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ORIGINAL PAPER

Applicability of Newmark method at regional, sub-regional and site scales: seismically induced Bullas and La Paca rock-slide cases (Murcia, SE Spain)

Martín Jesús Rodríguez-Peces · José Luis Pérez-García · Julián García-Mayordomo · José Miguel Azañón · Juan Miguel Insua-Arévalo · Jorge Delgado-García

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Abstract In this paper, the applicability of the Newmark method at regional, sub-regional and site scales has been investigated in the Lorca Basin (Murcia). This basin is located in one of the most seismically active regions of Spain. The area is very interesting for studying earthquake-induced slope instabilities as there are well-known cases associated with specific earthquakes. For the regional and sub-regional scales, a geographic information system has been used to develop an implementation of Newmark sliding rigid block method. Soil and topographic amplification effects have been particularly considered. Subsequently, 'Newmark displacement' maps for deterministic seismic scenarios have been produced. Some specific studies have also been performed using limit equilibrium methods to estimate the safety factor and the critical acceleration of certain slope

M. J. Rodríguez-Peces (✉) · J. M. Azañón
Departamento de Geodinámica, Facultad de Ciencias, Universidad de Granada, C/Fuentenueva s/n, 18002 Granada, Spain
e-mail: marpeces@ugr.es

J. M. Azañón
e-mail: jazanon@ugr.es

J. L. Pérez-García · J. Delgado-García
Departamento de Ingeniería Cartográfica, Geodésica y Fotogrametría, Universidad de Jaén, Campus de las Lagunillas, s/n. Edif. A3, 23071 Jaén, Spain
e-mail: jlperez@ujaen.es

J. Delgado-García
e-mail: jdelgado@ujaen.es

J. García-Mayordomo
Instituto Geológico y Minero de España (IGME), C/La Calera, 1, 28760 Tres Cantos, Madrid, Spain
e-mail: julian.garcia@igme.es

J. M. Azañón
Instituto Andaluz de Ciencias de la Tierra, Universidad de Granada-CSIC, Granada, Spain

J. M. Insua-Arévalo
Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain
e-mail: insuarev@geo.ucm.es

instabilities at a site scale. These instabilities were the rock slides related to recent seismic series at the Lorca Basin: 2002 Bullas ($M_w = 5.0$) and 2005 La Paca ($M_w = 4.8$). Finally, the safety factor, critical acceleration and Newmark displacement values estimated at different scales have been compared to determine which scale is most suitable for the Newmark method.

Keywords GIS · Murcia · Newmark · Rock slide · Site effect · 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. In fact, 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).

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 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 et al. 2000; Romeo 2000; Capolongo et al. 2002; Carro et al. 2003). In Spain, although there are very few studies on this subject, the Newmark method is always considered (e.g. García-Mayordomo 1999; Mulas et al. 2003; Delgado et al. 2006; Rodríguez-Peces et al. 2008). A review of these studies and their results can be found in García-Mayordomo et al. (2009).

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 by considering certain representative values of the input geotechnical and seismic parameters. In fact, the seismic input data are usually defined by single values of magnitude and epicentral location of the earthquakes that trigger slope instabilities. On the other hand, probabilistic methods have been developed because most data show high spatial variability and, therefore, they can be considered as random variables (e.g. geotechnical and ground motion parameters).

In this paper, the applicability of the Newmark method to the study of seismically induced slope instabilities has been investigated at regional, sub-regional and site scales. For the regional scale, an implementation of the Newmark sliding rigid block method using a GIS has been developed taking into account soil and topographic amplification effects. Subsequently, 'Newmark displacement' maps have been produced for several different input seismic scenarios. These maps allow the identification of areas with the highest potential hazard as well as other interesting areas for future detailed studies. The Lorca Basin (Murcia, SE Spain) was selected as the study area for a number of reasons: (1) it exhibits moderate-to-high seismic activity, (2) some of the most active faults in Spain are in the area of this basin and (3) there are well-known cases of disrupted slides, rock falls and rock slides associated with specific recent earthquakes (e.g. 1999 Mulas, 2002 Bullas, 2005 La Paca) (see Fig. 1). For the sub-regional and site scales, the well-known cases of the Bullas and La Paca rock slides (Fig. 2) have been selected, which are associated with the 2002 Bullas ($M_w = 5.0$, $I_{EMS} = \mathrm{V}$) and 2005 La Paca ($M_w = 4.8$, $I_{EMS} = \mathrm{VII}$) earthquakes, respectively (Benito et al. 2007; Gaspar-Escribano and Benito 2007). These earthquakes produced widespread damage at the villages of La Paca and Zarcilla de Ramos

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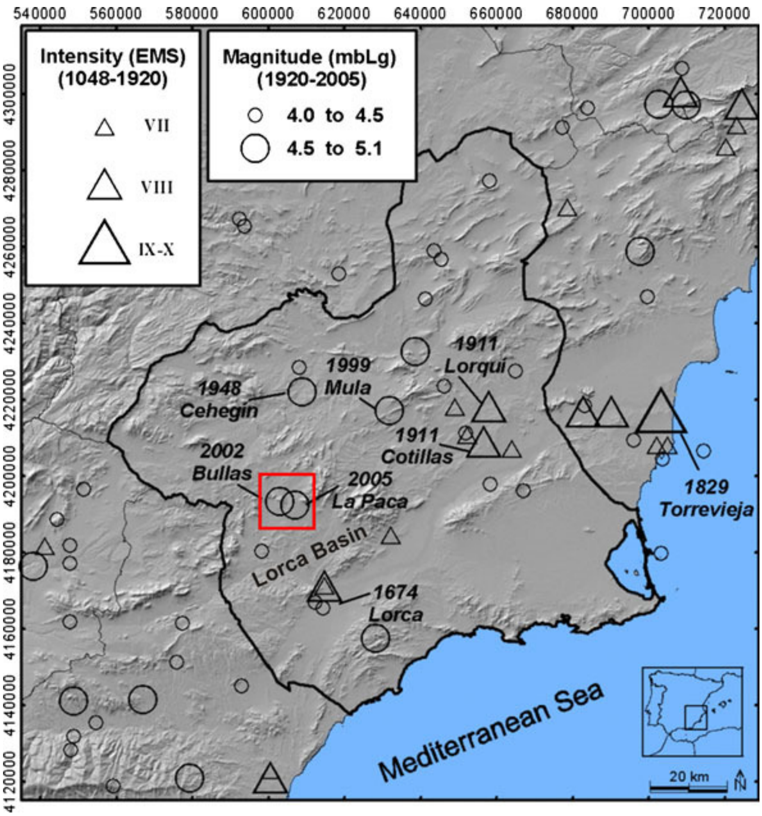

Fig. 1 Distribution of main historical and instrumental seismicity in the Murcia Region (SE Spain), particularly around Lorca Basin (modified from García-Mayordomo et al. 2007). The *red square* shows the location of the study area and the epicentres of the 2002 Bullas and 2005 La Paca earthquakes

and considerable social concern. For the site scale, a back-analysis of the Bullas and La Paca rock slides has been performed based on field and geotechnical data. The safety factor and the critical acceleration values were estimated using limit equilibrium methods. Finally, the results were compared with the previous GIS estimations to determine which scale is most suitable for the Newmark method.

2 Methodology

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 sliding rigid block method provides the minimum horizontal seismic acceleration to overcome shear resistance and start the displacement of the rigid block, provided the static safety factor is known:

$$a_c = (SF - 1)g \sin \alpha \tag{1}$$

where a_c is the critical acceleration (in gravity units, 1 g = 9.81 m/s^2), g is the acceleration of gravity, SF is the static safety factor, and α is the thrust angle. The critical acceleration is

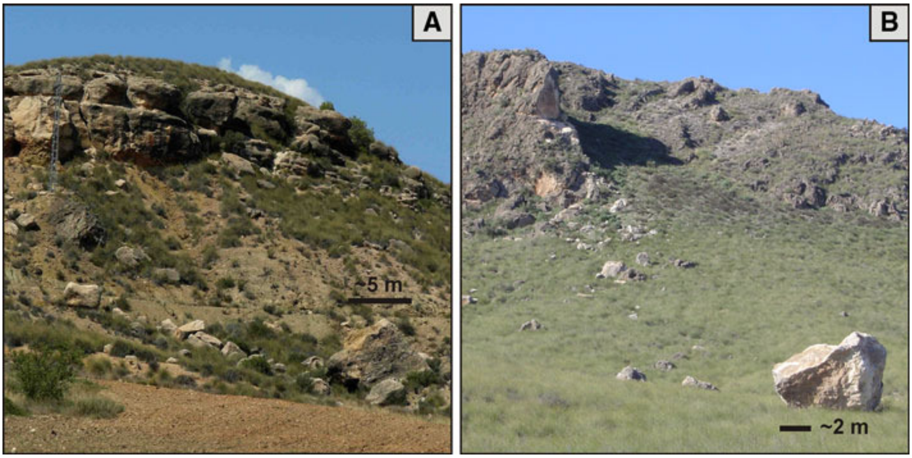

Fig. 2 Earthquake-triggered slope instabilities at the Lorca Basin. **a** Rock slide induced by 2002 Bullas earthquake ($M_w = 5.0$). **b** Rock slide induced by 2005 La Paca earthquake ($M_w = 4.8$). *Black lines* show the size of the main sliding blocks

an expression of slope capacity to resist seismic vibration. The safety factor was estimated at regional and sub-regional scales assuming the infinite-slope model proposed by Jibson et al. (2000) following the Mohr–Coulomb criterion. In this limit equilibrium model, the thrust angle is equal to the slope angle. However, when the safety factor is estimated by means of other limit equilibrium models considering rotational movement, α is the angle between the vertical and a line segment connecting the centre of gravity of the landslide mass and the midpoint of the slip circle (Newmark 1965). Finally, to estimate the displacement of the slope induced by earthquakes—i.e. Newmark displacement (D_N), the Jibson (2007) regression equation has been used. This equation correlates the Newmark displacement with critical acceleration and peak ground acceleration values:

$$\log D_N = 0.215 + \log\left[\left(1 - \frac{a_c}{PGA}\right)^{2.341}\left(\frac{a_c}{PGA}\right)^{-1.438}\right] \quad (2)$$

where D_N is the Newmark displacement (in centimetres), a_c is the critical acceleration (in gravity acceleration units), and PGA is the peak ground acceleration (in gravity units). For further details of the implementation of the Newmark method using a GIS, the reader is referred to Rodríguez-Peces et al. (2008) and Rodríguez-Peces (2010). Newmark displacement values obtained at the regional scale should not be considered a precise measurement of co-seismic slope displacement, but rather as an index of potential instability. In fact, the minimum Newmark displacement for a slope failure can vary widely depending on the instability type (e.g. coherent or disrupted landslides), lithology and geometry of the slope. However, some authors have found that critical Newmark displacement values range between 5 and 10 cm for coherent landslides (Wilson and Keefer 1983; Wieczorek et al. 1985; Jibson and Keefer 1993; Jibson et al. 2000). In the case of brittle rupture mechanisms, such as disrupted landslides, the critical Newmark displacement value can be as low as 2 cm (Capalongo et al. 2003; Rodríguez-Peces et al. 2008; Rodríguez-Peces 2010).

The modelling of the seismic input comprised two different deterministic scenarios: (1) the occurrence of the $M_w = 5.0$ 2002 Bullas and $M_w = 4.8$ 2005 La Paca earthquakes

(Benito et al. 2007; Gaspar-Escribano and Benito 2007); (2) the most probable earthquake for a 475-year return period ($M_w = 5.0$) (Gaspar-Escribano and Benito 2007). The average peak ground acceleration (PGA) on rock for each earthquake has been calculated as a function of moment magnitude and epicentral distance by means of different ground-motion prediction equations (GMPEs) for the Mediterranean zone (Skarlatoudis et al. 2003; Ambraseys et al. 2005; Akkar and Bommer 2007; Bindi et al. 2010). The Bullas rock slide was located about 5 km from the epicentre of the 2002 Bullas earthquake ($M_w = 5.0$). The PGA on rock estimated using this magnitude–epicentral distance pair is 0.11 g (±0.03). The La Paca rock slide was located about 7 km from the epicentre of the 2005 La Paca earthquake ($M_w = 4.8$). In this case, the average PGA on rock is 0.06 g (±0.01). Nevertheless, other authors have estimated larger PGA values for this earthquake and for a very similar distance (8 km), for rock conditions the PGA ranges from 0.10 to 0.15 g (Buforn et al. 2005). Furthermore, Gaspar-Escribano and Benito (2007) estimated a PGA on rock between 0.08 and 0.13 g for an epicentral distance of 5 km, and 0.07–0.11 g for an epicentral distance of 10 km. The average PGA on rock estimated using these results is 0.08 g (±0.02).

Since the PGA refers to rock conditions, the PGA values have to be corrected to take into account possible site effects (i.e. soil and topographic ground motion amplification; Table 1). Soil amplification factors were adopted from the values derived in the RISMUR Project (Benito et al. 2006), which represents the best-quality data available for the Murcia Region. This project developed a geotechnical classification of the geological units based on the average shear-wave velocity in the upper 30 m of the materials following Borcherdt (1994), NCSE (2002), NEHRP (2003) and Eurocode-8 (CEN 2004) criteria.

The topographic amplification factor (TAF) was evaluated following Eurocode-8 provisions (CEN 2004): (a) Slopes lower than 15° or ridges with a relative height <30 m: TAF = 1.0 (no topographic amplification); (b) slopes between 15 and 30° and a relative height >30 m: *TAF* = 1.2; and (c) slopes steeper than 30° and a relative height >30 m: *TAF* = 1.4. At Bullas rock-slide location, TAF was found null, while for La Paca rock-slide emplacement, a *TAF* = 1.2 was estimated.

Finally, the PGA on rock values were multiplied by both amplification factors. Considering these seismic amplification factors, the estimated PGA at the Bullas and La Paca rock-slide locations are 0.20 g (±0.05) and 0.11 g (±0.03), respectively.

2.1 Regional and sub-regional scales

To produce the critical acceleration maps, a lithological map was first drawn using digital geological maps (Baena-Pérez 1972; Kampschuur et al. 1972) of the Institute of Geology and Mines of Spain (IGME, Instituto Geológico y Minero de España). Three lithological

Table 1 Lithological groups, shear strength parameter values considered in the estimation of safety factors at regional and sub-regional scales (initial range of values of parameters shown in brackets) and seismic amplification factors

Lithological group	γ (kN/m^3)	c (kPa)	ϕ (°)	*SAF*
Dolomites and limestones	25 (23–27)	46 (0–108)	30 (21–39)	1.0
Conglomerates, sandstones and argillites	22 (20–24)	31 (4–16)	33 (27–39)	1.8
Argillites, marls, sandstones and gypsums	21 (18–24)	36 (35–117)	26 (22–30)	1.8

γ Unit weight, *c* cohesion, ϕ friction angle, *SAF* soil amplification factor

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groups have been distinguished as a function of general shear resistance of the materials and their behaviour versus slope instabilities (Table 1). Average values of specific weight, cohesion and friction angle have been assigned to each lithological unit. These parameters were derived from geotechnical bibliography and available geotechnical tests (cf. Rodríguez-Peces 2010). Shear strength parameters for rock-type lithological groups correspond to rock discontinuities. In the case of soils, these parameters are related to both intact material and discontinuities. Then, cohesion and friction angle values were estimated by iteration until all safety factors obtained were higher than one (stability conditions). Table 1 shows the shear strength parameters and seismic amplification factors considered in the forthcoming calculations.

The digital elevation model (DEM) used for the Bullas and La Paca rock slides at the regional scale has a 25 × 25 m pixel size. This DEM was obtained from digital topographic maps of the Murcia Region developed by the Spanish Geographic Institute (IGN, Instituto Geográfico Nacional). At the sub-regional scale, high-resolution DEMs corresponding to the Bullas and La Paca rock-slide locations have been used (Fig. 3). These DEMs were derived using a terrestrial laser scanner (OPTECH) with wide coverage (1,000–1,500 m). The data capture was carried out at different places and from different points of view, so that the entire area was captured at a centimetric resolution (10 × 10 cm). All the individual scans have been integrated into a single local reference system and later transferred to a global reference system (UTM-30 ED50). Finally, the point cloud was edited manually using different filters to remove vegetation and existing fallen blocks of rock. Thus, a DEM with a pixel size of 2.5 × 2.5 m corresponding to the ground level was interpolated from the point cloud.

2.2 Site scale

A back-analysis has been performed for both the Bullas and La Paca rock slides to estimate the safety factor and critical acceleration values. Two-dimensional slope-stability analysis

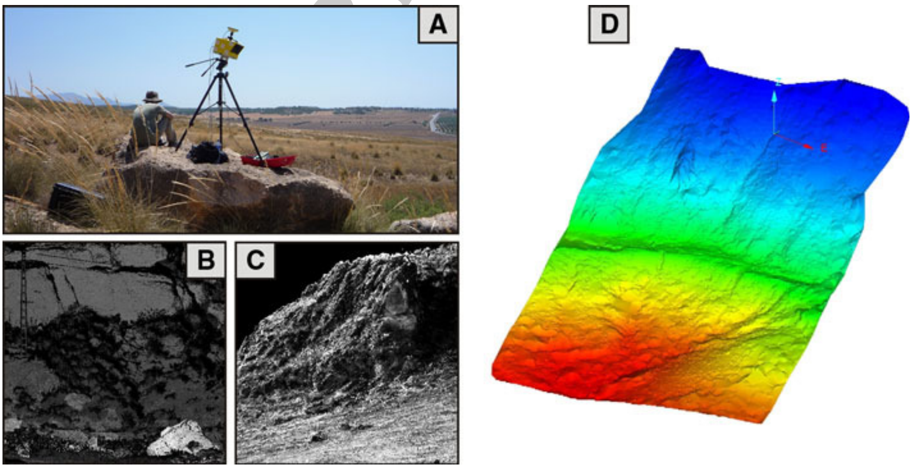

Fig. 3 Preparation of the high-resolution digital elevation models using a terrestrial laser scanner. **a** Scanning process. **b** Point cloud for the 2002 Bullas rock-slide area. **c** Point cloud for the 2005 La Paca rock-slide area. **d** Interpolated high-resolution DEM for the 2002 Bullas rock-slide area

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software (Slide, Rocscience Inc. 2003) has been used for this purpose. This program calculates safety factors for circular and non-circular slope failure surfaces based on a number of widely used limit equilibrium methods. We decided to use the simplified Janbu method because it is the only limit equilibrium technique that estimates the safety factor values for non-circular failure surfaces and satisfies the force equilibrium by not considering shear forces between slices.

Several field surveys have been performed to obtain the geometry and the mechanical behaviour of materials related to both the Bullas and La Paca rock slides. The slope profile was first derived from the high-resolution DEM (0.10 × 0.10 m) obtained from the terrestrial laser scanner survey cited above. This cross-section represents the observed main path of the sliding blocks corresponding to each rock slide. In both cases, a non-circular slope failure surface has been set based on field observations. In addition, several laser scanner captures of the main sliding blocks and the failure surface of both rock slides have been carried out at millimetric resolution. The individual captures have been integrated and transferred to the global reference system using the same method explained at the sub-regional scale (Fig. 4). From the resulting point clouds, a high-resolution DEM (1 × 1 mm) of the joint surface related to each rock slide has been extracted from the corresponding face of each rock block and from the in situ failure surface. Subsequently, different joint surface profiles have been derived from each failure surface using the average plane of the surface as a reference.

In situ and geotechnical tests have been performed in order to obtain the shear strength parameters of the materials related to the failure surface. The Barton-Bandis failure criterion (Barton and Choubey 1977; Barton and Bandis 1990) was used for estimating peak shear strength of joints in the rock-type materials. The joint wall compressive strength (JCS) has been estimated using different empirical equations developed for carbonate rocks relating Schmidt hammer rebound versus JCS (cf. Aydin and Basu 2005). The *N*-type Schmidt hammer rebound (R_N) was obtained following the most recent procedure suggested by Aydin (2009). Several methods have been proposed for evaluating the joint roughness coefficient (JRC) of a discontinuity. The most common procedure is to visually compare standard roughness profiles of 10 cm length (Barton and Choubey 1977), but this method is only valid for small-scale laboratory specimens and it is highly subjective. An alternative method for a longer profile length is the measurement of the surface roughness amplitude from a straight edge (Bandis 1980). However, this method has limitations because the maximum asperity amplitude is measured in millimetres. In actual field conditions where the surface is long, the JRC must be estimated for the full-scale surface. This paper uses a mathematical formula developed to estimate JRC from the joint surface profiles derived from high-resolution DEMs. Tse and Cruden (1979) derived an empirical correlation based on the root mean square (RMS) of the local surface slope of a profile.

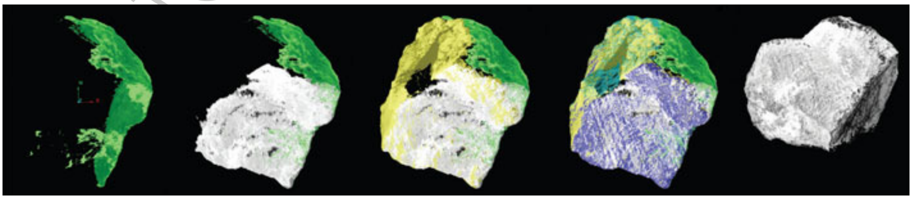

Fig. 4 Getting the point cloud of the main rock blocks of the 2005 La Paca rock slide by merging single laser scanner captures

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Yang et al. (2001) improved this relation more recently, obtaining a correlation coefficient of $R = 0.99326$:

$$\mathrm{JRC} = 32.69 + 32.98 \log Z_2 \tag{3}$$

where

$$Z_2 = \sqrt{\frac{\sum_i^{N-1} (z_i - z_{i+1})^2}{(N-1)\Delta s^2}}$$

and N is the number of discrete measurements of the roughness amplitude in the profile, Δs is the constant distance between two adjacent amplitude readings, z_i is the profile height measured relative to a reference line, and Z_2 is the root mean square of the profile first derivative. An average JRC was obtained considering a measurement range of 10 cm to compare with the standard roughness profiles of Barton and Choubey (1977). Finally, the JRC value was corrected taking into account the scale effect by means of the expression proposed by Barton and Bandis (1990):

$$\mathrm{JRC}_N = \mathrm{JRC}_0 \left(\frac{L_N}{L_0}\right)^{-0.02 JRC_0} \tag{4}$$

where L is the length of the surface, and the suffixes N and 0 refer to the in situ block size and 10-cm laboratory-scale samples, respectively.

For the soil-type materials, soil samples were taken from the failure surface and a number of laboratory tests were performed: unsaturated and saturated unit weight determination (AENOR 1994a), specific gravity determination (AENOR 1994b), Atterberg limits determination (AENOR 1993, 1994c), engineering classification of soils (ASTM 2000), and direct shear test of soils under consolidated drained (CD) conditions (AENOR 1998).

Finally, all the data were used together to model the slopes for both rock slides. The critical acceleration was calculated using the Slide software iterating the seismic acceleration value until the resulting safety factor was equal to one (stability condition). This acceleration value is a more accurate estimation of the critical acceleration at the rock-slide locations as it was obtained considering a non-circular failure surface. However, the critical acceleration related to a circular failure surface was also obtained by means of (1) and the thrust angle determined at both rock-slide sites. Then, the static safety factor prior to each earthquake was estimated removing the seismic acceleration value.

3 Results and discussion

3.1 Regional scale (25 × 25 m)

At a 25 × 25 m pixel resolution, the Bullas rock-slide area shows safety factor values between 1.6 and 2.0 and critical acceleration values between 0.24 and 0.39 g (Fig. 5). In the case of the La Paca rock-slide area, the safety factors are between 1.4 and 2.0 and the critical accelerations are between 0.22 and 0.50 g (Fig. 6). In both cases, the most likely source areas for slope instabilities can be identified by finding the lowest safety factor and critical acceleration values.

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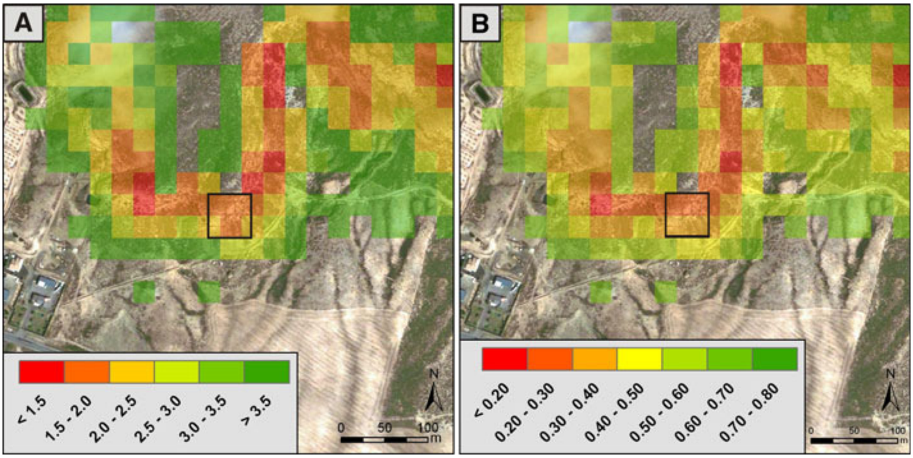

Fig. 5 Safety factor (**a**) and critical acceleration (**b**) maps at a 25 × 25 m pixel resolution (*regional scale*) for the Bullas rock-slide area. The critical acceleration is given in gravity units (1 g = 9.81 m/s^2). The *black square* indicates location of Bullas rock slide

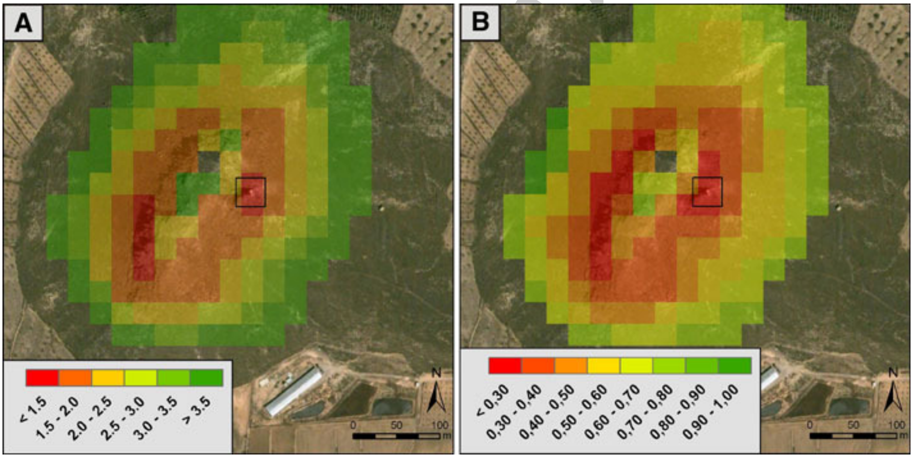

Fig. 6 Safety factor (**a**) and critical acceleration (**b**) maps at a 25 × 25 m pixel resolution (*regional scale*) for the La Paca rock-slide area. Critical acceleration is given in gravity units (1 g = 9.81 m/s^2). The *black square* indicates location of La Paca rock slide

Estimated Newmark displacements at the regional scale for the occurrence of the most probable earthquake for a 475-year return period ($M_w = 5.0$) show low values for both cases, mostly lower than 2 cm (Tables 2, 3). However, the seismic scenarios performed for the 2002 Bullas and 2005 La Paca earthquakes show Newmark displacements = 0. These results imply that these slopes did not move during these earthquakes. This is because the safety factor values obtained in both cases are relatively high, and so the critical accelerations are relatively high too (Tables 2, 3). Therefore, a regional map with a 25 × 25 m pixel size turns out to be unsuitable for estimating the Newmark displacement for the Bullas and La Paca rock slides. However, safety factor and critical acceleration maps at

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Table 2 Comparison between static safety factor (*SF*), critical acceleration (a_c, gravity units) and Newmark displacement (D_N, cm) values estimated for regional, sub-regional and site scales at Bullas rock slide

Scale	Regional	Sub-regional	Site
SF	1.64 (±0.03)	1.12 (±0.07)	1.07 (±0.02)
a_c	0.25 (±0.01)	0.06 (±0.04)	0.04
D_N 2002 Bullas (M_w = 5.0)	0.0	4.7 (1.5–15.3)	9.9 (3.0–31.9)
D_N 475 years RP (M_w = 5.0)	0.1 (0–0.4)	12.8 (3.9–41.3)	26.8 (8.3–86.8)

Table 3 Comparison between static safety factor (*SF*), critical acceleration (a_c, g units) and Newmark displacement (D_N, cm) values estimated for regional, sub-regional and site scales at La Paca rock slide

Scale	Regional	Sub-regional	Site
SF	1.46 (±0.01)	1.05 (±0.05)	1.02 (±0.02)
a_c	0.25 (±0.002)	0.02 (±0.02)	0.01
D_N 2005 La Paca (M_w = 4.8)	0.0	13.6 (4.2–43.8)	41.3 (12.8–133.5)
D_N 475 years RP (M_w = 5.0)	0.4 (0.1–1.2)	56.5 (17.4–182.7)	171.8 (53.1–555.8)

regional scales (Figs. 5, 6) can still be very useful for a preliminary identification of areas with the greatest potential hazard, which can be studied later in more detail.

3.2 Sub-regional scale (2.5 × 2.5 m)

The safety factor values obtained at a 2.5 × 2.5 m pixel resolution at the Bullas rock-slide site range from 1.0 to 1.9, and the critical acceleration values range between 0.02 and 0.40 g (Fig. 7). At the La Paca rock-slide site, the safety factors range from 1.0 to 1.7 and the critical accelerations from 0.03 to 0.45 g (Fig. 8). At this scale, the safety factor and

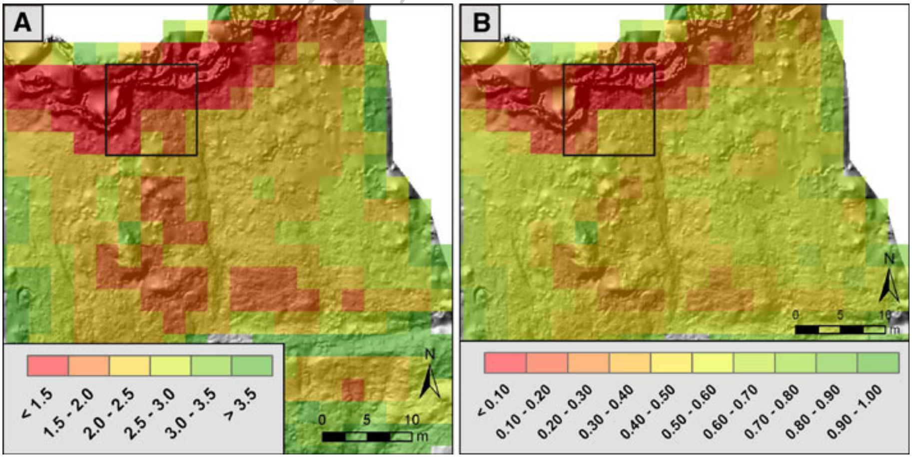

Fig. 7 Safety factor (**a**) and critical acceleration (**b**) maps at a 2.5 × 2.5 m pixel resolution (sub-regional scale) for the Bullas rock-slide area. The critical acceleration is given in gravity units (1 g = 9.81 m/s^2). The *black square* indicates location of Bullas rock slide

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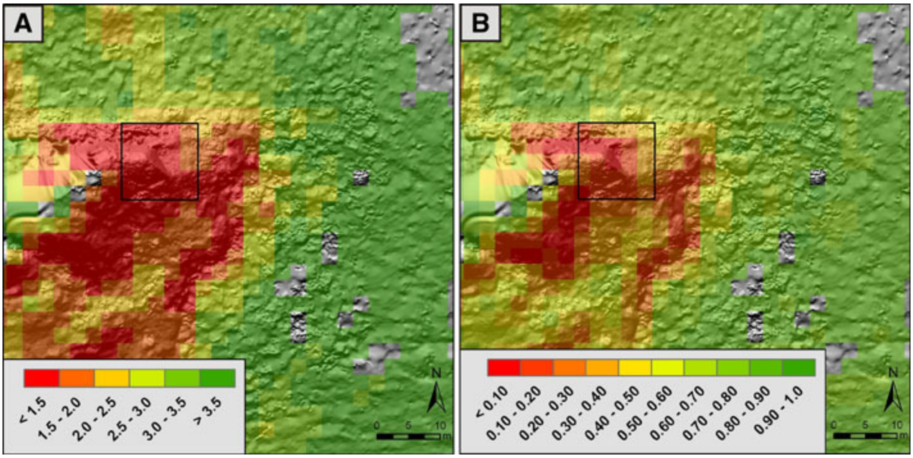

Fig. 8 Safety factor (**a**) and critical acceleration (**b**) maps at a 2.5 × 2.5 m pixel resolution (sub-regional scale) for the La Paca rock-slide area. The critical acceleration is given in gravity units (1 g = 9.81 m/s^2). The *black square* indicates location of La Paca rock slide

critical acceleration values are lower than the ones calculated at the regional scale (Table 1). Furthermore, in both cases, the safety factor prior to each earthquake is very close to the instability condition (i.e. $SF < 1.00$). In contrast to the results obtained at the regional scale, the most likely source areas for slope instabilities, those that show the lowest safety factor and critical acceleration values, can be identified with greater accuracy (Figs. 7, 8). In fact, the rupture areas of the 2002 Bullas and 2005 La Paca rock slides can be accurately identified by means of the safety factor and critical acceleration maps at the sub-regional scale.

The occurrence of the most probable earthquake for a 475-year return period ($M_w = 5.0$) produces Newmark displacement values >5 cm (Tables 2, 3), which are also larger than the ones obtained at the regional scale. Specifically, the 2002 Bullas and 2005 La Paca earthquakes produce Newmark displacements = 4.7 and 13.6 cm, respectively (Tables 2, 3). These values are in agreement with the critical Newmark displacement of 5 cm suggested by others authors for the occurrence of coherent-type landslides. However, the lower bounds of estimated Newmark displacement for the Bullas and La Paca rock slides (2 and 4 cm, respectively) are closer to the minimum value of 2 cm required to trigger disrupted-type slope instabilities.

3.3 Site scale

3.3.1 Bullas rock slide

Two different materials are involved in the failure surface corresponding to the Bullas rock slide: cemented conglomerates over a thick layer of Triassic marls (Fig. 9). The conglomerates are composed of decimetric carbonate grains embedded in carbonate-rich cement, so its geotechnical behaviour is closer to that of a limestone. Assuming a unit weight of 24.68 kN/m^3 (±2.27) and a mean Schmidt hammer rebound of $r_N = 51$ (±2), the average joint wall compressive strength (JCS) is 95 MN/m^2 (±39) and the residual friction angle is 30° (±3). The average JRC derived from the high-resolution profiles is 20 (±1)

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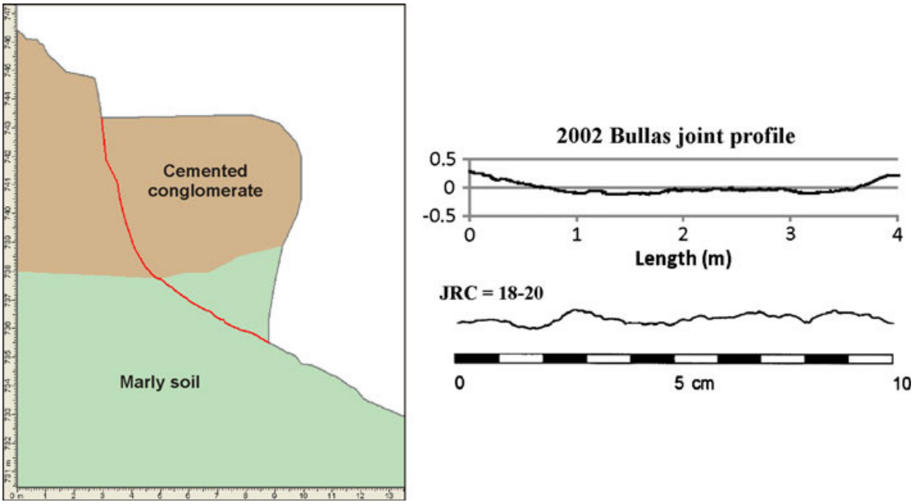

Fig. 9 Slope model used in the stability analysis of the 2002 Bullas rock slide. The *red line* represents the actual failure surface. A comparison between the actual roughness profile along the down-dip direction (in metres) and standard roughness profiles of 10 cm from Barton and Choubey (1977) is also shown

(Fig. 9). This numerical estimate agrees with a standard roughness profile with a JRC of 18–20. Considering the total length of the joint profile (about 4 m), the corrected *JRC* is 4. For the Triassic marls located at the bottom of the rock block, the unit weight is 20.21 kN/m^3, the cohesion value is 33.35 kN/m^2, and the friction angle is 23.4°. This soil is classified as a low-plasticity clay (CL) since the liquid limit is 42.40% and the plastic index is 18.12%.

The estimated safety factor and critical acceleration values prior to the 2002 Bullas earthquake were 1.07 and 0.04 g, respectively. These values are slightly lower than those obtained at the sub-regional scale (Table 2). The safety factor value is also close to instability and within the range of the safety factors estimated at the sub-regional scale. A thrust angle of 47° and a critical acceleration of 0.05 g (±0.01) have been estimated assuming a circular approximation of the failure surface by means of (1). This critical acceleration is slightly greater than the value obtained using the Slide software (0.04 g), which is a more accurate estimation because it takes into account the actual asperity and shape of the failure surface.

The average PGA value estimated considering the seismic scenario for the 2002 Bullas earthquake was 0.20 g. Implementing this acceleration into the slope model, an unstable safety factor of 0.76 (±0.04) was obtained. At the Bullas rock slide, the Newmark displacement was 10 cm, obtained by combining the PGA and critical acceleration values by means of (2). This result is slightly larger than the Newmark displacement found at the sub-regional scale (about 5 cm) but within the displacement range estimated at that scale (Table 2). A Newmark displacement of 3 cm can be found considering the lower bound of the estimates. This displacement can be viewed as a more accurate critical value required for the occurrence of this disrupted-type slope instability. The estimated Newmark displacement for the occurrence of the most probable earthquake for a 475-year return period (27 cm) was also larger than the value obtained at the sub-regional scale (Table 2).

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3.3.2 *La Paca rock slide*

At the La Paca rock slide (Fig. 10), the failure surface developed in a rock (Triassic dolomites). Considering a unit weight of 26.50 kN/m^3 (±2.03) and a Schmidt hammer rebound of $r_N = 35$ (±4), the average joint wall compressive strength (JCS) is 43 MN/m^2 (±18), and the residual friction angle is 30° (±4). The average JRC derived from the high-resolution profiles is 17 (±5). This estimation is consistent with a JRC of 16–18 derived from the standard roughness profiles (Fig. 10). Considering the total length of the joint profile (about 14 m), the corrected JRC is 4.

The estimated safety factor and critical acceleration values prior to the 2005 La Paca earthquake were 1.02 and 0.01 g, respectively. These values are also similar to those obtained at the sub-regional scale (Table 3). In this case, the safety factor is very close to the instability condition ($SF < 1.00$). Assuming a circular approximation of the failure surface, the estimated thrust angle is 69° and the critical acceleration is 0.02 g (±0.01), which is slightly greater than the former result. As in the previous case, the above estimate of the critical acceleration using Slide is a more accurate value.

An unstable safety factor of 0.83 (±0.03) was obtained using the average PGA value corresponding to the 2005 La Paca earthquake (0.11 g) for the slope. Considering this PGA and the critical acceleration derived above, the mean Newmark displacement at the La Paca rock-slide location was about 40 cm. In this case, the critical Newmark displacement required to trigger the rock slide is 13 cm. These relatively large displacement values are explained because the safety factor prior to the earthquake was very low, and so the critical acceleration was also very low. Furthermore, these results are on the same order of magnitude as the Newmark displacements obtained at the sub-regional scale, although slightly higher (Table 3). The estimated Newmark displacement for the occurrence of the most probable earthquake for a 475-year return period was also slightly greater than the value obtained at the sub-regional scale (Table 3).

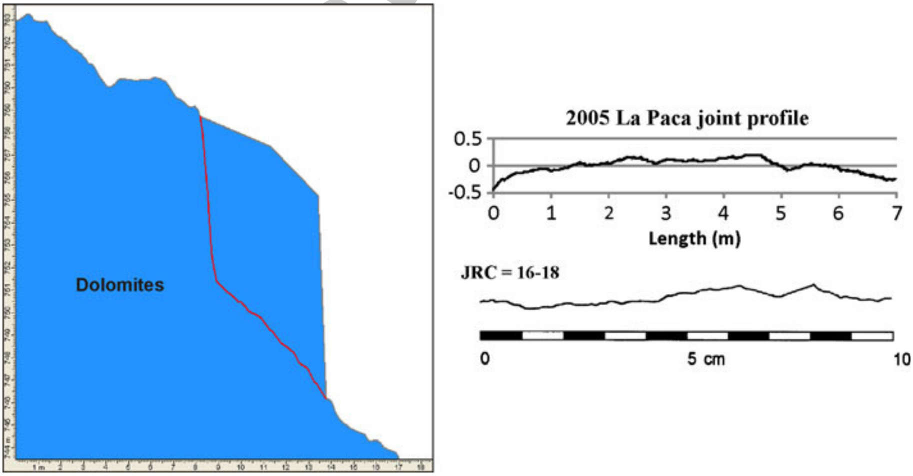

Fig. 10 Slope model used in the stability analysis of the 2005 La Paca rock slide. The *red line* represents the actual failure surface. A comparison between the actual roughness profiles along the down-dip direction (in metres) and the standard roughness profiles of 10 cm from Barton and Choubey (1977) is also shown

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4 Conclusions

It has been shown in this paper that the evaluation at a regional scale of earthquake-triggered landslides can provide incorrect estimates of the Newmark displacements. This was the case of the well-known seismically induced Bullas and La Paca rock slides in SE Spain, where the estimated Newmark displacements at a regional scale were 0 at both sites. However, the results obtained here at a sub-regional scale seem to be in good agreement with those obtained when detailed studies at a site scale are carried out. This conclusion should be contrasted with the study of more cases of seismically induced slope instabilities.

Results obtained on the regional scale are heavily influenced by the grid size of the digital elevation model and by the dimensions of the slope instability. In this regard, a regional map with a pixel size much bigger than the slope instability provides safety factor and critical acceleration values larger than those obtained using a better-resolution digital elevation model.

The simplifications and uncertainties assumed at the regional and sub-regional scales can be allowed considering that the safety factor, critical acceleration and even the Newmark displacement values estimated at both the sub-regional and site scales are very similar. Therefore, this situation justifies the infinite-slope limit equilibrium method and the shear strength parameters applied at the regional scale. Hence, the regional-scale maps are useful as a first-order approximation to detect areas with the highest susceptibility and hazard in order to earmark them for future specific studies at a larger scale. The estimated PGA and Newmark displacement values would be much more accurate if representative accelerograms were available for each earthquake at the slide sites, a condition that is currently not met.

A critical Newmark displacement value of 3 cm has been obtained from the detailed studies performed at the site scale. This value can be considered as a minimum threshold to trigger disrupted-type slope instabilities similar to the Bullas and La Paca rock slides. These earthquake-triggered slope failures seem to be related to slopes with safety factors close to instability and, therefore, to low critical acceleration values.

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References

AENOR (1993) UNE 103-104/93 Test for the plastic limit of a soil. Asociación Española de Normalización y Certificación, Madrid, p 2
AENOR (1994a) UNE 103-301/94 Determination of a soil density. Method of the hydrostatic balance. Asociación Española de Normalización y Certificación, Madrid, p 2
AENOR (1994b) UNE 103-302/94 Determination of the relative density of the particles of a soil. Asociación Española de Normalización y Certificación, Madrid, p 3
AENOR (1994c) UNE 103-103/94 Determination of the liquid limit of a soil by the Casagrande method. Asociación Española de Normalización y Certificación, Madrid, p 9
AENOR (1998) UNE 103-401/98 Determination of the shear strenght of a soil with the direct shear box. Asociación Española de Normalización y Certificación, Madrid, p 34
Akkar S, Bommer JJ (2007) Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East. Bull Seismol Soc Am 97:511–530
Ambraseys NN, Douglas J, Sarma SK, Smit PM (2005) Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: horizontal peak ground acceleration and spectral acceleration. Bull Earthq Eng 37:1–53

ASTM (2000) ASTM-D 2487/00 standard classification of soils for engineering purposes (unified soil classification system). ASTM, West Conshohocken, p 11

Aydin A (2009) ISRM Suggested method for determination of the Schmidt hammer rebound hardness: revised version. Int J Rock Mech Min Sci 46:627–634

Aydin A, Basu A (2005) The schmidt hammer in rock material characterization. Eng Geol 81:1–14

Baena-Pérez J (1972) N° 931: Zarcilla de Ramos, Spanish geologic map 1:50,000 scale (2ª serie). Instituto Geológico y Minero de España, Madrid

Bandis SC (1980) Experimental studies of scale effects on shear strength and deformation of rock joints. PhD. Thesis, University of Leeds, Leeds

Barton N, Bandis S (1990) Review of predictive capabilities of JRC-JCS model in engineering practice. In: Proceedings of the international conference rock joints, Balkema, pp 603–610

Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mech 10:1–54

Benito B, Gaspar-Escribano JM, García-Mayordomo J, Jiménez ME, García Rodríguez MJ (2006) Proyecto RISMUR: evaluación de la peligrosidad sísmica. Instituto Geográfico Nacional y Protección Civil de Murcia, Madrid

Benito B, Capote B, Murphy P, Gaspar-Escribano JM, Martínez-Díaz JJ, Tsige M, Stich D, García-Mayordomo J, García MJ, Jiménez ME, Insua-Arévalo JM, Álvarez-Gómez JA, Canora C (2007) An overview of the damaging, low magnitude La Paca earthquake (Mw 4.8) on January 29th, 2005. Context, seismotectonics, and seismic risk implications for Southeast Spain. Bull Seismol Soc Am 97:671–690

Bindi D, Luzi L, Massa M, Pacor F (2010) Horizontal and vertical ground motion prediction equations derived from the Italian accelerometric archive. Bull Earthq Eng 8:1209–1230

Borcherdt RD (1994) Estimates of site-dependent response spectra for design (methodology and justification). Earthq Spectra 10:617–673

Buforn E, Benito B, Sanz de Galdeano C, Fresno C, del Muñoz D, Rodríguez I (2005) Study of the damaging earthquakes of 1911, 1999, and 2002 in the Murcia, south eastern Spain region: seismotectonic and seismic-risk implications. Bull Seismol Soc Am 95:549–567

Capolongo D, Refice A, Mankelow J (2002) Evaluating earthquake-triggered landslide hazard at the basin scale through GIS in the upper Sele river valley. Surv Geophys 23:595–625

Carro M, De Amicis M, Luzi L, Marzorati S (2003) The application of predictive modelling techniques to landslides induced by earthquakes: the case study of the 26 September 1997 umbria-marche earthquake (Italy). Eng Geol 69:139–159

CEN (Comité Européen of Normalisation) (2004) Eurocode 8: design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings. EN 1998-1, Brussels

Delgado J, Peláez JA, Tomás R, Estévez A, López Casado C, Doménech C, Cuenca A (2006) Evaluación de la susceptibilidad de las laderas a sufrir inestabilidades inducidas por terremotos. Aplicación a la cuenca de drenaje del río Serpis (provincia de Alicante). Revista de la Sociedad Geológica de España 19(3–4):197–218

García-Mayordomo J (1999) Zonificación Sísmica de la Cuenca de Alcoy Mediante un Sistema de Información Geográfico. In: Proceedings of the 1st national congress of earthquake engineering, Murcia, vol. Ib, pp 443–450

García-Mayordomo J, Gaspar-Escribano JM, Benito B (2007) Seismic hazard assessment of the Province of Murcia (SE Spain): analysis of source contribution to hazard. J Seismol 11(4):453–471

García-Mayordomo J, Rodríguez-Peces MJ, Azañón JM, Insua Arévalo JM (2009) Advances and trends on earthquake-triggered landslide research in Spain. In: Proceedings of the volume abstract of 1st international workshop on earthquake archaeology and palaeoseismology, Baelo Claudia, p 4

Gaspar-Escribano JM, Benito B (2007) Ground motion characterization of low-to-moderate seismicity zones and implications for seismic design: lessons from recent, Mw 4.8, damaging earthquakes in southeast Spain. Bull Seismol Soc Am 97:531–544

Jibson RW (2007) Regression models for estimating coseismic landslide displacement. Eng Geol 91:209–218

Jibson RW, Keefer DK (1993) Analysis of the seismic origin of landslides: examples from the New Madrid seismic zone. Geol Soc Am Bull 105:521–536

Jibson RW, Harp EL, Michael JA (2000) A method for producing digital probabilistic seismic landslide hazard maps. Eng Geol 58:271–289

Kampschuur W, Langenberg CW, Baena J, Velando F, García-Monzon G, Paquet J, Rondeel HE (1972) N° 932: coy; Spanish geologic map 1:50,000 scale (2ª serie). Instituto Geológico y Minero de España, Madrid

Keefer DK (1984) Landslides caused by earthquakes. Geol Soc Am Bull 95:406–421

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MS Code : NHAZ1334 ☑ CP ☑ DISK

Luzi L, Pergalani F, Terlien MTJ (2000) Slope vulnerability to earthquakes at subregional scale, using probabilistic techniques and geographic information systems. Eng Geol 58:313–336

Miles SB, Ho CL (1999) Rigorous landslide hazard zonation using Newmark's method and stochastic ground motion simulation. Soil Dyn Earthq Engin 18:305–323

Mulas J, Ponce de León D, Reoyo E (2003) Microzonación sísmica de movimientos de ladera en una zona del Pirineo Central. In: Proceedings of the 2nd national congress of earthquake engineering, pp 13–26

NCSE-02 (Norma de Construcción Sismorresistente Española) (2002) Code of earthquake-resistant building: General part and construction. B.O.E. de 11 de octubre de 2002, pp 35898–35967

NEHRP (National Earthquake Hazards Reduction Program) (2003) Recommendation prevision for seismic regulation for new buildings and other structures. In: Proceedings of the building seismic safety council, Washington, D.C. Federal Emergency. FEMA

Newmark NM (1965) Effects of earthquakes on dams and embankments. Géotechnique 15:139–160

Rodríguez-Peces MJ (2010) Analysis of earthquake-triggered landslides in the south of Iberia: Testing the use of the Newmark's method at different scales. PhD Thesis, University of Granada, Spain

Rodríguez-Peces MJ, García-Mayordomo J, Azañón-Hernández JM, Jabaloy A (2008) Evaluación regional de inestabilidades de ladera por efecto sísmico en la Cuenca de Lorca (Murcia): implementación del método de Newmark en un SIG. Boletín Geológico y Minero 119(4):459–472

Romeo R (2000) Seismically induced landslide displacements: a predictive model. Eng Geol 58:337–351

Skarlatoudis AA, Papazachos BN, Margaris N, Theodulidis C, Papaioannou I, Kalogeras EM, Scordilis EM, Karakostas V (2003) Empirical peak ground-motion predictive relations for shallow earthquakes in Greece. Bull Seismol Soc Am 93(6):2591–2603

Tse R, Cruden DM (1979) Estimating joint roughness coefficients. Int J Rock Mech Min Sci Geomech Abstr 16:303–307

Wieczorek GF, Wilson RC, Harp EL (1985) Map showing slope stability during earthquakes in San Mateo County California. US geological survey miscellaneous investigations map I-1257-E, 1:62,500 scale

Wilson RC, Keefer DK (1983) Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California, earthquake. Bull Seismol Soc Am 73:863–877

Yang ZY, Lo SC, Di CC (2001) Reassessing the joint roughness coefficient (JRC) estimation using Z_2. Rock Mech Rock Eng 34(3):243–251