EVALUATION OF EARTHQUAKE- TRIGGERED LANDSLIDES IN EL SALVADOR USING A GIS- BASED NEWMARK MODEL

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ABSTRACT :

In this work, a model for evaluating earthquake-triggered landslides hazard following the Newmark methodology is developed in a Geographical Information System (GIS). It is applied to El Salvador, one of the most seismically active regions in Central America, where the last severe destructive earthquakes occurred in January 13th and February 13th, 2001. The first of these earthquakes triggered more the 500 landslides and killed at least 844 people. This study is centred on the area (10x6km) where the most tragic landslide occurred (Las Colinas landslide).

The model is based on the Newmark method, which treats a potential landslide as a rigid block sliding on an inclined plane. It requires inputs characterizing the geological conditions and the intensity of earthquake ground motions. The procedure includes factors such as earthquake magnitude, source-site distance, strength of geologic materials, ground water conditions and slope.

The data set used in the application includes an earthquake-triggered landslides inventory for the 2001 earthquakes, a 1:100,000-scale geologic map of the region, digital cartography, strong-motion records, data on engineering properties of geologic units, and high-resolution (10 m) digital elevation models of the topography, all of them integrated in the GIS. Displacements of possible landslides along the slope (Newmark displacements) are computed from the Arias Intensity (I_a), and the Critical Acceleration (a_c); the latter is inferred from the Factor of Safety (Fs). Newmark displacements have been applied to predict a landslide hazard map at regional scale, in areas where ground-shaking and geological conditions are well known.

KEYWORDS: Newmark model, landslides, hazard, GIS, El Salvador

1. INTRODUCTION

In January and February of 2001, El Salvador experienced several destructive earthquakes, which caused hundreds of landslides of varying sizes. The high seismicity zone, in addition to potentially heavy rains, resulted in an elevated hazard zone. The sequence of seismic events that occurred in El Salvador during 2001, was initiated with an earthquake on January 13 (Mw 7.7), which destroyed nearly 108 000 houses, killed at least 944 people, and caused massive damage due to the subsequent landslides, among these, the Las Colinas landslide was the most tragic. A considerable amount of soil (200 000m^3) was fluidised on a mountain ridge rising south behind the Las Colinas area of Nueva San Salvador (Santa Tecla, La Libertad). The death toll is estimated at approximately 585 persons. This earthquake was followed by numerous aftershocks, and more earthquakes in the centre od the region.

The hazard map of the Newmark Displacement was modeled for a scenario corresponding to the January 13th 2001 earthquake on the El Salvador. We have proposed the Newmark´s approach to the assessing earthquake-triggered landslides hazard in a Geographical Information System (GIS). This method is based on a simple model of a block sliding on an inclined plane. The results are the Newmark Displacement (ND), that reflect the distance of sliding during the seismic shaking in centimeters.

2. DATA

The methodology for the assessment of earthquake-triggered landslides hazard using a GIS. The evaluation of susceptibility requires data input of variables representing physical parameters known to contribute to the initiation of landslides. Data requirements for the hazard analysis included soil parameters, topography, fault location and strong motion registers. Drained cohesion, friction angle and unit weight of the regional soils were estimated based on soil surveys studies and geology map of the area.

El Salvador GIS is composed of diverse information: 1:100.000 geological map, 1:25.000 Digital Cartography, precipitation data, ground strong motions records, epicentres catalogue, inventory of landslides,…. The data were provided by the Servicio Nacional de Estudios Territoriales de El Salvador (SNET), and the Universidad Centroamericana Simeón Cañas (UCA). All these layers from different sources and formats have been integrated into GIS. There are other layers generated maps and requirements (Digital Terrain Model (DTM), slope map, curvature, effective cohesion, etc.) for the assessment hazard.

3.NEWMARK METHOD

The original Newmark's Method (Newmark, 1965) is based on a simple model of a block sliding on an inclined plane. It aims at computing the distance of sliding during the seismic shaking, the Newmark Displacement (ND). The Newmark Displacement is computed from an acceleration time history by integrating twice the values larger than the critical acceleration (the threshold acceleration required to initiate sliding). This procedure can be applied to GIS.

One of the most popular simplified Newmark models was developed by Jibson (1993). This relationship is based on Arias intensity (Ia), rather than peak ground acceleration, to better characterize the damaging effects of ground motion. The regression equation was calibrated by double-integrating eleven acceleration time histories, including ten from California.

$$\log ND = 1.46 * \log I_a - 6.642 * a_c + 1.546 \quad (3.1)$$

where ND is in centimeters, Ia is in meters per second, and ac is in terms of g.

Later, the relationship was updated using 555 records from 13 earthquakes (Jibson *et al,* 1998). The equation takes the following form:

$$\log ND = 1.521 * \log I_a - 1.993 * \log a_c - 1.546 \qquad (3.2)$$

Then, slope stability calculations using this method consist in first calculating a static factor of safety (Fs), followed by a calculation of the yield acceleration from Newmark's equation.

3.1. Acceleration Critical

The first step in conducting a Newmark's analysis is to define the critical acceleration above which the slope will deform. Assuming negligible loss in shear resistance during shaking, the critical acceleration in terms of gravity (a_c) for a slope with planar slip can be determined with

$$a_c = (FS - 1) \cdot \sin \alpha \qquad (3.3)$$

where F_S is the static factor of safety and α is the slope angle.

Many different models exist for the calculation of Safety Factors, we use the simplest model, the so-called infinite slope model. This two dimensional model describes the slope stability of slopes with an infinitely large failure plane. The Safety Factor is calculated according the following formula (Brunsden and Prioir, 1979). In order to evaluate the factor of safety for an infinite slope for dry conditions can be expressed as Eq. 3.4.

$$F_S = \frac{c' + \left(\gamma d \cos^2 \alpha \tan \phi'\right)}{\gamma d \sin \alpha \cos \alpha} \qquad (3.4)$$

where c' is the drained cohesion; γ is the unit weight of the material; d is the vertical depth to failure; α is the slope angle; and Φ' is the drained effective angle of internal friction for the landslide material.

3.2. Arias Intensity

Arias intensity is defined as the sum of all the squared acceleration values from seismic strong motion records. Arias intensity has been found to be a fairly reliable parameter to describe earthquake shaking necessary to trigger landslides. Arias (1970) defined this measure of the shaking content of a strong-motion record as

$$I_a = \frac{\pi}{2g} \int_0^d \left[a(t)^2\right] dt \qquad (3.5)$$

where g is the acceleration of gravity, d is the duration of the strong shaking, a is the ground acceleration, and t is time. Arias intensity measures the total acceleration content of the record, it provides a more complete characterization of the shaking content of a strong-motion record than does the peak ground acceleration.

4. APPLICATION TO SAN SALVADOR AREA

A Newmark analysis is applied to San Salvador region using GIS for the 13th January of 2001 earthquake scenario.The epicentre was located off the western coast of El Salvador, at 12.80°N/88.79°W, in the subduction zone between the Cocos and Caribbean plates, with a magnitude Mw 7.7 and a focal depth of 40 km (Benito et al., 2004). The first step in Newmark's displacement method is determining the critical acceleration of each morphological unit, centered in the area of San Salvador (10 x 6 Km), so it was accomplished using Eq. 3.2.

4.1. Evaluation of Acceleration Critical

The GIS-based Newmark analysis requires creation of a critical acceleration map. The thrust angle for each pixel is approximated by calculating slope from a digital elevation model (DEM). Then, we determine static safety factors using the infinite slope model.

First, we have analyzed the geologic map and compiled information based on the estimated soil properties, effective cohesion, angle friction and unit weight of each lithologic unit. The geotechnical properties were assigned to the geologic units of the digital geologic map, wich has been classified in six classes: hard rock, soft rock, medium, soft, and very soft soil (Figure 1).

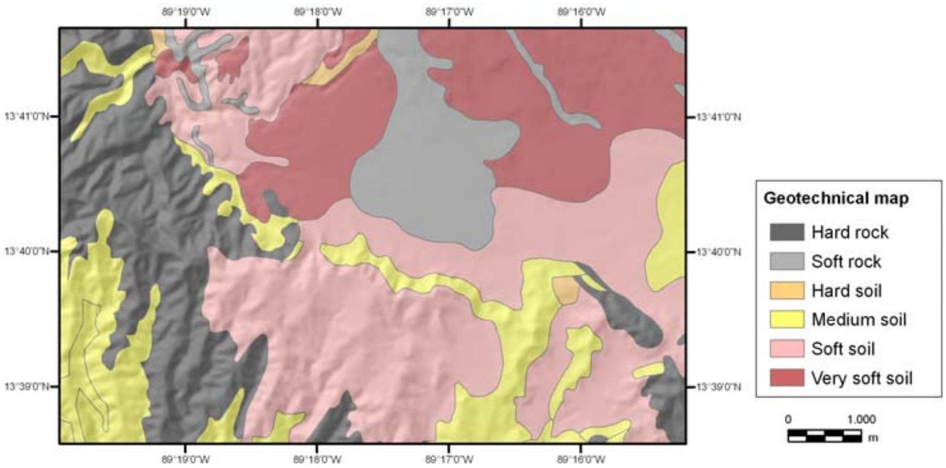

Figure 1 Geotechnical map of San Salvador area (10 x 6 km)

The geotechnical parameters used in the Newmark analysis in the calculation of this application is show in the table 1.

Table 1 Geotechnical parameters: unit weight, friction angle and effective cohesion

Class	Classification	Unit weight(KN/m^3)	Friction Angle (º)	Cohesion (KN/m^2)
1	Hard rock	26	45	300
2	Soft rock	22	40	200
3	Hard soil	11	30	60
4	Medium soil	15	30	30
5	Soft soil	11	20	30
6	Very soft soil	11	20	23

The areas of slope less than 3 degrees and curvature between 0.2 and -0.2, were excluded from analysis because of negligible hazard from landslides. The factor safety (Fs) was calculated using the Eq. 3.4, which are shown in the figure 2.

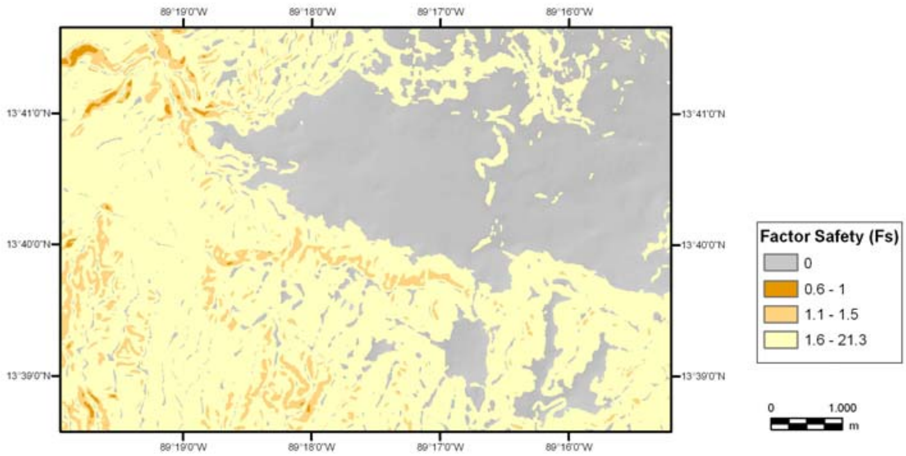

Figure 2 Factor safety (Fs) using the expression: with dry conditions

Then, critical acceleration values were calculated to each pixel in the map for both dry, which is represented in the figure 3.

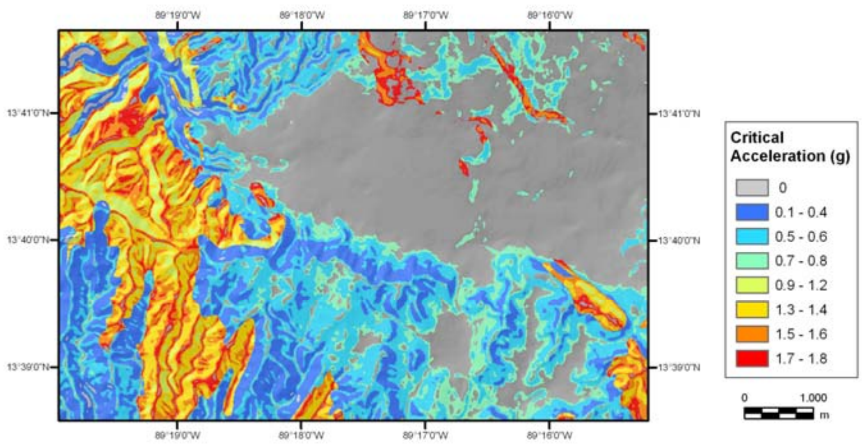

Figure 3 Critical acceleration *(a_c)* expressed in g unit.

4.2. Evaluation of the Arias Intensity

For the calculation of the spatial distribution of Arias intensity, we have selected an attenuation based on California earthquake data (Wilson and Keefer, 1985).

$$\log I_a = -4.1 + M - 2\log R \tag{4.1}$$

A map is created from the Eq. 4.1, which shows the Arias intensity that could be produced on 13th january 2001 scenario (figure 4), with a given earthquake magnitude (Mw 7.7), earthquake depth (40 km) and distance from earthquake's epicenter.

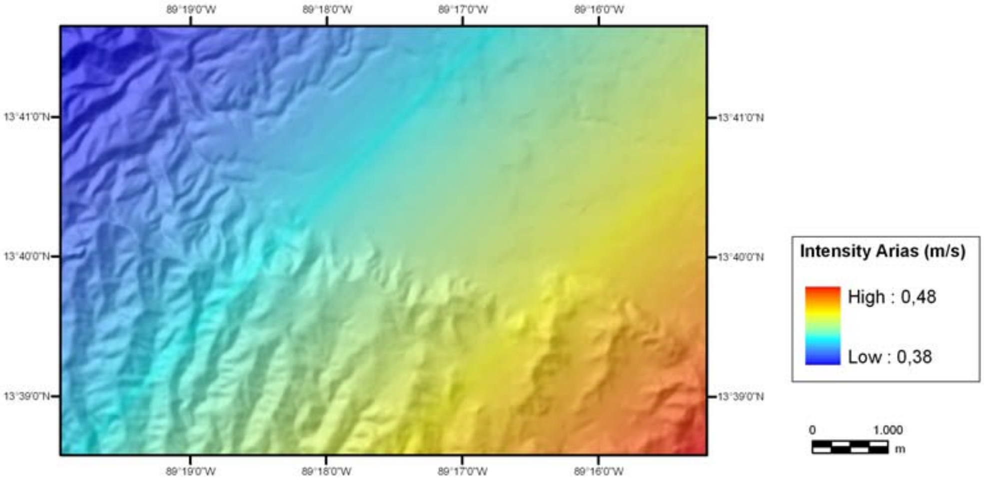

Figure 4 Estimated Arias intensity (g) in rock

In El Salvador, landslides triggered by earthquakes occur as soil and rock slides on volcanic slopes, and more abundantly as soil falls and slides on slopes formed from volcanic ash. This fact suggests that topographic amplification of seismic shaking (Ashford et al., 1997) is produced, together with the geologic amplification, probably due to the low density of the pyroclastic materials. Then, the estimated Arias Intensity consider both effects folowing expresion:

$$I_{a\_site\_effect} = I_a * A_G * A_T \tag{4.2}$$

According to the relation between s wave velocity (v_s) of the bedrock and the respective lithologic unit, it is possible estimate the amplification by geology, such as it is shown in the table 2.

Table 2 Amplification factor (A_G) due to the lithology unit.

Class	Classification	Amplification Factor (A_G)
1	Hard rock	1
2	Soft rock	1.1
3	Hard soil	1.7
4	Medium soil	2
5	Soft soil	2.2
6	Very soft soil	2.8

The influence of surface topography has been noted in several earthquakes reports and demonstrated in instrumental studies (Faccioli, 1991); however, there is not enough data to derive a correlation between topography and amplification. Theoretical and numerical models indicate that seismic waves are amplified at ridges crests (convex features such as cliffs) and deamplified in valleys (concave features). For the amplification due to topography, we used the curvature map, and assign a factor in function of the range of the table 3.

Table 3 Amplificaton factor due to topograhpy

Class Range	Amplification Factor (A_T)

-10.0	-1.5	0.5
-1.5	-0.9	0.5
-0.9	-0.5	0.7
-0.2	0.2	1
0.2	0.5	1.5
0.5	0.9	1.5
0.9	1.5	2
1.5	10	2

In the figure 5, we estimate Arias Intensity *(Ia)* considering local effect, due to geology and topography amplification factor (Eq. 4.2).

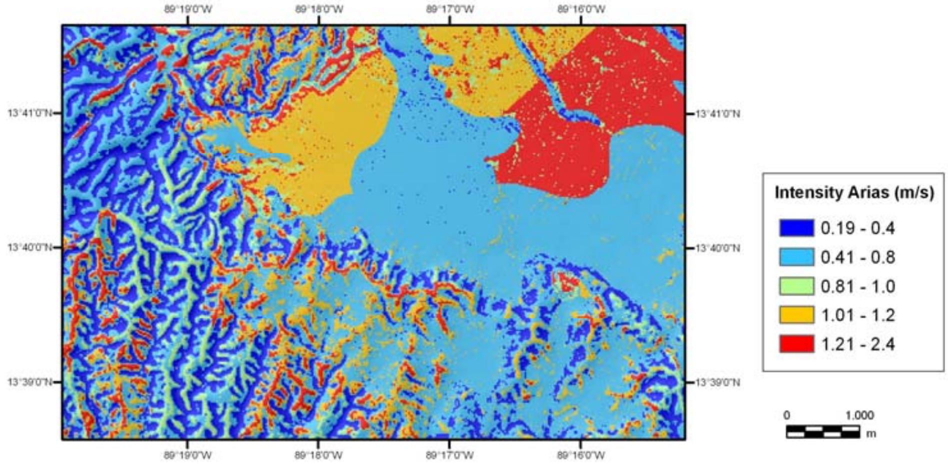

Figure 5 Estimated Arias Intensity *(I_a)* with geology and topography amplification factor.

The final step consists in a GIS-based Newmark analysis is to calculate a map of Newmark displacement (ND) based on the maps of critical acceleration and earthquake ground motion. We used the most current simplified Newmark model to perform this step, such as Jibson *et al.* (1998), (Eq. 3.2). This map shows the Newmark displacement (figure 6), which consist in sum the individual displacements that occur at each instance that the earthquake accelerogram exceeds the critical acceleration of the slope.

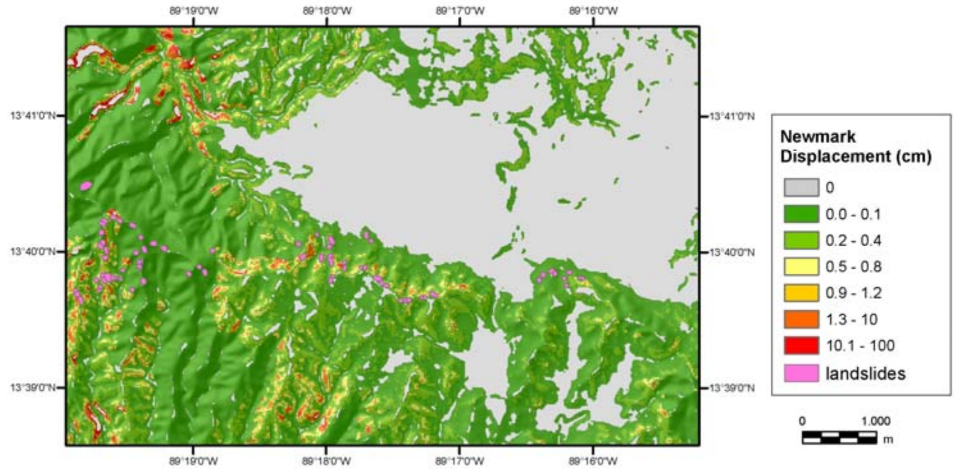

Figure 6 Newmark Displacement for the 13th January 2001 earthquake scenario in San Salvador, considering site effect, together the inventory landslides.

The map includes six levels of relative hazard in terms of Newmark's displacement (cm): low (0.0-0.1), moderately low (0.2-0.4), moderate (0.5-0.8), moderately high (0.9-1.2), high (1.3-10), and very high (10.1-100). Newmark's displacement is considered a relative index of slope-performance, rather than an estimation of real-world deformation (Jibson et al., 1998). Thus, zones of high hazard should be interpreted as having a hazard that is greater than moderately high and less than very high. Zones of low hazard may be interpreted as having the lowest relative hazard within the mapped area. The high and very high zones could experience some dense concentrations of landslides (landslides per pixels), while low hazard zones will only experience a few isolated landslides. The likelihood of slope failure increases with greater levels of hazard. In the model, the landslide densities were calculated for each: low zones (0.9), moderate (1.5), moderate high (2.8), high and very high (0.5). The major area affected by landslides is given in the moderately high class. In the figure 6, we note that most areas of highest hazard are associated with relatively weak bedrock units (soft soil class).

5. CONCLUSION

Newmark's method is based on physical parameters and takes into account shaking characteristics with varying source to site distances. From data sets as the topography, geology, shear strength, and seismic shaking of an area or region, and following GIS-based Newmark analysis, we can estimate hazard maps showing the spatial distribution of slope-failure probability.

The probability equation (Eq. 3.2, and therefore Eq. 4.1) can be applied using any set of ground-shaking conditions of interest. However, when we apply it to regions with different conditions increases the uncertainty of the results. It is due to this equation was calibrated from different earthquake data, mainly California earthquake events, but not specific strong motion data of El Salvador. In future investigations, recalibration for use in the region of El Salvador is desirable. Other possible research on landslide hazard zonation can be carried out for saturated ground-water conditions. An important aspect in this work has been that, effects of local soil conditions and topography on ground motion amplification were considered.

Newmark's displacement approach is suited for small and medium scale analysis to identify potential areas of seismically induced landslides. The hazard map produced (Figure 6) can be useful in emergency tasks, prevention and mitigation planning.

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