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An Introduced Methodology for Estimating Landslide Hazard for Seismic andRainfall Induced Landslides in a Geographical Information System Environment

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An Introduced Methodology for Estimating Landslide Hazard for Seismic and Rainfall Induced Landslides in a Geographical Information System Environment

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Abstract

The demand for estimating landslide hazard has evolved during the last decade. Landslides are characterised among the most severe natural hazards, which can cause casualties, fatalities, harm or detriment in natural and man-made environment.

In the first part of this paper the results of the research conducted on slope deformation due to seismic loading are presented. According to field observations deformation and displacement of natural and man-made slopes in strong earthquakes are common phenomena, even though they are associated to moderate magnitude seismic events. These permanent displacements are due to seismic loading, and are produced because the material, through which acceleration pulses have to travel before reaching the ground surface, has a finite strength, and stresses induced by strong earthquakes may overcome this strength limit and bring about failure. Many methods were developed in order to assess the earthquake induced ground displacements due to seismic energy flow. We applied the simplified Newmark's model, in order to study the problem of slope stability estimation and induced permanent deformations.

In the current paper, the outcome of the studies attached to slope stability estimation under static and dynamic conditions considering the factors controlling safety conditions is introduced. These principal factors were first introduced to an artificial neural network and the estimated factor of safety and displacement were subsequently implemented in a geographical information system. A software tool was developed in order to produce landslide hazard maps due to static and dynamic loading, implementing failure criteria.

In the second part, the results of the investigation of slope hydrology conditions in slope stability are presented. In these cases the factor of safety decreases due to prolonged precipitation and eventually the slope may fail. A parametric study of the effect of suction zone in slope stability of unsaturated soils is examined. This study focuses on slope behaviour under rainfall conditions.

Introduction

Landslides are studied systematically, in order to evaluate the nature of the hazard and the damages to human life, buildings and infrastructures, transportation systems, utilities and lifelines. They are complicated processes, mainly because of the many different causal factors involved in the manifestation of the phenomenon i.e.

lithology, geological structures and joints, geomorphologic features, slope angle, relative relief, land use, ground water conditions, climate and seismic activity. Climate and seismic activity change periodically and they are the two main natural triggering causal factors contributing to landsliding.

Slope movements are associated to quick changes in the position of masses both in natural or man-made slope cuts and fills during civil-works, and the driving forces, are body forces such as the gravity and the seismic action. The influence of climate on landslide processes can be considered either as a weathering factor, acting slowly, or as a rapid influencing factor such as rainfall, snow or frost. This paper is considered to present methods of landslide assessment, using various criteria and finally proposing a dynamic landslide susceptibility model.

Particularly in the last two decades, the assessment of landslide, hazard and risk has become an important subject for engineers earth scientists, in order to support the various stakeholders. There is also an increasing awareness, of the socioeconomic significance of landslides and an increased pressure of development and urbanization in terms of sustainable development.

Landslide occurrence in Greece

Complex structure and strong tectonic fracturing influence landslide occurrence in the Greek territory resulting in serious problems in population and the economy. In western and central Greece many factors favor slope instability, such as strong relief, lithology, neotectonics, seismicity and occasional heavy precipitation. Eastern Greece depicts more stable characteristics since this part of Greece consists mostly of compact and cohesive metamorphic rocks. It is characterized by less intensive tectonics, and receives less precipitation.

Figure 1, demonstrates the general landslide distribution in Greece according to landslide events covering the period of the last forty years (Koukis et al 1992). According to (Papazachos and Papazachou 1989), earthquake induced landslides follow the same general distribution presented in the above figure.

Landslide causative factors

Popescu (1994), proposed factor of safety variation (FS) as a function of time, for a given slope. Seasonal rainfall and evaporation, is reflected in seasonal variations in the FS. Landslide causative factors can be separated to preparatory causal factors and triggering causal factors. The computed value of FS is a clear and simple distinction between stable and unstable slopes. According to Crozier (1986), it is preferred to characterize existing slopes as stable, marginally stable, and actively unstable.

Introduced methods of slope stability estimation in the GIS environment

One of the main advantages that GIS offer is the development of hazard occurrence models, permitting evaluation of results and adjusting the input variables with new data.

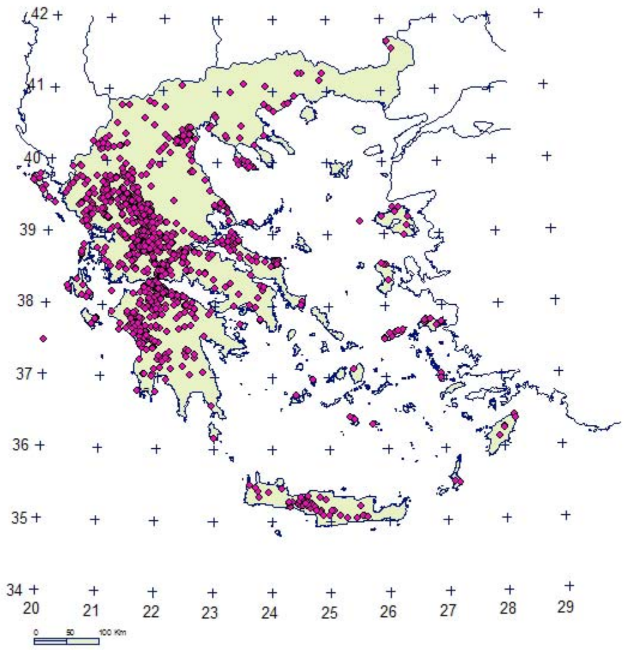

Figure.1 Landslide distribution in Greece.

Because of the fact that deterministic models require homogeneity of the data used for the analysis, averaged values of the geotechnical properties are used. The data required in the spatial analysis with GIS may include information on lithology, structure and geomorphology, since these factors are not time dependant.

In order for the analysis to be performed, we use the following approaches according to assumed failure mechanism:

- Deterministic modeling for circular landslides

$$F = 4.32 \cdot \left(\frac{c' \cdot \mathrm{cosec}\beta}{\gamma \cdot \mathrm{H}} \right) + 1.22 \cdot (1 - r_u) \cdot \cot\beta \cdot \tan\phi + 0.005 \quad (1)$$

- Deterministic modeling for plane landslides

$$F = \frac{\tan\phi'}{\tan\beta} \quad (2)$$

  where β is the slope angle, H the height of the slope, r_u the pore pressure ratio, c' the effective cohesion of the soil, γ the unit weight and φ' the internal effective friction angle.

- Deterministic modeling for wedge failure.

  The comprehensive method of (Hoek and Bray, 1981) is implemented in the GIS tool (Charalambous 2006). The stability of each slope is examined depending on the existing principal discontinuity families.

- Back – propagation algorithm for safety factor prediction for the three different failure mechanisms already examined.

  In terms of supervised encoding gradient descent method was applied in order to predict static safety factor and earthquake induced displacements. The input data (Sakellariou and Ferentinou, 2005) for slope stability estimation consist of values of the following input parameters: unit weight γ, cohesion c, angle of internal friction , slope angle, height, and pore water pressure ratio , for soil or highly fractured rock slopes. As an output, the networks estimate the factor of safety that can be modeled as a function approximation problem, and stability S that can be modeled both as a function approximation problem and a classification problem, assuming a circular mode of failure. Certain routines are developed in order to export data from the GIS environment and load them in the Matlab v6.5 environment in order to estimate FS through computational neural networks. The outcome of the training procedure is imported in the GIS landslide hazard assessment tool.

Produced Landslide Hazard Zonation Maps

Natural hazard is defined as the probability of occurrence of potentially damaging phenomena within a specified period of time and within a given area (Varnes 1984). Zonation refers to the division of the land in homogeneous areas or domains according to the degree of actual or potential hazard (Varnes 1984). Hence the proposed models are able to predict landslide prone areas without any clear indication of when they are likely to take place. In this paper hazard is used as a quantitative estimation of landslide occurrence over a given region, a time period is not defined in the model.

The particular model can be applied at regional or medium scale, and is characterized as hybrid model combining both methods of index overlay maps, neural network technologies, or simplified statistical equations in order to estimate in a deterministic mode the rate of landslide hazard.

In this geotechnical landslide hazard model, the probability of landslide occurrence is expressed through FS value or reliability index. Many regions were used as case studies Vouraikos valley (Sakellariou et al, 2001), near the city of Aigio (Ferentinou 2004), a site near Metsovo junction (Charalambous 2006). The proposed methodology has two basic advantages over the already widely used deterministic methods.

- FS is calculated for every single terrain unit of the study area. Applying this method we overcome, the problem of spatial extrapolation of FS value, which was calculated only for certain slopes in the entire area.
- The proposed tool is a dynamic tool which enables the user to alter the values of the geotechnical parameters, add parameters, for example the existence of piezometric level or the influence of a seismic event, of certain magnitude. Each of the above scenarios is modeled, and an appropriate landslide hazard map can be produced. it is possible to optimize the model, simulating the available data, in order to model the engineering geological regime of the study area, referring to the temporal variability of the geotechnical parameters.
- Using the proposed model one can estimate FS, assuming the circular, planar, wedge or rock fall failure mode, overcoming the limitations stemming from infinite slope model.

This tool was initially developed in Arc/Info 7.0.1 Macro language and it is called “Landslide Hazard Analysis” (Figure 2). Three versions of the software have already were also created optimizing its benefits (Ferentinou 2004, Charalambous 2006).

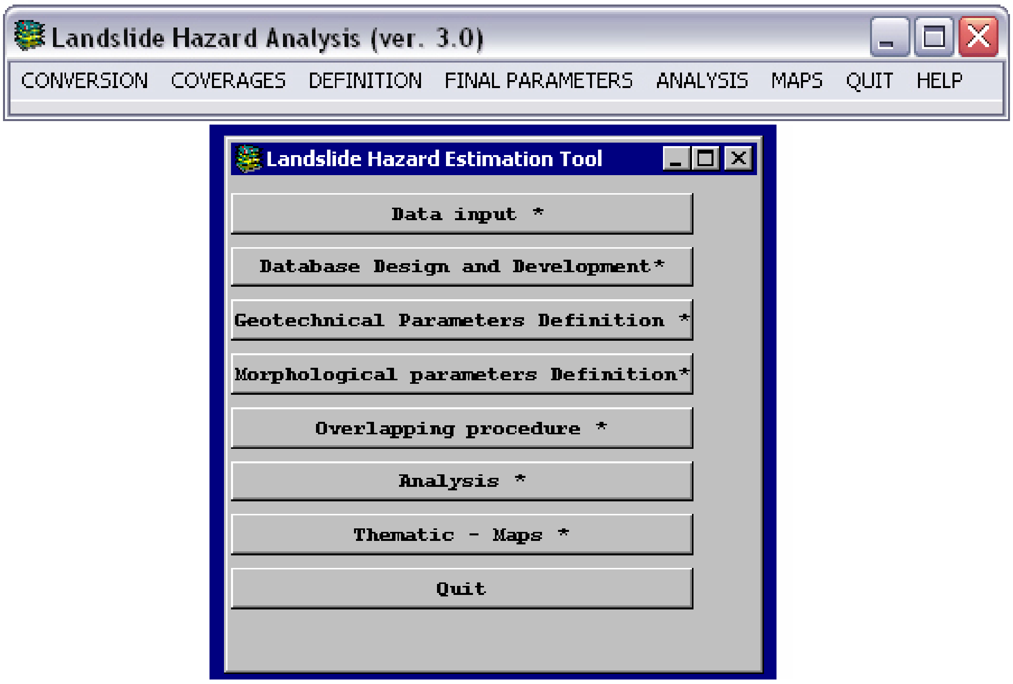

Figure.2 Landslide Hazard Estimation Tool main pop-up menu.

Seismic induced landslides

In this section a landslide hazard assessment methodology is introduced, which couples both geographical information system technology and artificial neural networks. In terms of a geotechnical model of landslide hazard assessment the selected study area is an area of high seismicity near the city of Aigio. In this model failure criteria under static or dynamic conditions for soil slopes were implemented through suitable algorithms. Static FS was initially estimated through the use of computational neural networks. The boundary of maximum distance R_e, of earthquake induced landslides due to a shock event coming from the Aigio active fault of magnitude Ms = 6.0, was also assessed (Ferentinou 2004), based on empirical relations for Greece (Papadopoulos et al 2000). The model introduced by Ambraseys et al (1995), was applied in order to estimate co-seismic displacements. The aforementioned authors relied on Newmark’s method and considered that displacements induced to natural and man-made slopes are developed in three stages. In the current research the deformation during the first stage was estimated.
The graphs depicting the attenuation of permanent displacements caused by an earthquake of surface wave magnitude M = 5.0, 6.0 and M = 7.0 as a function of source – site distance, were employed.

Equation (3) which is an empirical attenuation relation for one-way displacement on slopping ground:

$$\log(u) = -2.41 + 0.47M_s + -0.010r + \log[(1-q)^{2.64}(q)^{-1.02}] + 0.58p \quad (3)$$

u : displacement (maximum cumulative slip caused by a particular time – history) due to one-way, down-slope motion in cm.

k_y : critical acceleration, k_m maximum acceleration. The focal depth is h h and the source distance d d, with $r = (d^2 + h^2)^{0.5}$ in km.

M_s : surface wave magnitude., ($p = 1.646$ probability of excess 5%).

Rock fall analysis in GIS environment

Rock falls are mainly related to water impact i.e. rain freeze – thaw, snowmelt, differential erosion, springs and earthquake events. In Greece rock falls are very common and strongly related to earthquakes. A 3-D Rock fall simulation model was developed (Charalambous 2006). The model is implemented in an application developed in ArcGIS, called “Rockfall Analysis”. Via this application, the 3-D trajectory of a rock particle is calculated based on the geotechnical and geometrical properties of the ground, namely, the digital terrain model of the study area, the initial location of the rock, the magnitude and the direction of the initial velocity and the material properties (frictional characteristics and the 3-D coefficients of restitution of the ground). The calculation of the trajectory, as well as the vertical projection of the rock fall, is accomplished in ArcMap environment. Furthermore, using ArcScene the capability of the 3D representation and the animation of the rock fall is given, providing a better visualization of the rock fall as would have occurred in reality (Figure 3).

Figure.3 3D representation of rock fall analysis in a GIS environment, (Charalambous 2006).

Rainfall induced landslides

The introduced Landslide Hazard Assessment Tool was used in order to initially perform a screening analysis and characterise the study area according to anticipated F.S, limits. A certain marginally stable slope was selected, which lies in the area characterized by 1< FS < 1.25. In order to conduct a more accurate analysis, both positive and negative pore water pressures have been taken into account. Two powerful commercially software were used in order to estimate FS and the critical slip surface, Slide v5.0 and Face2 v6.0, both provided by Rocscience. Slide performs a 2D limit equilibrium analysis for evaluating the stability of circular and non-circular failure surfaces in soil and rock slopes. In the current study we used Bishop method. Phase2 is a 2-dimensional elasto-plastic finite element program for calculating stresses and displacements. Slope stability problems are analyzed using the Shear Strength Reduction (SSR) technique. This technique allows the user to perform a finite element slope stability analysis and compute the Strength Reduction Factor (SRF) which is equivalent to the FS of the slope. In fact, the strength parameters of the slope are reduced by a certain value of SRF and then the finite element stress analysis is computed. This process is repeated for different values of SRF, until the model becomes unstable. The determined SRF is, actually, the safety factor of the slope. FS determined by SLIDE is 1.04, while with PHASE the critical value of SRF was estimated at 0.96 (Figure 4). The above results show a good convergence with GIS initial screening.

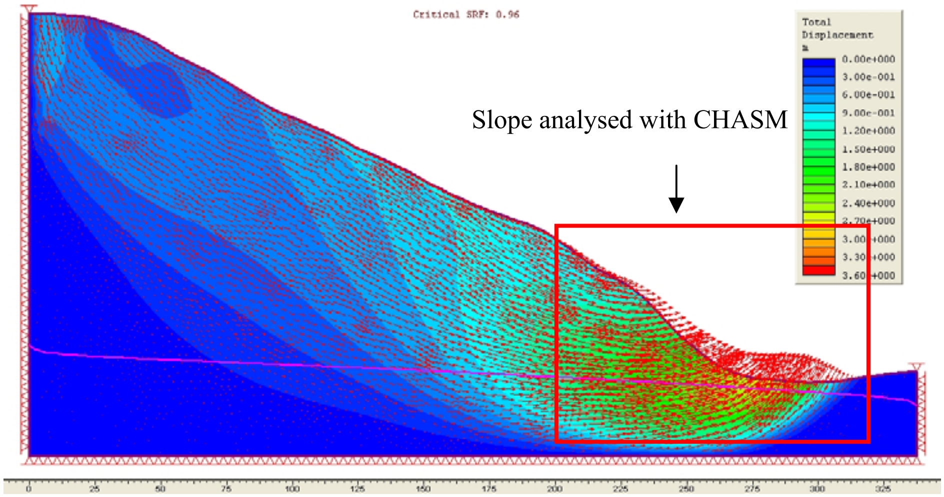

Figure.4 Displacement analysis using PHASE2.

In order to study precipitation effect on the specific slope the Combined Hydrology and Stability Model (CHASM, Anderson et al 1991) was used. The model simulates dynamic stability conditions, allowing identification of the minimum FS, the characteristics of the failure and the time of occurrence for any particular initial slope condition and rainfall event. The main characteristic of the model is that a dynamic 2D hillslope hydrology model is coupled directly to a two-dimensional slope stability model. Positive and negative pore pressures are calculated during each iteration, taking into account their change due to the rainfall duration.

The procedure adopted in the modeling of the slope hydrological system is a forward difference explicit, block-centered finite difference scheme (Anderson 1991). The parameters that were designated were: evaporation, rainfall parameters, initial surface soil water conditions, initial groundwater table, slope height, slope angle, permeability and the soil strength parameters (c’ and φ’) and, the unsaturated parameters of the soil (zone that suction extends, φ^b angle) can be, also, designated. In order to estimate rainfall rate we relied on reference reports and rainfall data from the study area. FS was calculated at 1.16. A scenario of 96hr simulation with, rainfall duration 24hr was selected and resulted to F.S. further reduction to 1.04 which proves that the current slope is prone to landsliding due to precipitation and that FS diminishes even after the end of the rainfall event due to negative pore pressures.

Conclusions

In the current paper a methodology is presented which produces landslide hazard maps due to static or dynamic loading, implementing failure criteria. GIS were proved to be an indispensable tool for managing geological geotechnical, seismic and climate information. Moreover, they offer the potential of a complete analysis, using tools of spatial analysis, as well as the implemented algorithms in order to produce landslide hazard assessment models. In terms of rainfall induced landslides the proposed model was used as a screening tool in order to detect landslide prone areas, and further analyse them applying sophisticated analytical and numerical tools.

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