SUCCESSES AND FAILURES IN FIGHTING LANDSLIDES: SOME EXPERIENCES FROM ITALY AND ELSEWHERE

By Paolo Canuti, Nicola Casagli, Filippo Catani;
Earth Science Department, University of Firenze

ABSTRACT

When is an action taken to cope with a hazardous mass movement considered a success ? When is it necessary to admit failure ? This paper attempts to give an answer to these questions by examining the three main aspects of a landslide risk management programme: prediction, prevention (or mitigation) and emergency planning. Examples of successes and failures are given with reference to some of the best known case histories that have occurred, more or less recently, in Italy and elsewhere in the world. The recent developments of scientific research regarding the different aspects of landslide risk management are briefly outlined.

As far as the prediction phase is concerned, the state-of-the-art on landslide risk assessment and the basic differences between spatial and temporal prediction are briefly summarized and discussed. The GIS database of the Emilia-Romagna region, containing over 30 000 individual landslides, is presented as a successful example of a spatial prediction containing elements for temporal forecasting. The exceptional 1996 Versilia rainstorm that triggered more than 450 debris flows, causing 13 casualties, is described as a representative case of an unpredictable event.

A general framework for the main strategies and techniques employed for landslide risk prevention is proposed. A successful case history, the urban transformation accomplished in the second half of the 19th century on the San Miniato hill of Florence is presented: the architectonic transformation, of high artistic and landscape value, was combined with an effective stabilization of the hill, the instability of which was documented in a number of historic documents starting from the 11th century. The 1998 Sarno disaster is illustrated as an example of prevention failure: a series of debris flows caused 161 casualties in the suburbs of Sarno and Quindici, where uncontrolled urban development took place on areas historically exposed to high hazard.

The basic requirements of a successful emergency plan are therefore discussed, such as monitoring and warning systems and simulation techniques for risk scenario analyses The emergency plan devised and implemented after the occurrence of the 1993 La Josefina landslide in Ecuador is presented as a success: the landslide produced a dam on the Rio Paute and the successive emergency measures managed to reduce the losses caused by the dam breaching and overtopping to a minimum Finally, the well-known 1963 Vaiont disaster is proposed as a representative example of unsuccessful emergency planning: more than 1 700 casualties were caused by the catastrophic flood wave generated by the sudden failure of a huge mass of rock into a reservoir

1.
INTRODUCTION

Landslides and, in general, mass movements of earth receive less attention from the mass media and policy makers than other natural disasters such as earthquakes, volcanic eruptions and floods, probably because they are less impressive. However, they undeniably represent one of the major risks for the safety and welfare of people, property and wealth. Very often the damage caused by landslides is strongly underestimated, since they frequently represent a relevant part of multi-hazard disasters such as earthquake-induced failures, rainfall-induced floods and debris flows, or rock avalanches and lahars triggered by volcanic eruptions. A worldwide survey carried out by the International Association of Engineering Geology for UNESCO between 1971-1974 showed that 14 per cent of all casualties caused by natural disasters are connected with landslides. In the same period, an average of 600 people were killed by landslides each year (Varnes, 1981) This figure, however, gives only a partial idea of landslide impact on public safety, as single major events that have occurred in this century have caused, in some cases, over ten thousands victims (Schuster, 1996)

Schuster (1996) has published an updated review on the socio-economic significance of landslides showing that Japan is the most severely affected nation, suffering an estimated total loss of 4×10^9 US $ per year (value referred to 1990). It is followed by the United States, Italy and India, where the estimated losses ranges between 1×10^9 US $ and 2×10^9 US $ each year These losses include both direct and indirect costs. The first involve costs of repair, replacement or maintenance of damaged property and installations. Indirect costs include loss of productivity, reduced real estate value, loss of tax revenues and other induced economic effects not directly produced by the landslides (Schuster, 1996). According to Schuster, a significant proportion of landslides affect transportation facilities or lifelines such as railways, highways, channels and pipelines, producing both Civil Protection problems and damage to economic activities. Another important aspect that must be taken into consideration relates to cultural heritage and environmental and ecological resources, the damage caused by landslides can in some cases be of inestimable value.

The mitigation of damage caused by natural disasters and risk reduction is one of the institutional duties of UNESCO. In 1976, the United Nations Disaster Relief Organization (UNDRO) promoted the constitution of a "landslide commission" within the IAEG, where a global framework for landslide hazard and risk analysis was defined (Varnes and IAEG, 1984). The 42nd General Assembly of the United Nations decided that the period between 1990–2000 would be the International Decade for Natural Disaster Reduction (IDNDR). In this context a Working Party on the World Landslide Inventory (WP/WLI) was formed by the main international geotechnical societies. With the enlargement of the International Union of Geological Sciences (IUGS), the WP/WLI was transformed into the IUGS Working Group on Landslides (IUGS/WGL). The main outcomes of this activity consist in the publication of suggested methods for landslide description and inventory (WP/WLI, 1990, 1991, 1993*a*, 1994; IUGS/WGL, 1995; Cruden and Varnes, 1996), a multilingual glossary on landslides (WP/WLI, 1993*b*), and a review of the state-of-the-art on quantitative risk assessment for slopes and landslides (Cruden and Fell, 1997).

The socio-economic significance of landslides has been recognized in recent decades, following the occurrence of several disasters. The reasons can be listed as follows:

1) landslide hazard is growing both in developing countries, due to continuous deforestation, and in industrialized countries, because of the gradual abandonment of rural areas;
2) global climate change appears to negatively affect hazard through increased annual precipitation in some countries, or higher frequency and intensity of extreme meteorological events in others;
3) the exposure of the elements at risk has risen rapidly in recent decades due to demographic growth and to increased urbanization and development; if this tendency seems to have been reversed in technologically advanced nations, it is now a major problem in developing countries where the population is growing rapidly and regional development is often uncontrolled;
4) the vulnerability of the elements at risk is also on the rise given the growing complexity of the socio-economic structure of industrialized countries; even events causing minor direct loss can generate major indirect losses linked, for example, to the interruption of productive activities, loss of competition, non-fulfilment of contracts, legal or insurance problems and even psychological effects;
5) acceptable risk thresholds have been drastically reduced in more developed nations as today's society no longer tolerates losses from natural unexpected events.

For these reasons, the mitigation of landslide effects has, in recent decades, become even more challenging. The objective of this paper is to provide a general framework for the definition of the effectiveness of society's fight against landslides, providing case studies of both successful achievements and distressing failures The first step in landslide mitigation is to examine what type of phenomenon a landslide represents. A landslide is a mass of rock, debris or earth, which moves down a slope under the action of the force of gravity (Cruden, 1991). Despite this simple definition a landslide is a very complex phenomenon. It is characterized by five fundamental mechanisms of movement (fall, topple, slide, spread and flow) and their combinations (Cruden and Varnes, 1996). The material involved can range in size and consistency from hundreds of millions of cubic meters of solid rock to single particles of soil. The rate of movement ranges over ten orders of magnitude, from imperceptible creeping (velocity $<10^{-7}$ m/s) to catastrophic, extremely rapid, failures (velocity $>10^{4}$ m/s) (IUGS/WGL, 1995). The material can move as a whole, like a solid block, or flow like a fluid depending on the water content. The activity of the movement can vary spatially and through time and between different parts of the same displaced mass (WP/WLI, 1993*a*). A landslide can occur as a first-time rupture of intact material or along a pre-existent sliding surface. The first case is less common but usually has more violent effects given the brittle characteristics of failure, whereas re-activations occur more frequently but are usually characterized by limited displacements and slow rates of movement, because of the non-brittle nature of the pre-existing slip surface (Hutchinson, 1987, 1988).

Another aspect that must be considered in a landslide risk analysis is the induced risk. A landslide, in fact, may be the triggering cause of another type of hazard: a volcanic eruption, as in the 1980 Mount St. Helen event in the state of Washington (USA); groundwater pollution, when industrial plants or waste disposals are damaged; or a flood, when the landslide causes the blockage of a stream or river channel. This last case is perhaps the most common and can produce dangerous consequences: a landslide dam represents a potential source of flood hazard since it may cause flooding both upstream, by water impoundment, and downstream, by breaching and overtopping of the dam.

The type of action that can be taken in the face of landslide hazard is the main aspect that needs to be discussed, before proceeding to the examination of successes and failures in combating landslides. Generally speaking, a hazardous phenomenon can be either forecasted, prevented and mitigated or tackled with an emergency plan. The three main phases concerning landslide risk management are the following:

(a) **prediction**: includes all the activities aimed at studying and determining the causes of landslides, at identifying the risks and at the zonation of the areas exposed to risk;

(b) **prevention**: includes all the activities aimed at avoiding or reducing to a minimum the possibility of occurrence of loss as consequence of landslide events, based on the knowledge acquired in the prediction phase;

(c) **emergency planning**: consists of the decisional and operational framework for the protective measures to put into effect in situations of crisis.

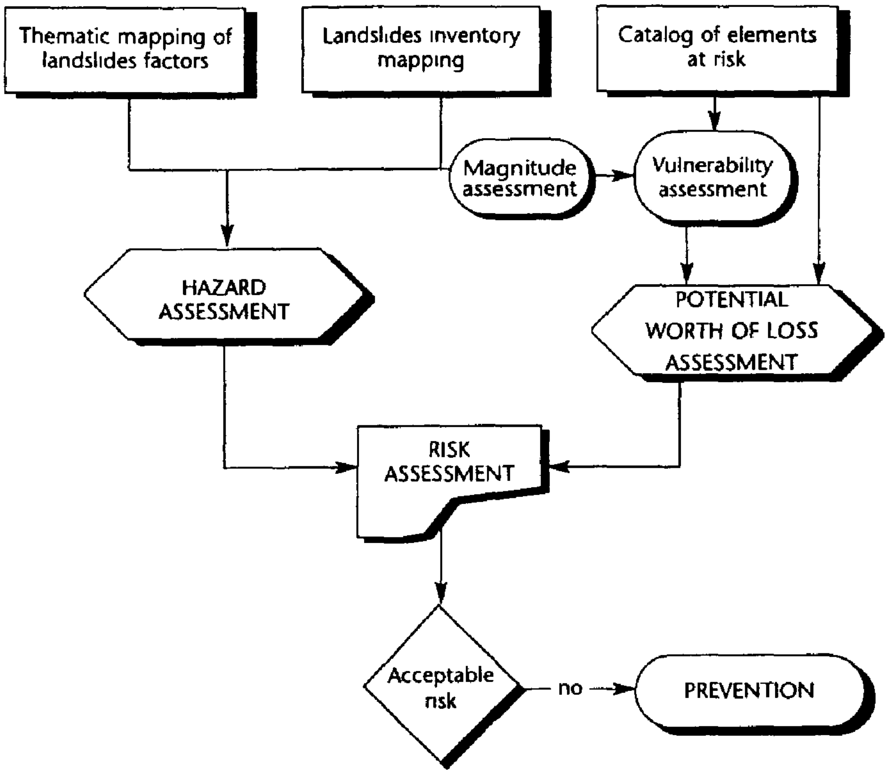
In the following sections these three aspects of landslide management will be discussed in detail. For each of them, two case studies are presented and briefly commented on: one relating to a success and one to a failure. The case studies presented are well-known events where the authors had a direct research experience and, in some cases, a direct operational responsibility as members of the National Group for Hydrogeological Disaster Prevention (GNDCI), an organization funded by the Italian Civil Protection Department, with the aim of supplying technical support to the Government in the fight against landslides and floods. Many of them are Italian examples, where the authors have gained most of their experience, but they are chosen as representative of landslide phenomena and socio-economic contexts that can be easily encountered in other parts of the World.

2. PREDICTION

A formal framework for landslide risk prediction is shown in Figure 1. The basic initial information is represented by the description of the state of nature (Einstein, 1988; Wu *et al.*, 1996) which can be divided into the following three aspects:

(a) thematic mapping of landslide factors: providing all the relevant information on slope instability causes, such as lithology, bedrock structure, debris cover, vegetation, groundwater, slope gradient and aspect, etc.;

Figure 1. Formal framework for landslide risk prediction.



(b) landslide inventory mapping: providing all the relevant information on slope instability effects, such as past landslide distribution, type of movement and of mobilized material, state, style and distribution of activity;

(c) catalogue of the elements at risk: including information on population, property, buildings, transportation infrastructures, lifelines, socio-economic activities, cultural heritage, environmental and ecological resources, classified by typology and by value.

From the combined interpretation of information regarding slope instability causes and effects, it is possible to predict landslide hazard, defined as the probability that a catastrophic phenomenon may occur in a defined area during a given period of time (Varnes and IAEG, 1984). The analysis of the characteristics of past landslides supplies indications of the geometrical and mechanical severity (magnitude or intensity) of the expected events. Cross-analysis of landslide magnitude and the type of elements at risk permits the assessment of vulnerability, which represents the degree of loss of an element or group of elements at risk, as consequence of the occurrence of a natural phenomenon of a given magnitude (Varnes and IAEG, 1984). Vulnerability, in fact, depends on the type of element at risk, in particular on its susceptibility to suffer a loss, and on the magnitude of the landslide, which is linked to its damage potential. By combining the vulnerability with the value of the elements at risk it is possible to assess the potential worth of loss (Einstein, 1988), which is independent from the probability of occurrence of the landslide event. The total risk, which expresses the expected amount of loss, is obtained by combining the potential worth of loss with landslide hazard.

Methods for the quantitative assessment of the potential worth of loss have been developed within the *Plans d'exposition aux risques* (PER) of the French Government (DRM, 1985, 1988) and formalized by Einstein (1988) in the framework of the Decision Theory. The development of methods for the quantitative assessment of landslide hazard is one of the main topics of scientific research in the field of engineering geosciences. These are usually based on GIS mapping and analysis for predictions over extensive areas and on geotechnical numerical modelling for single site predictions.

Compared to other types of natural disasters, landslides pose a series of additional problems that must be solved for a complete hazard analysis. This is due to the wide variability of slope movements in terms of type of movement, type of material, water content, and rate of movement. The following steps are necessary for a complete hazard assessment (Hartlén and Viberg, 1988).

(a) Temporal prediction: the forecasting of when a landslide will occur on a specified slope
(b) Spatial prediction: the forecasting of where a landslide has the highest probability of occurring within a specified area.
(c) Type prediction: consists in determining the type of movement that is most likely to occur (e.g. rock fall, earth slump, etc).
(d) Magnitude prediction: this consists in determining the geometrical and mechanical severity of the expected event; the parameters to be investigated and predicted are landslide volume, rate of movement, and released energy. The magnitude closely controls the vulnerability of the elements at risk. A correct risk analysis should consider different hazard levels for events with different magnitude by evaluating frequency-magnitude relationships.
(e) Evolution prediction: is the forecasting of travel distances, retrogression limits and lateral expansion. This is another fundamental aspect as it involves the delimitation of the "hazard basin" of existing and potential landslides.

2.1 THE EMILIA-ROMAGNA REGION. A DATABASE OF 32 000 LANDSLIDES FOR PREDICTION PURPOSES

The Emilia-Romagna region, located in the northern sector of the Apennine chain, is one of the areas in Italy more extensively affected by landslides that periodically cause severe damage to property and productive activities. Amongst the most recent events having occurred on its territory, several can be singled out. The 1994 Corniglio earth slide with a volume of over 200×10^6 m^3 caused the loss of important food processing plants (Larini *et al.*, 1997; Gottardi *et al.*, 1998). The 1994 Silla landslide caused a prolonged interruption of activity in mechanical industrial plants (Canuti *et al.*, 1998). Finally, the 1994 San Benedetto landslide dam posed serious civil protection problems linked to the expected failure of the blockage on the Sambro river (Casagli *et al.*, 1995)

Slope instability in the region has been well-known for centuries and several historic documents report landslide problems that occurred during previous centuries. Fortunately, the majority of the landslides in the region are characterized by a slow rate of displacement Common velocities are a few centimetres per day and only exceptionally have velocities of up to tens of meters per day been recorded. Apart from a few rare cases, therefore, landslides in the region do not pose a risk to the safety of people, but can, nonetheless, have severe consequences on the economy of the region, owing to the damage caused to urban areas, isolated buildings and, in particular, transportation facilities (Canuti *et al.*, 1999).

The vast majority of the landslides occurring in the region are re-activations of pre-existing slope movements that take place with an intermittent, irregular recurrence, usually in response to prolonged rainfall. In consequence, it is clear that a detailed inventory map of past and existing landslides, based on air-photo interpretation and on field surveys, represents the basis for a spatial and typological prediction of landslide hazard, since it permits us to detect and classify the phenomena which can be re-activated in the future. In the 1970s, the Regional Administration started a systematic inventory of landslides, covering the whole Emilia-Romagna region (which extends over an area of 12,685 km^2 excluding flood plains) at a scale of 1:25 000 and afterwards at 1:10 000 This work is now nearly complete and has lead to the detailed mapping of 32,337 individual landslides, covering a total area of 2 554 km^2 (20.1 per cent of the area of the hilly and mountainous ranges). All the data have been stored in a GIS and are now accessible to the general public by means of telematic networks.

After the series of events which affected the region between 1994-96, the Regional Civil Protection Service promoted the constitution of a technical-scientific group to develop a hazard map to be used for prediction purposes. The type of data processing adopted is not substantially different, in methodology and content, from cases cited in the scientific literature and employed for cartographic projects by other public administrations, such as the French national project ZERMOS (Humbert, 1976, 1977; Antoine, 1977) and PER (DRM, 1985, 1990). The