, will require detailed knowledge on the rock mass that is to be excavated which in part may be derived from extrapolating data from existing near-by outcrops.

Two considerations about the study described above have to be mentioned. First of all, one should ideally be able to quantitatively relate the rock mass properties to the degree of weathering. Second, since the weathering degree of a rock mass will change with time, the zonation of a slope into units as described above is only valid for a specific moment in time (i.e. the time of observation). By quantifying the degradation processes that will occur in that slope, the zonation can be extrapolated into the future as a function of time. Both these considerations are currently investigated at ITC and are part of ongoing research by the authors.

References

1. Cragg, D.J. ; Ingman, J.: Rock weathering descriptions: current difficulties. In: *Quarterly Journal of Engineering Geology* 28 (1995), pp. 277-286.
2. Fookes, P.G. ; Gourley, C.S. ; Ohikere, C.: Rock weathering in engineering time. In: *Quarterly Journal of Engineering Geology* 21 (1988), pp. 33-57.
3. Franco Rodriguez, D.Y. (2001): *Slope stability and differential weathering along the road N420 near Tarragona, modelled in GIS*. M.Sc. thesis, International Institute for Aerospace Survey and Earth Sciences – ITC, Delft, 2001.
4. Gruenthal, G. ; Mayer-Rosa, D. ; Lenhardt, W.A.: Abschätzung der Erdbebengefährdung für die D-A-CH-Staaten – Deutschland, Österreich, Schweiz. In: *Bautechnik* 75 (1998), Nr. 10, pp. 3-17.
5. Hack, H.R.G.K.: *Slope Stability Probability Classification*. International Institute for Aerospace Survey and Earth Sciences – ITC, Delft, 1998.
6. Hencher, S.R. ; McNicholl, D.P.: Engineering in weathered rock. In. *Quarterly Journal of Engineering Geology* 28 (1995), pp. 253-266.
7. Hill, S.E. ; Rosenbaum, M.S.: Assessing the significant factors in a rock weathering system. In: *Quarterly Journal of Engineering Geology* 31 (1998), pp. 85-94.
8. Hoek, E. ; Bray, J.: *Rock slope engineering*. Institute of Mining and Metallurgy, London, 1981.
9. Low, B.K.: Reliability analysis of rock wedges. In: *Journal of Geotechnical and Geoenvironmental Engineering*, June 1997, pp. 498-505.
10. Price, D.G.: A suggested method for the classification of rock mass weathering by a ratings system. In: *Quarterly Journal of Engineering Geology* 26 (1993), pp. 69-76.
11. Terlien, M.T.J.: *Modelling Spatial and Temporal Variations in Rainfall-Triggered Landslides*. PhD Thesis of Utrecht University, ITC Publication Nr. 32, 1996.
12. Varnes, D.J.: *Landslide Hazard Zonation: a review of principles and practice*. UNESCO, Natural Hazards, No. 3, 1984.
13. Van Westen, C.J.: *Application of Geographic Information Systems to Landslide Hazard Zonation*. PhD Thesis Delft University of Technology, ITC Publication Nr. 15, 1993.
14. Van Westen, C.J. ; Van Duren, I. ; Kruse, H.M.G. ; Terlien M.T.J: GISSIZ – Training Package for Geographic Information Systems in Slope Instability Zonation. ITC Publication Nr. 15, Vol. 2, 1993.

Authors

Dr.-Ing. Niek Rengers, Ir. Marco Huisman, Dr. Robert Hack and Dr. Jan Rupke, International Institute for Aerospace Survey and Earth Sciences (ITC), Kanaalweg 3, NL-2628-EB Delft, the Netherlands, E-Mail huisman@itc.nl