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Comparing Newmark's method at regional, sub-regional and site scales: seismically-induced La Paca rock-fall case (Murcia, SE Spain)

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Abstract

The Lorca Basin (Murcia) is located in one of the most seismically active regions of Spain. This area is very interesting for studying earthquake-induced slope instabilities as there are well known cases associated to specific earthquakes (e.g., Bullas 2002, La Paca 2005). In this work we present our investigations at regional and site scales. For the regional scale, we have used a GIS to develop an implementation of Newmark's sliding rigid block method. We have particularly introduced a new variation to consider soil and topographic amplification effects. Subsequently, we have produced "Newmark displacement" maps for both probabilistic and deterministic seismic scenarios. We have found that rock-falls produced during the last earthquakes in Lorca Basin are associated to Newmark displacements lower than 2 cm. To support this hypothesis we have applied the Newmark method to La Paca rock-fall at a site scale. We have performed a back-analysis to estimate the static safety factor and the critical acceleration. Finally, we have compared the Newmark displacement calculated at La Paca rock-fall at a site scale with our GIS estimations in order to improve the calibration of Newmark's method at the regional scale.

Key-words: GIS, Newmark, Rock-falls, Topographic amplification

1. Introduction

Seismically-induced slope instabilities are one of the most hazardous secondary effects of earthquakes. They can cause damage to buildings and infrastructure and widespread loss of human life. Damage and fatalities from triggered landslides and other ground failures has sometimes exceeded damage directly related to strong shaking and fault rupture during earthquakes (Keefer, 1984).

Slope instability hazard is the probability of occurrence of a potentially damaging slope rupture within a special period of time and within a given area (Varnes, 1984). Factors which determine the slope instability hazard of an area can be divided into two groups: the first one is the quasi-static variables which contribute to landslide susceptibility, such as geometrical aspects, geology, geomechanical parameters and underground water condition; the second one are the dynamic variables which tend to trigger these slope movements in an area of given susceptibility, such as rainfall, earthquakes and even mankind activities. It is clear that the probability of slope instability depends on both the quasi-static and the dynamic variables. In the case of seismically-induced slope instabilities, factors are related to the energy and propagation of the earthquake (magnitude, attenuation and amplification), strength parameters of slope (safety factor), previous conditions of the slope and deformational behaviour of the materials against the seismic vibration (liquefaction, collapses).

In 1965, the Civil Engineer Nathan M. Newmark developed a simple method to estimate the permanent displacement induced by earthquakes in earth dams (Newmark, 1965). Later, Wilson and Keefer (1983) developed a variation of Newmark's sliding rigid block method and applied it successfully to natural slopes. Nowadays, this method is very often applied in regional assessments of seismically-induced slope instabilities (e.g. Miles and Ho, 1999; Luzi and Pergalani, 1996, 2000; Luzi et al., 2000; Murphy et al., 2002; Refine and Capalongo, 2002; Carro et al. 2003; Murphy and Mankelow, 2004). However, there are few studies in Spain that used this approach (e.g. García-Mayordomo, 1999; Coral Moncayo, 2002; Mulas et al., 2003; Delgado et al., 2006).

The assessment of earthquake triggered landslide hazard may be undertaken using both deterministic and probabilistic techniques. Deterministic methods are usually used to obtain a value of the expected displacement because they fix certain representative values for the input geotechnical and seismic parameters. However, probabilistic methods have been developed because most of the data can be considered as random variables.

Because all slope instabilities related variables and the susceptibility are spatially distributed, it is ideal to use a tool that can manage the spatial data for this hazard assessment. Recently, the emerging capabilities of Geographic Information Systems (GIS) provide strong functions in spatially distributed data processing and analysis. At the same time, using deterministic methods adapted to GIS can analyze easily and effectively slope stability for anticipating the slope failures.

In this work, we present our investigations about seismically-induced slope instabilities at regional, sub-regional and site scales. For the regional scale, we develop an implementation of Newmark's sliding rigid block method using a GIS. In addition, we particularly develop a new variation of Newmark's method to consider soil and topographic amplification effects. Subsequently, we produce "Newmark displacement" maps for several different input seismic scenarios. These maps will allow to identify areas with the highest potential hazard as well as other interesting areas for future detailed studies. To do this, we select the Lorca Basin (Murcia, SE Spain) because it exhibits a high seismic activity, some of the most active faults in Spain are in the surroundings of the basin and there are well known cases of disrupted slides and rock-falls associated to specific earthquakes (e.g., Bullas 2002, La Paca 2005). For a sub-regional and site scales, we select the well known case of La Paca rock-fall (Fig. 1) that it is associated to La Paca 2005 earthquake (m_{bLg}=4.7, I_{EMS}=VII). This earthquake produced widespread damages within the villages of La Paca and Zarcilla de Ramos and a very important social concern. We apply the Newmark method at sub-regional site scale in order to calculate the Newmark displacement corresponding to La Paca rock-fall. For the site scale, we based on field data to perform a back-analysis of La Paca rock-fall to estimate the static safety factor previous to the earthquake and the critical acceleration. Finally, we compare this displacement with our GIS estimation in order to improve the calibration of Newmark's method at the regional scale.

Figure 1. Rock-fall induced by 2005 La Paca earthquake (m_{bLg}=4.7, I_{EMS}=VII) in Triassic dolomites.

2. Materials and Methods

Several models have been proposed for evaluating co-seismic landslide displacements. The most popular is that proposed by Newmark (1965), where the slope instability acts as a rigid block sliding on an inclined surface. The Newmark's sliding rigid block method (1965) permits obtain the minimum horizontal seismic acceleration to overcome shear resistance and start the displacement of the rigid block:

$$a_c = (SF - 1)\ g\ \sin(\alpha) \qquad (1)$$

where a_c is the critical acceleration (in gravity units, 1g = 9.8 m/s^2), g is the gravity acceleration, SF is the static safety factor and α is the slope angle. The critical acceleration is an expression of slope capacity to resist the seismic vibration. This capacity depends exclusively of slope geometry (slope) and strength parameters of the material of the slope (safety factor). Therefore, the critical acceleration is an index of seismically induced slope instabilities susceptibility. The next step is to estimate the displacement of the slope induced by earthquakes –i.e., Newmark displacement (D_N). To do this in a regional scale we use regression equations that relate Newmark displacement to ground motion parameters such as Arias Intensity or Peak Ground Acceleration (PGA) (cf. Jibson, 2007). We based on GIS technology to the construction of Newmark displacement maps. This construction results from processing and computing several sets of maps. The first aim of this calculation is to obtain a critical acceleration map, provided we know the static safety factor. The second aim is to estimate Newmark displacements combining the critical acceleration map with peak ground acceleration (PGA) maps obtained to different seismic scenarios.

2.1. Calculation of safety factor and critical acceleration maps

To produce the critical acceleration map, firstly we arranged a lithological map from 1:50000 scale digital geological map (Baena-Pérez, 1972) from the Spanish Geological Survey (IGME). We have distinguished 3 lithological groups (Table 1) in function of general shear resistance of lithologies and their behaviour against slope instabilities. We assigned average values of specific weight, cohesion and friction angle to each lithological unit. We obtained these strength parameters from geotechnical bibliography and available geotechnical tests (cf. Rodríguez-Peces, 2008). Because of slope instabilities are controlled by previous fractures in rock-type lithologies, we assigned cohesion and friction angle values proper of discontinuity to rock-type lithological groups. Then, we calculated by iteration of ranges of cohesion and friction angle values until all safety factors obtained were higher than one (stability conditions). Finally, Table 1 shows adopted strength parameters values to next calculations.

Table 1. Lithological groups, strength parameter values considered in the calculation of safety factor (initial range of values of the strength parameters are in brackets) and seismic amplification factors.

Lithological group	Specific weight (kN/m^3)	Cohesion (kN/m^2)	Friction angle (º)	Soil amplification factor	Topographic amplification factor
Dolomites and limestones	25 (23-27)	46 (0-108)	30 (21-39)	1	1.2
Conglomerates, sandstones and argillites	22 (20-24)	31 (4-16)	33 (27-39)	1.8	1
Argillites, marls, sandstones and gypsums	21 (18-24)	36 (35-117)	26 (22-30)	1.8	1

To apply the method at regional scale, we derived a slope map from a 25x25 meters pixel digital elevation model. This digital elevation model was obtained from digital topographic maps of the Spanish Instituto Geográfico Nacional (IGN). At sub-regional scale, we derived a slope map from a 2.5x2.5 meters pixel digital elevation model. This digital elevation model was obtained from a terrestrial laser scanner survey at La Paca rock-fall location.

We calculated safety factor map assuming a simple limit equilibrium model with an infinite slope following Mohr-Coulomb criterion. To do this, we computed strength parameters maps with the slope map using next equation (Jibson et al., 2000):

$$SF = \frac{c'}{\gamma t \, sen\alpha} + \frac{\tan\phi'}{\tan\alpha} - \frac{m\gamma_w \tan\phi'}{\gamma \tan\alpha} \qquad (2)$$

where c' is the effective cohesion, ϕ' is the effective friction angle, α is the slope angle, γ is the specific weight of slope material, γ_w is the specific weight of water, t is the normal thickness of rupture surface and m is the saturation degree of rupture surface. Because of precipitations are low and water table is usually deep (over 50 m depth) at the studied area, we have considered a null saturation degree of rupture surface. Moreover, we have set a normal thickness of the rupture surface of 3 meters because slope instabilities are of a small size in the study area (1 to 6 m fallen rock blocks and 1 to 3 m superficial alteration beds thickness), mainly rock-falls and low magnitude landslides.

Finally, we combined the safety factor map with the slope map using equation (1) to produce the critical acceleration map.

2.2. Seismic scenarios and estimation of Newmark displacement maps

To estimate Newmark displacements, we have considered both probabilistic and deterministic seismic input scenarios.

Probabilistic seismic scenarios consider a hazard map in terms of peak ground acceleration (PGA) on rock corresponding to the 2475-year return periods (exceedance probability of 2% in 50 years) in Murcia Region (SE Spain). We took this map from previous publications related to RISMUR Project (Benito et al., 2006; García-Mayordomo et al., 2007).

Deterministic seismic scenarios consider either the occurrence of M_w=4.8 2005 La Paca earthquake (Benito et al., 2007; Gaspar Escribano and Benito, 2007) or the most probable earthquake for a 475-year return period (M_w=5.0) (Gaspar-Escribano et al., 2008). We calculated PGA on rock as a function of distance to the epicentre of the 2005 La Paca earthquake using the attenuation equation of Sabetta and Pugliese (1996). La Paca rock-fall is located at 7.2 km from the epicentre of the 2005 La Paca earthquake. In this situation the PGA is 0.09g. The estimated PGA range for a M_w=4.8 earthquake at an epicentral distance of 8 km for rock conditions is between 0.10g and 0.15g, which corresponds to an intensity range VI-VII (Buforn et al., 2005). Other estimations are PGA between 0.12g and 0.20g for an earthquake with M_w=4.8 at an epicentral distance of 5 km for rock conditions and PGA between 0.08g and 0.12g for the same earthquake at an epicentral distance of 10 km for rock conditions (Gaspar-Escribano y Benito, 2007). Therefore, we have considered an average PGA equal to 0.12g for the occurrence of 2005 La Paca earthquake (M_w=4.8).

PGA values of each seismic scenario are referred to rock conditions. Therefore, we need correct PGA values to allow for soil and topographic amplification effects. We adopted the soil amplification factors (Table 1) obtained in the RISMUR Project (Benito et al., 2006). Then, we multiply these amplification factors by the PGA on rock values. Moreover, we evaluated the topographic amplification factor considering slope and relative height of ridges, following Eurocode-8 provisions (CEN, 2004).

Finally, we computed each PGA map with the critical acceleration map by means of Jibson (2007) regression equation that correlates Newmark displacement to critical acceleration ratio (a_c/PGA):

$$\log D_N = 0.215 + \log\left[\left(1 - \frac{a_c}{PGA}\right)^{2.341}\left(\frac{a_c}{PGA}\right)^{-1.438}\right] \qquad (3)$$

where D_N is the Newmark displacement (in centimetres), a_c is the critical acceleration (in gravity units) and PGA is the peak ground acceleration (in gravity units). There are few published regression equations that correlates Newmark displacement to others parameters, such as Arias Intensity (Romeo, 2000; Jibson, 2007). We compared these equations to select one that provides the best results. We selected regression equation (3) in function of the ratio critical acceleration and PGA because this equation was drawn from many seismic records with magnitudes equivalent to the magnitudes of earthquakes considered in this study and because it presents a relative high statistic correlation (R^2=84%).

2.3. Calculation of real values of safety factor and critical acceleration

We have performed a back-analysis of the La Paca rock-fall to estimate the real values of static safety factor and the critical acceleration. To do this we used a 2D slope stability analysis software (Rocscience Inc. SLIDE). This program calculates safety factors for circular and non-circular slope failure surfaces based on a number of widely used limit equilibrium techniques.

We firstly derived a slope profile from a high resolution digital elevation model obtained from a terrestrial laser scanner survey at La Paca rock-fall location. This slope profile represents the path of the observed fallen rock blocks observed in the field. We set a non-circular slope failure surface and we have based on field data to obtain the strength parameters of the failure surface.

In our slope model, we fitted the seismic acceleration value by iteration until the safety factor obtained was equal to one (stability conditions). This value of seismic acceleration represents a more accurate estimation of the critical acceleration of the La Paca rock-fall. Then, we removed the seismic acceleration to obtain the real static safety factor previous to the 2005 La Paca earthquake.

3. Results and Discussion

3.1. Results at regional scale

At La Paca rock-fall area at a 25x25 meters pixel resolution the safety factor values are between 1.4 and 2 and the critical acceleration values are between 0.22g and 0.50g (Fig. 2).

In general, estimated Newmark displacements at regional scale show low values, mostly lower than 2 cm (Rodríguez-Peces, 2008; Rodríguez-Peces et al., 2008). The deterministic seismic scenario for the occurrence of the most probable earthquake for a 475-year return period (M_w=5.0) shows similar results to the probabilistic seismic scenario for a 2475-year return period. However, the deterministic seismic scenario for 2005 La Paca earthquake (M_w=4.8) do not show Newmark displacements.

La Paca rock-fall is located in areas with Newmark displacements lower than 2 cm in the majority of the seismic scenarios considered. Therefore, low values of Newmark displacement are potentially enough to generate rock-falls. This proposal is coherent with the fact that most identified slope instabilities in Lorca Basin are rock-falls. To support this hypothesis we must apply the Newmark method at a site scale.

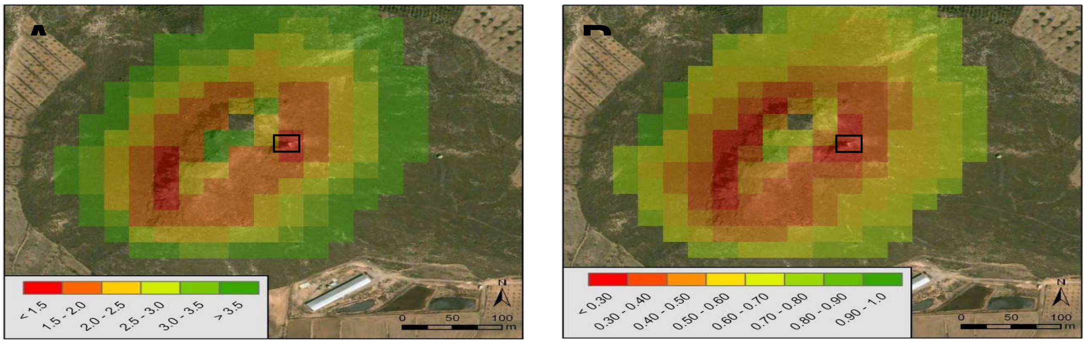

Figure 2. Safety factor (A) and critical acceleration (B) maps at La Paca rock-fall area at a 25x25 meters pixel resolution (regional scale). The critical acceleration is given in g units (1g=9.81 m/s^2). The black square indicates La Paca rock-fall failure surface location.

3.2. Results at sub-regional scale

At La Paca rock-fall site at a 2.5x2.5 meters pixel resolution the safety factor values are between 1.0 and 1.7 and the critical acceleration values are between 0.03g and 0.45g (Fig. 3).

Estimated Newmark displacements show higher values, which are, locally, higher than 5 cm. The deterministic seismic scenario for 2005 La Paca earthquake (M_w=4.8) show Newmark displacements lower than 2 cm. Deterministic seismic scenario for the occurrence of the most probable earthquake for a 475-year return period (M_w=5.0) shows similar results to the probabilistic seismic scenario for a 2475-year return period. They show higher Newmark displacements, which are higher than 2 cm and, locally, higher than 5 cm (Rodríguez-Peces, 2008; Rodríguez-Peces et al., 2008).

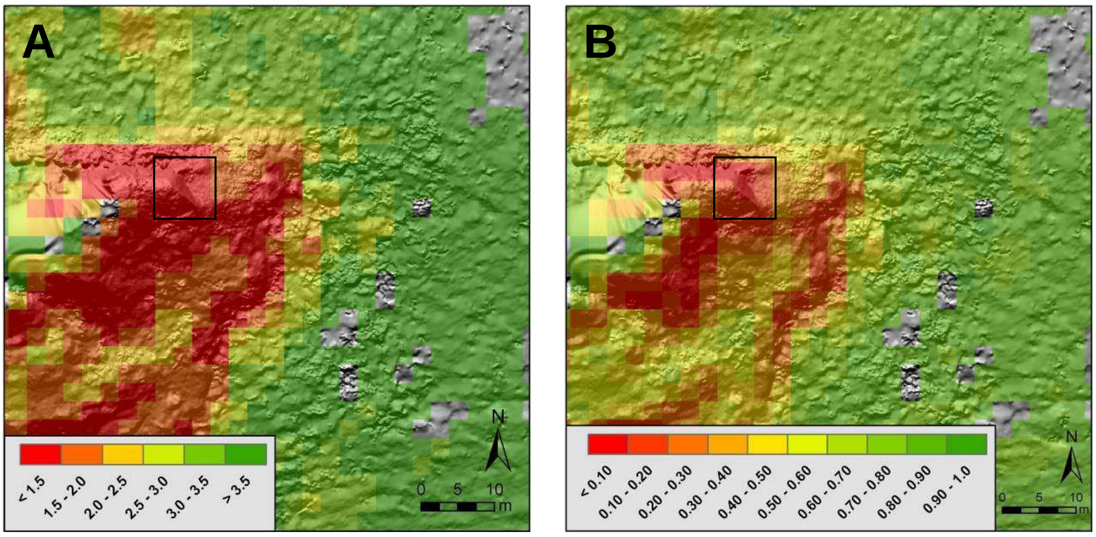

Figure 3. Safety factor (A) and critical acceleration (B) maps at La Paca rock-fall area at a 2.5x2.5 meters pixel resolution (site scale). The critical acceleration is given in g units (1g=9.81 m/s^2). The black square indicates La Paca rock-fall failure surface location.

3.3. Results at site scale

The real value of critical acceleration estimated using the Slide software and the high resolution slope profile of the La Paca rock-fall is 0.09g. This value is a good assessment because it is lower than the average peak ground acceleration value estimated to 2005 La Paca earthquake (0.12g). The average real static safety factor obtained to La Paca rock-fall location is 1.15 (Table 2).

Table 2. Static safety factor values obtained for a non-circular slope failure surface at La Paca rock-fall location based on different limit equilibrium techniques provided by the Slide sofware.

	Ordinary/Fellenius	Bishop simplified	Janbu simplified	Corps. of Eng. nº 1	Corps of Eng. nº 2	GLE/Morgenstern-Price	Average value
Safety Factor	1.09	1.18	1.09	1.18	1.22	1.16	1.15

3.4. Results comparison

At the specific La Paca rock-fall location we have done a comparison between the static safety factors, critical acceleration and Newmark displacement values for regional, sub-regional and site scales (Table 3).

For the regional scale (25x25 meters pixel resolution map) we obtain a relative high value of safety factor and, consequently, a relative high critical acceleration. In fact, deterministic seismic scenario for 2005 La Paca earthquake (M_w=4.8) do not show Newmark displacements. Therefore, a regional map with 25x25 meters pixel resolution is not appropriate to estimate Newmark displacement at the specific La Paca rock-fall location. However, the regional safety factor and critical acceleration maps allow identifying areas with the highest potential hazard and interesting areas for detailed studies.

For the sub-regional scale (2.5x2.5 meters pixel resolution map) we obtain lower values of safety factor and critical acceleration. In this case, the safety factor previous to the earthquake is very close to the instability condition –i.e., SF=1.0. The deterministic seismic scenario for 2005 La Paca earthquake (M_w=4.8) shows a Newmark displacement of 1.8 cm at La Paca rock-fall location.

For the site scale we obtain similar safety factor and critical acceleration values than at sub-regional scale. The real safety factor previous to the earthquake is slightly higher but it also is nearby to the instability condition. In this case, the deterministic seismic scenario for 2005 La Paca earthquake (M_w=4.8) also shows a Newmark displacement of 1.8 cm at La Paca rock-fall location. Therefore, the sub-regional scale map is better appropriate to estimate Newmark displacement at La Paca rock-fall location.

Table 3. Comparison between static safety factor, critical acceleration and Newmark displacement values for regional, sub-regional and site scales to the specific La Paca rock-fall location.

Scale	Static Safety Factor	Critical acceleration (g units)	D_N La Paca (cm)	D_N M_W=5 (cm)	D_N 2495-year return period (cm)
Regional (25x25 m)	1.46	0.25	-	0.35	0.29
Sub-regional (2,5x2,5 m)	1.10	0.08	0.18	3.82	3.50
Site (Slide)	1.15	0.09	0.18	1.98	2.79

4. Conclusions

Implementation of Newmark methodology in a GIS is a simple and reliable tool to do a regional and sub-regional assessment of seismically-induced slope instabilities, but this method must be contrasted with detailed studies at a site scale.

The regional scale safety factor and critical acceleration maps with 25x25 meters pixel resolution show areas with the highest potential hazard and interesting areas for future particular studies. However, the regional scale maps are not appropriate to estimate Newmark displacement at the specific La Paca rock-fall location.

The sub-regional scale safety factor and critical acceleration maps with 2.5x2.5 meters pixel resolution let to identify the area where La Paca rock-fall took place with reasonable precision. Moreover, the sub-regional scale maps are better appropriate to estimate Newmark displacement at La Paca rock-fall location.

The site scale real safety factor and critical acceleration values estimated by means of the back-analysis of the La Paca rock-fall failure surface are very similar to the sub-regional scale safety factor and critical acceleration values.

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