GIS Methodology for Zonification of Slope Stability under Earthquakes

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ABSTRACT

Recent earthquakes in Colombia have shown the great importance of landslide triggering. Considering these conditions, a study was carried out to develop a methodology for zonification of slope stability under earthquakes, based on representative variables of geomorphology, geology and soil profiles.

This methodology covered compilation of existing information about geological, geomorphologic and geotechnical studies, analyses of earthquake ground response, definition of dynamic behavior of representative soil profiles, and development of topographical and geotechnical models taking full advantage of Geographical Information System (GIS) tools.

This paper describes the resulting GIS methodology and discusses its reliability, based on its application to simulate triggering of landslides in the city of Armenia (Colombia), using the 1999 Armenia earthquake.

INTRODUCTION

Public entities in regions with important potential of landslides associated to earthquakes have been focused on finding new choices to evaluate regional hazard and vulnerability. These new choices are addressed to prioritize zones or sectors which present greater susceptibility to this kind of events. This philosophy makes possible to consider this topic not only for development planning, but also for designing disaster prevention and mitigation programs.

Different approaches have been developed worldwide in order to get reliable methodologies for zonification of slope stability under earthquakes. This kind of approaches analyzes landslide hazard by dividing the area in a square-cell grid, considering every cell as an independent unit of its neighbor cells. The main shortcoming of this approach seems to be the great need of taking into account marked relationships among the cells due to particular geomorphologic conditions like slope geometry, potential failure surface and sliding mass, among others.

Since slope stability depends on geometrical, geological and geotechnical conditions, it is necessary to consider representative parameters to carry out analyses of a specific slope and zonification of regional slope stability.

This paper describes a GIS methodology for zonification of slope stability under earthquakes, which was developed for particular applications in Colombia. This methodology permits the definition of sectors or regions according to their landslide susceptibility combining sloping ground, flow direction, geological characteristics, shearing strength of representative soil profiles and earthquake hazard, using GIS tools. The application of this methodology for several cities in Colombia has shown its reliability in prioritizing zones, considering their landslide hazard level associated to earthquakes.

BASIC INFORMATION

The GIS methodology for zonification of slope stability under earthquakes, requires basic information like the topographical and geological maps, and the geotechnical and seismic zonification of the region. It is important to point out that greater detail of basic information leads to greater detail in zonification results. The results of analysis are expressed in terms of landslide susceptibility maps under static and dynamic conditions. If geotechnical zonification is not available, it is possible to get this information based on site investigations, field observations, geophysical tests and laboratory tests, among others.

Geological and geotechnical zonification must involve description about origin and composition of rocks and soils, and geotechnical parameters for representative soil profiles of the zone. Geotechnical parameters involve data such as classification, shearing strength, groundwater conditions (water table) and earthquake ground response, for rock accelerations with different exceedence rates.

Since slope stability under static conditions constitutes fundamental clue in its expected dynamic behavior, this methodology is oriented to identify intrinsic properties or factors that control slope stability. That is why this methodology includes interpretation of aerial photographs in order to identify critical sites, considering landslide potential. Field observations of critical sites are carried out in order to find man-made factors like cuts, bodies of fill material, problems of water management and land use. These factors must be taken into account in the complete analysis, due to their ability to weaken slope stability through increasing the effective weight of materials and building up the pore pressure.

METHODOLOGY OF ANALYSIS

GIS methodology for landslide hazard evaluation has two main stages. The first one involves the generation of a map that represents slope stability under static conditions. This analysis evaluates landslide susceptibility associated to geological, topographical features, geotechnical and man-made conditions.

The second stage of analysis considers all the factors included in the static analysis and a triggering factor which represents earthquake hazard. Estimation of representative earthquake force involves not only regional conditions to define different rock acceleration levels, but also amplification phenomena of different soil profiles.

Landslide susceptibility under static conditions

Generation of digital terrain model. Representation of geometric conditions of every slope in the region is carried out through generation of a Digital Terrain Model (DTM) using GIS tools. DTM is based on information of surface features and location of rivers and creeks (topographical information). Figure 1 shows the digital terrain model of the city of Armenia, which was used for its slope stability zonification.

Generation of sloping ground map. A sloping ground raster map is generated based on the DTM. This map represents sloping ground variation in the studied zone. Figure 2 shows a sloping ground map of the city of Armenia. This city presents steeped surfaces like most of the cities in Colombia, which reflects the great importance of landslide phenomena in this country.

It is important to point out that this map does not allow the identification of slope configuration by itself. That is why it is necessary to evaluate the flow direction, variable that makes possible identification of individual slopes.

Generation of flow direction map. The generation of the flow direction map is based on the following eight flow directions: north, south, east, west, northeast, northwest, southeast and southwest. Figure 3 shows the concept of flow direction, which makes possible regional identification of individual slopes.

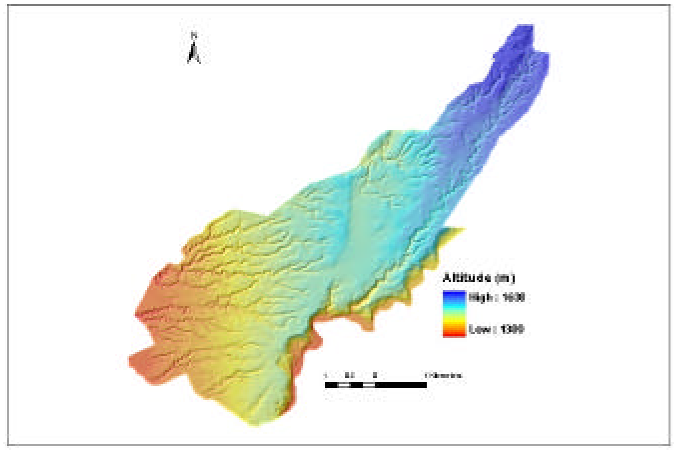

Fig. 1. Digital terrain model of the city of Armenia.

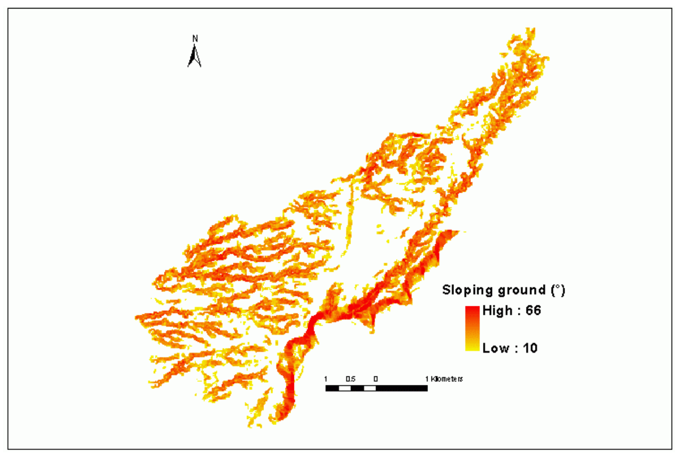

Fig. 2. Sloping ground map of the city of Armenia.

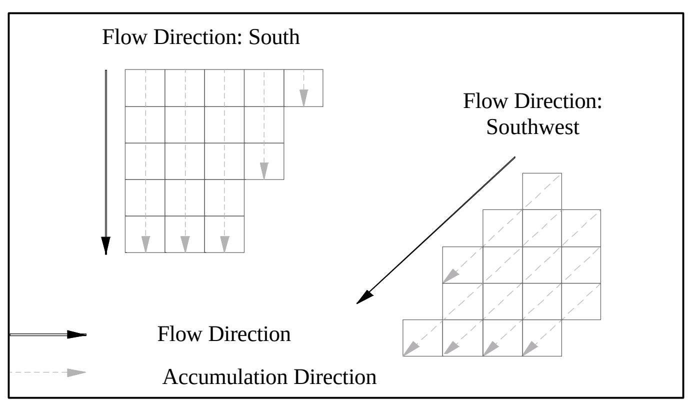

Fig. 3. Flow direction.

The main philosophy of this method is to analyze regional slopes in the same way as it is evaluated the stability of a particular slope.

The flow direction map allows the identification of independent slopes and makes possible estimation of their geometrical parameters. Slope height is estimated through comparison among flow direction of a cell with the correspondent flow direction of neighbor cells, so that the cells with the same flow direction belong to the same slope. After the definition of independent slopes, their maximum heights are estimated using their correspondent maximum and minimum levels.

In addition, the sloping ground variation is defined for every slope, in order to estimate parameters that represent in the best way its geometric conditions. The representative sloping ground is defined based on their distributions along the slope. Statistical analysis of sloping ground distributions and stability analysis of slopes for different materials are used to determine the representative sloping ground of every slope. In some cases a weighted average is applicable, taking into account the thickness of soil profiles, while in other cases maximum sloping ground is the best parameter to characterize the slope. Figure 4 shows the flow direction map of the city of Armenia, which points out the great importance of this parameter to identify individual slopes in a region.

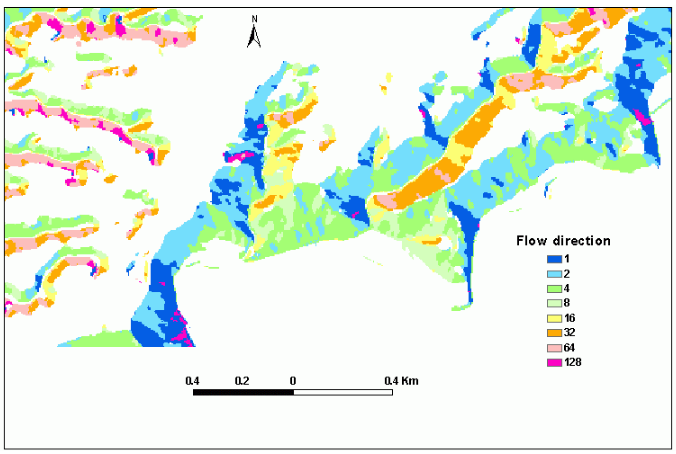

Fig. 4. Flow direction map of the city of Armenia.

Geotechnical characterization of the region. This step involves identification of representative soil profiles of the region and definition of their geotechnical properties, based on geological characteristics, site investigations, and field and laboratory tests, among others.

Representative soil profiles consist of particular sequence of layers, where every sequence can have different thickness distribution. This consideration makes more complex the analysis, since stability conditions of slopes in different locations where a specific soil profile is present, are not necessary the same, because these conditions depend on the thickness of the different layers which compose the complete soil profile.

Geotechnical characterization is addressed to determine static and dynamic properties of different layers of every soil profile. Static parameters involve the effective weight of materials, the pore pressure conditions and the shearing strength parameters (cohesion and internal friction angle) of different layers that compose every representative soil profile.

Information of dynamic soil properties was composed by field and laboratory tests. These data allow the estimation of the relationships between shear wave velocity and depth, and of the variation of the shear modulus and damping ratio of soils with cyclic shear strain. Variation of dynamic soil properties with depth shows a wide range, which depends on soil origin, weathering levels, and moisture conditions, among others.

Characterization of dynamic behavior is carried out considering regional seismic hazard and local site effects. Regional seismic hazard analysis is carried out following a probabilistic approach. This probabilistic method involves evaluation of all seismic sources with influence in the city and permits the estimation of the maximum acceleration at rock level for different return periods. Local site effects are evaluated in terms of the ratio between maximum ground acceleration and maximum acceleration at rock level.

Estimation of the representative ratio between maximum ground acceleration and maximum acceleration at rock level for every site, involves theoretical models and data from recorded earthquakes. This approach permits calibration of theoretical models of ground surface motion. It points out the importance of knowing, in a detailed way, the complete soil profile above the bedrock to discern its seismic response. This condition is important to take into account the impedance ratio of soil-bedrock, and also to include the soil thickness of the complete soil profile in the analysis of earthquake ground response; because both factors have deep influence on the ratio between maximum ground acceleration and maximum acceleration at rock level.

It is important to point out that the studies of landslide hazard of the city of Armenia included evaluation of the 1999 Colombia earthquake, which triggered important landslides in this place.

Figure 5 shows the geotechnical raster map for the city of Armenia. Every cell of this map has associated information about static and dynamic properties, which were used in the stability analysis.

Geotechnical analysis of the city of Armenia allowed the definition of representative soil profiles (Figure 5). Geological and geotechnical conditions of this city have an important relationship with Aeolian deposits. In general, soil profiles in Armenia presents a surface layer of volcanic ash with a very low density, associated to its origin. Thickness of ash deposits varies widely in the city of Armenia, depending on surface features, and it was figured out that thickness of this particular layer has a very important effect on earthquake ground response. Low stiffness of ash deposits with respect to underlying layers explains the marked effect of this surface layer on local site effects. Most of the representative soil profiles of the city of Armenia are composed by ash volcanic deposits lying different kind of materials such as residual soils, volcanic formations and alluvial deposits.

There are soil profiles covered by man-made hydraulic fills lying ash deposits. The construction method of hydraulic fills consist of mixing the soil with large quantities of water, conveying the mixture to the construction site through pipes, then depositing it at the desired site. These hydraulic fills were also sampled and analyzed, in order to get static and dynamic properties to evaluate their expected behavior, considering susceptibility to landslide.

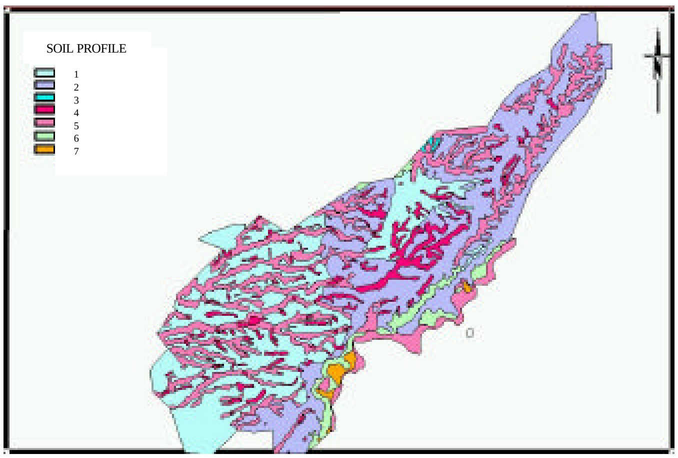

Fig. 5. Geotechnical map of the city of Armenia.

Characterization of man-made factors. Since slope stability in urban zones has a marked influence of man-made factors, this methodology is addressed to identify representative man-made factors with deep influence on slope stability in a specific region. That is why interpretation of aerial photographs of different periods, field observations of sites which have shown stability problems and analysis of historical cases are carried out. This information allows not only the identification of man-made factors but also the adjustment of intrinsic factors. Intrinsic factors involve geotechnical properties and surface features. The most important man-made factors identified in Colombia are related to problems of water management and land use. These factors generate increasing of the effective weight of materials and building up of pore pressure, which cause weakening of shearing strength of soil profiles.

The man-made factors are represented through maps, following the same configuration presented above for the other thematic maps.

Stability analysis under static conditions. This analysis combines information about surface features of every slope with its geotechnical properties.

Stability analysis are based on preparation of stability number charts for every representative soil profile, considering variations in sloping ground, shearing strength, groundwater conditions and potential failure surface. These charts follow the concept proposed by Taylor (1948); they are designed to estimate critical height of slopes for particular conditions of sloping ground and geotechnical properties. Application of this methodology requires this kind of charts to be developed for typical geometric and soil profile conditions of the region, so that they may be representative of expected slope behavior under static conditions.

The ratio between critical height and real height constitutes the measurement of slope stability. This ratio is considered as a safety factor and its variation is evaluated to define different levels of landslide hazard under static conditions. Ranges of safety factors allow the preparation of a landslide hazard map under static conditions. The landslide hazard map is useful to identify factors with marked influence on stability conditions, and in this way it is possible to find mitigation strategies. Figure 6 shows a sector of landslide hazard map under static conditions of the city of Armenia.

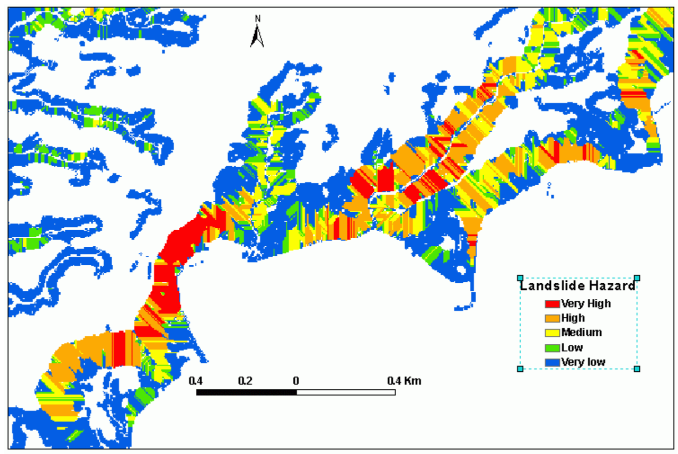

Fig. 6. Landslide hazard map under static conditions of the city of Armenia.

Comparison of resulting hazard map with real landslides: This step can not be applied for all cases, because there are not always available data. Application of this methodology in the city of Armenia showed good correlation between landslide hazard map and real conditions. It is important to point out that this methodology shows good reliability only if all controlling factors are involved; it depends on compilation and analysis of basic information. In the specific case of Armenia landslide hazard study, natural and man-made factors were considered for the analysis. It was found that water management problems play a very important role on stability conditions in this region. If these man-made factors would not be considered in analysis, the results would not reflect good correlation to real conditions.

Zonification of landslide susceptibility under earthquakes

Zonification methodology of landslide hazard under dynamic conditions constitutes the second stage of analysis and it is based on the results of the analysis under static conditions. Analysis starts with estimation of the stability number using the real height of every slope and its shearing strength properties. The stability number is used to estimate the critical sloping ground, which represents the maximum sloping ground that guarantees a stable slope. Comparison between the critical sloping ground (βcritical) and the real sloping ground (βreal) permits to evaluate the limit acceleration that the slope can bear keeping its stability. The real or representative sloping ground, as it was pointed out above, is based on analysis of sloping ground distribution along the slope. Figure 7 illustrates the concept of critical sloping ground.

Considering earthquake hazard conditions of the region for different return periods and results of earthquake ground response studies, it is possible to map the variability of the site maximum acceleration in the region. The ratio between the site maximum acceleration and the limit acceleration represents a safety factor of slope stability under earthquakes, and it is the clue parameter to generate the correspondent hazard map.

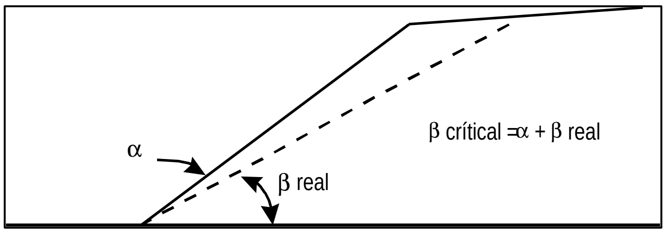

Fig. 7. Critical sloping ground.

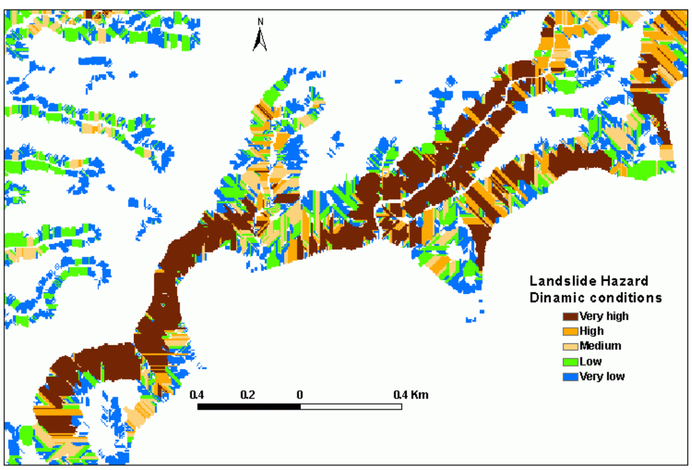

Fig 8. Landslide hazard map under earthquake conditions in the city of Armenia (Rock acceleration: 0.15 g).

Figures 8, illustrates the slope stability hazard under earthquakes in the city of Armenia, taking into account rock acceleration of 0.15 g. These analyses were also carried out for other rock acceleration values (0.05 g, 0.20 g and 0.30 g), in order to show the marked dependence of earthquake scenario on resulting landslide hazard map.

CONCLUSIONS

GIS methodology for zonification of slope stability under earthquakes is focused to involve all of the physical variables that control landslide susceptibility such as surface features, static and dynamic geotechnical properties. This approach points out the importance of identifying independent slopes, by using flow direction and sloping ground parameters. It was possible to conclude that the identification of independent slopes constitutes an important clue to carry out reliable stability analyses of a region.

Zonification of slope stability of the city of Armenia, using this methodology, allowed the identification of the great influence of man-made factors on landslide susceptibility, not only under static conditions but also under earthquakes.

Stability of every slope under earthquakes depends on its geometry, surface features, geotechnical properties and associated local site effects. Application of this methodology requires detail knowledge of seismic hazard and earthquake ground response, since variations on these factors generate important differences on expected response of different sectors of a region.

Zonification results of landslide hazard are so useful for government agencies, which have in charge disaster prevention and mitigation programs. These analyses provide information to prioritize risk management measures related to location of new infrastructure and provisions of land use, among others.

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