# Landslide Hazard Assessment Using GIS

Mowen Xie

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## Using GIS
(*with 70 figures in color*)

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# Preface

Landslide is one of the main natural disasters, and the landslide hazard assessment has become a major concern for the mountain area development. Geographic Information System(GIS), with its excellent spatial data process ability, has attracted a great attention in natural disaster assessment. In this book, the GIS-based landslide hazard assessment which is one of geotechnical engineering approaches, because its theory is based on the physical term, is considered as an acceptable method for analyzing the safety factor of the landslide.

All slope failures have a three-dimensional geometry, which varies in space even along a short distance. Therefore, it is rational to use a 3D model to analyse slope stability. Three-dimensional (3D) evaluation of slope stability is a widely addressed problem in the domain of geotechnical engineering. The growing popularity of the Geographical Information System (GIS), with capacities ranging from conventional data storage to complex spatial analysis and graphical presentation means it is also becoming a powerful tool for geotechnical engineers. In this book, combining the GIS grid-based data with four proposed column-based models of 3D slope stability analysis, new correspondent GIS grid-based 3D deterministic models have been devised in order to calculate the safety factor of the slope. Based on the four GIS-based 3D slope stability analysis models, a GIS-based program, 3DSlopeGIS, has been developed to implement the algorithm where the whole of the input data is in the same form as the GIS dataset. The 3DSlopeGIS system, namely an extension of the widely used GIS software package, represents a combination of the development in terms of the 3D slope stability analysis and the GIS-based Component Object Model (COM) skills. Since all related data are supplied in the GIS form, this new database approach will be very convenient for renewal and consulting of data on multiple occasions. Certain widely addressed examples have been evaluated in this book and the results show the correction and potential of this GIS-based tool as a means of assessing the 3D stability of a slope. Some practice problems have been assessed for mapping 3D landslide hazard and for evaluating the 3D stability of a slope using 3DSlopeGIS System.

Various methods of optimization or random search have been developed for locating the critical slip surface of a slope and the related minimum safety factor. But all these methods are based on a two-dimensional (2D) method and no one had been adapted for a search of the three-dimensional (3D) critical slip surface. In this book, a new Monte Carlo random simulating method has been proposed to identify the 3D critical slip surface, in which assuming the initial slip to be the lower part of an ellipsoid, the 3D critical slip surface in the 3D slope stability analysis is located by minimizing the 3D safety factor. Based on a column-based three-dimensional slope stability analysis model, a new Geographic Information Systems (GIS) grid-based 3D deterministic model is developed to calculate the 3D safety factor. Several practical examples, of obtained minimum safety factor and its critical slip surface by a 2D optimization or random technique, are extended to 3D slope problems to locate the 3D critical slip surface and to compare with the 2D results. The results show that, comparing with the 2D results, the resulting 3D critical slip surface has no apparent difference only from a cross section, but the associated 3D safety factor is definitely higher.

Many researchers take it for granted that the pixel (or grid) will be the study object, simply because grid-based objects can be easily obtained and managed. Grid-based objects are regularly distributed in space, so computer processing and manipulation is fast and algorithmically simple. But the grid cell does not bear any relation to the mechanism of slope failure and even to geological, geomorphologic or other environmental boundaries, so the results obtained by this approach are relatively inaccurate and unacceptable in physical terms. In this book, a GIS-based 3D model will be used for the slope stability analysis, because the 3D model will only be suitable for a mapping unit which has explicit geometric relationship with landslide, slope unit will be selected as mapping unit for 3D stability analysis.

The slope unit, that is, the portion of land surface that contains a set of ground conditions that differ from the adjacent units, possesses an explicit topographical form. Not the rectangular pixel which is now widely used as the study object for 1D landslide hazard mapping, in this study, the slope unit, is derived for the study object. Since a clear physical relationship exists between landsliding and the fundamental morphological elements of a hilly or mountain region, namely drainage and divide lines, the slope-unit-based results are more reliable than the grid-based results. Using a hydrologic model tool for the watershed analysis in GIS, an automatic process has been developed for identifying the slope unit. A GIS-based hydrologic model tool is employed to draw dividing lines for identifying slope units.

The principal source of variability in the 3D safety factor calculation will come from two geomechanical parameters: the cohesion $C$ and the friction angle $\phi$. In this book, assuming variables of $C, \phi$, and the 3D safety factor to be in the normal distribution, the 3D probability of the landslide is calculated by an approximate method which uses a probability in the range of $\mu \pm 3\sigma$, the 99.75% of precision in this range is enough for the landslide hazard assessment.

A rainfall-induced shallow landslide is a major hazard in mountainous terrain, but a time-space based approach is still an unsettled issue for mapping rainfall-induced shallow landslide hazard. Rain induces a rise of the groundwater level and an increase in pore water pressure that results in slope failures. A shallow landslide triggered by rainfall can be forecast in real-time by modeling the relationship between rainfall infiltration and decrease of slope stability.

In this book, an integrated infinite slope analysis model has been developed to evaluate the influence of infiltration on surficial stability of slopes by the limit equilibrium method. Based on this new integrated infinite slope analysis model, a time-space based approach has been implemented to map the distributed landslide hazard in a GIS and to evaluate the shallow slope failure induced by a particular rainfall event that accounts for the rainfall intensity and duration. The case study results in a comprehensive time-space landslide hazard map that illustrates the change of the safety factor and the depth of the wetting front over time. A promising approach, that combines an improved three-dimensional slope stability model with an approximate method based on the Green and Ampt model, is also used to estimate the time–space distribution of shallow landslide hazards. Once a forecast of rainfall intensity and slope stability-related data, e.g., terrain and geology data, are acquired, this approach is shown to have the ability to estimate the variation of slope stability of a wide natural area during rainfall and to identify the location of potential failure surfaces. The effectiveness of the estimation procedures described has been tested by comparison with a one-dimensional method and by application to a landslide-prone area in Japan.

Based on a new Geographic Information Systems (GIS) grid-based three-dimensional (3D) deterministic model and taking the slope unit as the mapping unit, the 3D safety factor index and failure probability are used for mapping landslide hazard. Assuming the initial slip to be the lower part of an ellipsoid, the 3D critical slip surface in the 3D slope stability analysis is located by minimizing the 3D safety factor using the Monte Carlo random simulation. The failure probability of the landslide is calculated using an approximate method in which the distributions of $C$, $\phi$ and the 3D safety factor are assumed to be in normal distribution. The method has been applied to a case study on three-dimensionally and probabilistically mapping landslide hazard.

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# Chapter 1 Landside and Geographic Information System

## 1.1 Introduction

Today, with population growth, increasing urbanization, and mountain and coastal development, many parts of the world are at significant risk from natural disasters. Escalating population and increased development on the coasts, fault zones, mountainous areas, and flood plains mean that increasing numbers of people are at risk from hazards.

Physical scientists define a natural hazard either as the probability that a reasonably stable condition may change abruptly (Scheidegger, 1994), or as the probability of occurrence of a potentially damaging phenomenon within a given area and in a given period of time (Varnes, 1984). The latter remains the most widely accepted definition for natural hazard and for maps portraying its distribution over a region. In many countries, the economic losses and casualties due to landslides are greater than commonly recognized and generate a yearly loss of property larger than that from any other natural disaster, including earthquakes, floods and windstorms.

Landslides have caused large numbers of casualties and huge economic losses in mountainous areas of the world. It has been estimated that nearly 600 people are killed every year worldwide as a consequence of slope failures. Approximately 90% of these deaths occurred within the Circum Pacific Region (Aleotti and Chowdhury, 1999). In the United States, landslides cause an estimated US$1-2 billion in economic losses and about 25-50 deaths annually, thus exceeding the average losses due to earthquakes (Schuster and Fleming, 1986). Li and Wang (1992) conservatively estimated that in China the number of deaths caused by landslides totalled more than 5000 during the 1951-1989 period, resulting in an average of more than 125 deaths annually, and annual economic losses of about US$500 million. Landslide costs in Japan, the United States, the Alpine nations (Austria, France, Italy and Switzerland) and India are quite similar in magnitude (US$1-5 billions per year) although, it is likely that actual costs are the highest in Japan.

While landslides have a significant impact, their importance is often under estimated as the landslide damage is considered simply as a result of the triggering process and thus is included in reports of other phenomena such as earthquakes, flood, *etc* (Schuster, 1996). Actually, landslides are various types of gravitational mass movements of the Earth's surface that pose the earth-system risk; they are triggered by earthquakes, rainfall, volcanic eruptions and human activities. Landslides are multiple hazards, involving typhoons/hurricanes, earthquakes, and volcanic eruptions, and sometimes causing tsunamis. Therefore, landslide disaster reduction requires cooperation of a wide variety of natural, social, and cultural sciences.

Each year the importance of assessing, preparing for and mitigating the potential effects of natural hazards, including landslides, increases. In recent years, the assessment of landslide hazard has become a topic of major interest for both geoscientists and engineering professionals as well as for local communities and administrations in many parts of the world. The aims of landslide hazard evaluation are: ① to understand the development and form of natural slopes and the processes responsible for different natural features; ② to assess the possibility of landslides involving natural or existing engineered slopes; ③ to assess the stability of slopes under short-term and long-term conditions; ④ to analyze landslides and to understand failure mechanisms and the influence of environmental factors; and ⑤ to enable the redesign of failed slopes and the planning and design of preventive and remedial measures, where necessary.

To address the landslide problem, governmental agencies need to develop a better understanding of landslide hazard and to make rational decisions on allocation of funds for management of landslide risk. However, it is widely accepted that the landslide problem is dominated by uncertainty. This uncertainty arises at all stages in the resolution of the problem, from site characterization to material property evaluation to analysis and design and consequence assessment (Morgenstern, 1997). Otherwise, most of the countries, especially the third world countries, have difficulty meeting the high costs of controlling natural hazards through major engineering works and rational land-use planning. Industrialized societies are increasingly reluctant to invest money in structural measures that can reduce natural risks. Hence, the new issue is to implement warning systems and land utilization regulations aimed at minimizing the loss of lives and property without investing in long-term, costly projects of ground stabilization.

Government and research institutions worldwide have long attempted to assess landslide hazards and risks and to portray its spatial distribution in maps. Within this framework, earth sciences, and geomorphology in particular, may play a relevant role in assessing areas at high landslide hazard and in helping to mitigate the associated risk, providing a valuable aid to a sustainable progress. Tools for handling and analyzing spatial data, *i.e.* Geographical Information System (GIS), may facilitate the application of quantitative techniques in landslides hazard assessment and mapping.

Landslide hazard evaluations are concerned with identifying critical geological, material, environmental, and economic parameters that will affect the project, as well as understanding the nature, magnitude, and frequency of potential slope problems. A number of methods have now been developed. All the proposed methods are based upon a few, widely accepted principles or assumptions (Varnes, 1984; Carrara *et al.*, 1991; Hutchinson, 1995), namely:

(1) Slope failures leave discernible morphological features; most of them can be recognized, classified, and mapped either in the field or through remote sensing, chiefly aerial photographs;

(2) Landslide is controlled by mechanical laws that can be determined empirically, statistically or in deterministic fashion. Conditions that cause landslides directly or indirectly linked to slope failure, can be collected and used to build predictive models of landslide occurrence;

(3) The past and present are keys to the future. The principle, which follows from uniformitarianism, implies that slope failures in the future will be likely to occur under the conditions which led to past and present instability;

(4) Landslide occurrence in space or time, can be inferred from heuristic investigations, computed through the analysis of environmental information, or inferred from physical models. Therefore, a territory can be zoned into hazard classes ranked according to different probabilities.

Ideally, evaluation of landslide hazard and its mapping should derive from all of these assumptions. Failure to comply with them will limit the applicability of any hazard assessment, regardless of the methodology used or the goal of the investigation.

## 1.2 Some basic concepts

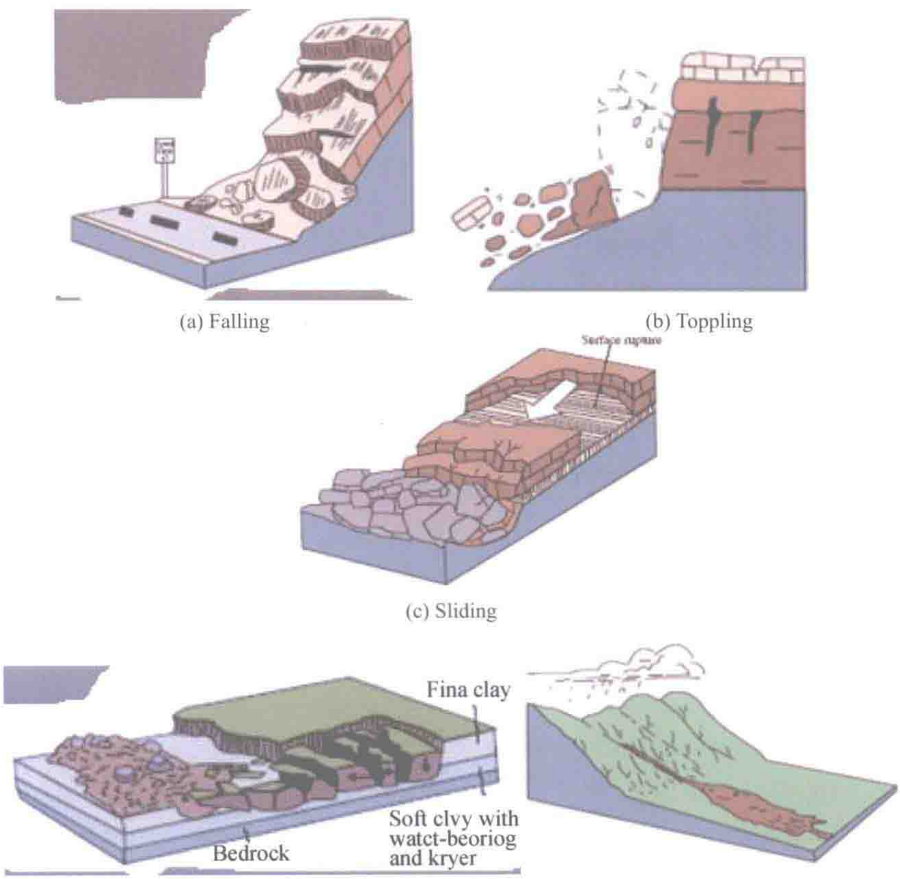
### 1.2.1 Types of landslides

It is important to distinguish types of landslides according to the rate of slope movement. Rates of movement range from less than 6 inches per year to more than 5 feet per second according to Cruden and Varnes (1992).

The kinematics of landslides (*i.e.*, how movement is characterized throughout the displaced mass) constitutes another way of classifying landslides. After Cruden and Varnes (1992), there are five kinematically distinct types of landslide movements (Table 1.1 and Figure 1.1): (a) Falling; (b) Toppling; (c) Sliding; (d) Spreading; (e) Flowing. Each type of landslide has a number of common modes. Falling and toppling are features frequently associated with rock slopes, whereas the latter three are related to soil slopes.

**Table 1.1 Classification of landslides according to type of material and movement after Varnes**

<table>
<tr><th colspan="2" rowspan="3">Type of movement</th><th colspan="3">Type of materlal</th></tr>
<tr><th rowspan="2">Bedrock</th><th colspan="2">Engineering solls</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="2">Falls</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="2">Topples</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="2">Slides</td><td>Rotational</td><td rowspan="2">Rock slide</td><td rowspan="2">Debris slide</td><td rowspan="2">Earth slide</td></tr>
<tr><td>Translational</td></tr>
<tr><td colspan="2">Lateral spreads</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2" rowspan="2">Flows</td><td rowspan="2">Rock flow<br>(deep creep)</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2">(soil creep)</td></tr>
<tr><td colspan="2">Complex</td><td colspan="3">Combination of two or more principal types of movement</td></tr>
</table>




(a) Falling (b) Toppling

(c) Sliding

(d) Spreading (e) Flowing

Figure 1.1 Five kinematically distinct types of landslide movements (from USGS)