2 Local Scale Seismic Landslide Susceptibility Assessment Based on Historic Earthquake Records Combined with Accelerometer Monitoring and Ambient Noise Data

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Abstract

Uncertainty in the quantification of earthquake loading poses one of the major difficulties in local scale seismic landslide susceptibility assessments. This problem can be exacerbated for slope settings that are likely to produce considerable amplifications of seismic shaking. We address this issue by examining the case of a historic landslide triggered by the 1627 Apulian (southern Italy) earthquake (epicentral intensity X on the MCS scale) in the peri-urban area of Caramanico (central Italy), distant ~120 km from the epicenter. The failure caused a large downslope displacement and destroyed several buildings. The slope seismic response is assessed using data from long-term accelerometer monitoring of the hillslope and from recent ambient noise measurements. This provided evidence of significant directional amplifications, e.g., by a factor of approximately 4 and 20, respectively in terms of peak horizontal acceleration and Arias Intensity during the 2009 Mw 6.3 L'Aquila earthquake that occurred 60 km NW of Caramanico. Then taking into account the site amplification, permanent displacements are calculated by applying a rigorous Newmark approach. This study shows that historical information on landslides triggered at apparently anomalously large distances from an earthquake epicentre can help to identify hillslopes influenced by site effects and that reconnaissance-type measurements of ambient noise can be useful to reveal directional amplifications. The importance of accurate assessments of other relevant input parameters (e.g., material properties, slip surface geometries, groundwater conditions) used in seismic slope modeling is also recognized.

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1 Introduction

Although the occurrence of high magnitude (>7) earthquakes in Italy seems very rare according to the historical records, weak to moderate seismic shaking is relatively common (Boschi et al. 2000) and known to have triggered many slope failures. Many potentially unstable areas of Italy are also densely populated and research on seismically-induced landsliding deserves high priority.

In this context, one of the major difficulties in seismic landslide hazard assessments is linked to the uncertainty in the quantification of earthquake loading (e.g. Wasowski et al. 2011 and references therein). This problem can be exacerbated especially for slope settings that are likely to produce considerable amplifications of seismic shaking. Site effects may often result from a combination of amplifications caused by slope litho-stratigraphic (soil) and topographic responses (e.g. Paolucci et al. 1999; Del Gaudio and Wasowski 2011) and their quantification is not simple. We address this issue with reference to the study area of Caramanico Terme, a thermal spa center and tourist resort located in the central Apennine Mountains, one of the most seismically active regions of Italy (Fig. 2.1).

The area is prone to landsliding and several examples of historically documented failures induced by earthquakes were discussed by Wasowski and Del Gaudio (2000). While this earlier work was focused mainly on rockfalls, with hazard being assessed by identifying susceptible areas and defining temporal occurrence in terms of seismic threshold exceedance probability, here we re-examine the case of a historic landslide triggered by an earthquake of epicentral intensity X on the MCS scale, occurred on 30 July 1627 in the Apulian region (southern Italy). The failure affected the peri-urban area of Caramanico, causing destruction of several buildings. This case is also of interest, because the 1627 landslide affected a hillslope that is now traversed by a 1.5 km long tunnel.

A preliminary study of the landslide indicated that despite the large epicentral distance (~120 km) the 1627 earthquake triggering could be compatible with general magnitude-distance relations (Keefer 1984). However, the slope stability analysis also showed that the seismic input inferred by using common attenuation relationships would have been insufficient to produce the failure (Wasowski et al. 2004).

In this work the seismic response of the slope failed in 1627 is re-assessed by considering the new data from the ongoing long-term accelerometer monitoring of the Caramanico area (Del Gaudio and Wasowski 2007, 2011) and from recent ambient noise measurements, which provided evidence of significant site amplifications, including directional effects (Del Gaudio et al. 2008; Del Gaudio and Wasowski 2012). We first provide background information on the geological setting of the area. This is followed by a reconstruction of the 1627 landslide event. Then the characteristics of the 1627 earthquake and ground motion estimates are provided. Finally, constrained shaking parameters are used to calculate permanent displacement (Dn) by applying the rigorous Newmark approach.

2 Background Information

The causes of landsliding in the area of Caramanico are related to the interaction of climatic, seismic and human factors. The environmental factors leading to slope instability have already been discussed (Wasowski 1998; Wasowski and Del Gaudio 2000), hence only a brief description of the local geological setting is presented here.

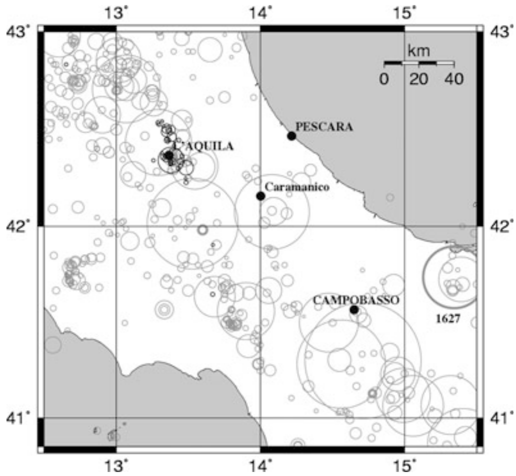

Fig. 2.1 Seismicity of south-central Italy: *circles* represent the focal volumes (according to Bath and Duda 1964) of earthquakes of magnitude >4 occurred from 1000 to 2011. *Grey circles* are mainshocks of historical earthquakes (data from Catalogue CPTI11, Rovida et al. 2011), including the Apulian 1627 earthquake. *Black circles* are instrumentally detected events occurred from 2007 to 2011 (data from the database of the ISIDe Working Group 2010). Note the event cluster corresponding to the 6.3 Mw 2009 L'Aquila earthquake

Three main lithological units are present in the study area (Fig. 2.2):

1. Quaternary/Holocene age sediments, which can be classified as soils. They include variably thick (from few to tens of meters) colluvial materials. These materials mantle large portions of the hillslope areas and include different sized carbonate clasts with or without a clayey-silty-sandy matrix.
2. A several meters thick deposit of carbonate megabreccia which forms the caprock of the Caramanico hillslopes (Quaternary?).
3. Marly mudstones, including rare sandstone intercalations (Early Pliocene), which form the local substratum.

The widespread instabilities of the Caramanico hillslopes can be broadly related to the spatial distribution of these three main lithotypes and their hydrogeological properties. The stability of the slopes is influenced by the presence of: (i) a low hydraulic conductivity mudstone substratum; (ii) a highly permeable megabreccia slope caprock which acts as an aquifer; and (iii) medium to low hydraulic conductivity colluvial soils, which overlie the mudstone aquiclude and can locally also act as an aquifer.

Limited piezometric measurements from sites covered by thick colluvia indicated groundwater levels at considerable depths, often close to the mudstone substratum interface (Wasowski et al. 2004).

3 Reconstruction of the 1627 Earthquake-Induced Landslide

Wasowski and Del Gaudio (2000) quoted several historical records to demonstrate the case of earthquake triggering for the 1627 Caramanico landslide. They also indicated that seismic trigger could be compatible with the magnitude-source distance threshold proposed by Keefer (1984).

3.1 Topographic Site Conditions

The descriptions reported by Almagià (1910) indicate that the 1627 event resulted in significant downslope displacements of a monastery built in 1448. The historical source quotes that the monastery "descended from the nearby mountain together with the ground, from the first level and ran to another site even farther, as did the walls and other houses, without however being dismembered or falling apart entirely". The movement caused overthrowing of several buildings in the area occupied today by the Caramanico cemetery. This area represents the accumulation zone of the 1627 landslide, because the frescos in the cemetery chapel built in 1756 contain the description stating that the monastery "funded on the nearby hill…was pushed down here by the impetus of the 1627 earthquake".

On the basis of the above considerations and taking into account the present morphology of the slope we infer that the detachment area of the 1627 landslide was located more than 100 m upslope from the cemetery site and speculate that the failure involved the slope area mantled by thick colluvia (Fig. 2.2). However, at present

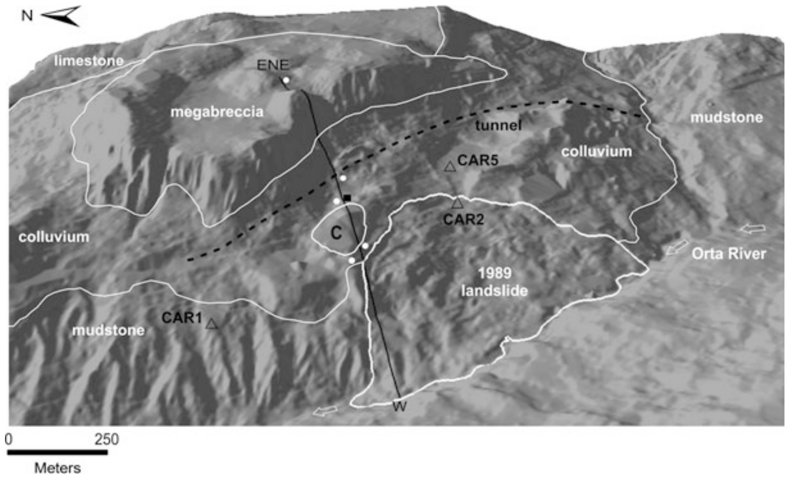

Fig. 2.2 DEM of the study area showing lithological units and measurement sites. *White lines* mark lithological contacts, approximate limits of the 1627 landslide deposit at the cemetery site (C) and the 1989 landslide. CAR1,2,5 mark the location of the accelerometric stations (reference station CAR4, located 2.5 km SE of Caramanico, is not shown). *Black rectangle* and *white dots* indicate, respectively, the site of HVNR measurement and borehole locations. Note also positions of the road tunnel and the profile shown in Fig. 2.3

it is difficult to pinpoint the exact location of the detachment area of the 1627 landslide.

3.2 Geological Site Conditions

A simplified geological profile across the failed hillslope is shown in Fig. 2.3. Local topographic and geologic complexities enhanced by landslide processes make the reconstruction of the subsurface conditions uncertain. Nevertheless, the overall hillslope morphology and the litho-stratigraphic relations inferred from borehole information are compatible with the occurrence of deep-seated landsliding. The presence of thick colluvium and the fact that despite a significant downslope translation the monastery was not destroyed, further suggest the occurrence of a deep and more or less coherent failure.

The uncertainty regarding the depth and geometry of the failure surface and the presence of the colluvium including abundant, more or less cemented coarse limestone detritus causes difficulties in the assessment of realistic in situ effective shear strengths. Thus some simplifying assumptions are adopted with reference to the geological material properties. Considering that the 1627 earthquake occurred in the middle of the summer (hot and typically dry season in Italy), "dry" conditions are assumed for the stability analysis. We also hypothesize that the failure surface developed within the colluvium.

4 The 1627 Earthquake and Constraints on Ground Motion Input Data

The 1627 Apulian earthquake occurred within the southern Apennine foreland which is characterised by major strike-slip sources (e.g. Del Gaudio et al. 2007). Historical macroseismic data (e.g. Boschi et al. 2000) indicate that the 1627 seismic sequence was characterised by four strong shocks (between 30 July–6 September), with epicentral intensity ranging from VIII-IX to X; the mainshock and the first strong aftershock occurred on July 30, only 15 min apart. The application of well established algorithms to the spatial distribution of intensity values (Gasperini et al. 1999) and the large amount of the macroseismic data allowed constraining the magnitude estimates to a value of 6.7 ± 0.2 for the mainshock (Rovida et al.,

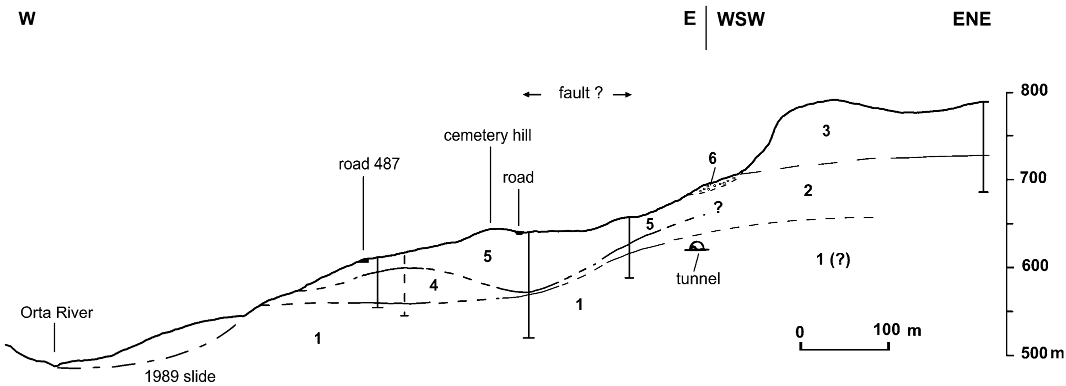

Fig. 2.3 Simplified geological profile of the hillslope, site of the 1627 earthquake-induced failure (after Wasowski and Del Gaudio 2000). Symbols: *1* mudstone substratum; *2* clay-rich silty sandy deposits with variable admixtures of carbonate debris; *3* carbonate megabreccia (caprock); *4* remoulded clay-rich materials with variable amounts of angular carbonate clasts; *5* variably cemented carbonate debris; *6* recent carbonate detritus of rock fall origin

2011). With the epicentre of the 1627 event distant about 120 km from the landslide site, the shaking felt in Caramanico would be expected much attenuated. In fact, the application of Italian attenuation relationships (Sabetta and Pugliese 1996; Bindi et al. 2009) results in low PGA and Ia values. In particular, under the deep soil conditions, the Ia values are below the median shaking intensity of 0.32 m/s, a threshold indicated by Harp and Wilson (1995) for triggering coherent-type landslides.

Obviously the uncertainties regarding the choice of seismic input data are large in case of historic events, which lack instrumental records. We address the problem by applying Ground Motion Prediction Equations (GMPE) calibrated on data from accelerometer sites on rock/stiff soil and by taking into account the local site effects revealed by the accelerometer monitoring at Caramanico.

4.1 Indications from Accelerometer Monitoring at Caramanico

The data acquired by an accelerometer monitoring network, established in 2002–2005 in Caramanico to study the dynamic response of slopes characterized by different topographic and geologic conditions, revealed the presence of significant site amplifications (Del Gaudio and Wasowski 2007, 2011). For the present study of interest are three accelerometer stations located on the hillslope affected by the 1627 landslide (Fig. 2.2):

(a) CAR1, on a slope in Pliocene mudstones, dipping 18° to WSW;
(b) CAR2, 600 m to SSE of CAR1, within the same hillslope locally dipping 11° to WSW, but on the head of a landslide that in 1989 mobilized a 30–40 m thick colluvium overlying the same mudstone formation cropping out at CAR1;
(c) CAR5, about 200 m east of CAR2, on the same colluvium unit as in CAR2, but upslope from the 1989 landslide crown, in gently inclined (<7°) area.

An additional station (CAR4) located 2.5 km SE of Caramanico, on limestones forming a gentle slope, was used as reference.

Given the similarities of the subsurface geology (thick colluvia overlying the mudstones), one can infer the dynamic response of the slope that failed in 1627 from the accelerometer records of CAR1 and CAR5. An evaluation of the potential amplification was carried out by considering peak values of horizontal acceleration (PHA) and Arias Intensity measured along horizontal directions (Ia_{max}) registered at CAR1 and CAR5 during the same events. The relative amplification factors are plotted in Fig. 2.4. The comparison of the

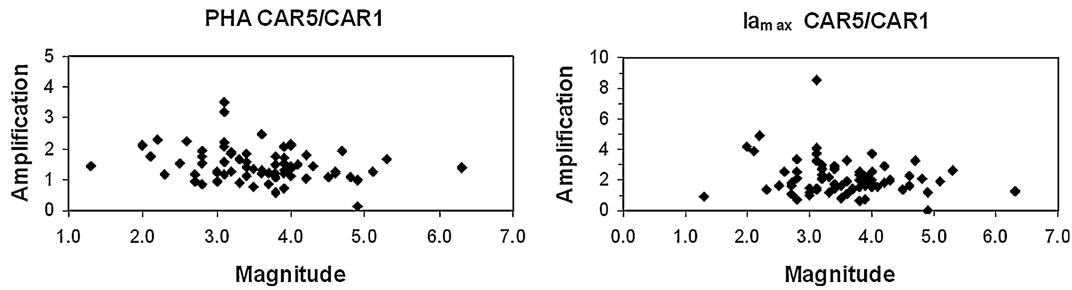

Fig. 2.4 Relative amplification factors at station CAR5 with respect to CAR1 for peak horizontal acceleration (PHA) and maximum Arias intensity measured along horizontal directions (Ia_{max}), as a function of event magnitude

recordings demonstrated that the ground motions at CAR5 are consistently amplified with respect to CAR1. The relative amplification factors average around 1.5–2.2 for PGA and Ia, respectively (with maxima of 4.5 and 8.5). Del Gaudio and Wasowski (2011) documented the presence of very similar relative amplifications between CAR2 and CAR1as well.

It is also of interest to compare time series of horizontal acceleration registered at CAR1 and CAR5 (Fig. 2.5) for the mainshock of the 6 April, 2009 l'Aquila Mw6.3 earthquake, with epicentre located about 60 km NE of Caramanico (Fig. 2.1). The comparison reveals that, even though the peak value at CAR5 was only 40 % larger than at CAR1, for several shaking cycles (along directions different from N–S) ground acceleration was up to 2–3 times higher at CAR5. At site CAR2 ground accelerations were even larger, especially along WSW directions (Del Gaudio and Wasowski 2011).

Notably, in comparison to the reference station on rock (CAR4), the observed amplification factors were considerably higher, especially for the events of magnitude larger than 4. In terms of PGA, amplification factors between 2 and 6 were observed at CAR2 and CAR5 (with a value of 4 for the strongest Mw 6.3 L'Aquila event); in terms of Ia, CAR5 was characterized by amplifications of 9–32 (but with the minimum of 9 just for the strongest earthquake), whereas even larger values (15–35) were found at CAR2.

The observations at site CAR2 provided evidence of site response directivity phenomena that can occur on some slopes along potential sliding

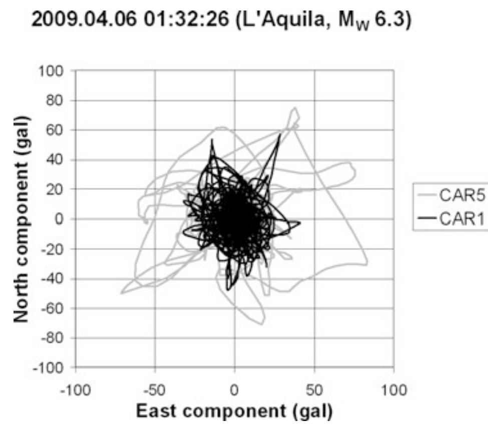

Fig. 2.5 Times series of the horizontal acceleration registered for the mainshock of 2009 L'Aquila earthquake at stations CAR1 and CAR5

directions as an effect of directional resonance affecting deep-seated landslides (Del Gaudio and Wasowski 2007). As shown by Del Gaudio et al. (2008), the presence of resonance conditions (and, possibly, its directional character) can be detected via seismic noise analysis, according to the Nakamura technique (Nogoshi and Igarashi 1971; Nakamura 1989); directivity can be inferred by calculating spectral ratios between horizontal and vertical components of noise recording (HVNR values) along different azimuthal directions. Importantly, resonance conditions, with HVNR peak values close to 4, i.e. similar to the values of 4–5 observed at CAR5 and CAR2, respectively, were identified through recent measurements carried out in the 1627 landslide area (Del Gaudio and Wasowski 2012).

Table 2.1 Summary of ground motion input data and corresponding Newmark displacement estimates

	PGA (g)	Dn (cm)		
		$a_c = 0.01$ g	$a_c = 0.02$ g	$a_c = 0.05$ g
Caramanico				
Bedrock	0.038	6.7	1.9	0
Amplified conditions MIN	0.054	8.2	2.2	0
Amplified conditions INTERM	0.061	11.1	3.9	0.2
Amplified conditions MAX	0.066	12.3	4.2	0.6
El Centro (NS component)				
Bedrock	0.033	4.9	0.3	0
Amplified conditions MIN	0.052	6.4	1	0
Amplified conditions INTERM	0.060	10	2.1	0
Amplified conditions MAX	0.064	10.6	2.4	0
El Centro (EW component)				
Bedrock	0.051	15	2.4	0
Amplified conditions MIN	0.062	18.4	4.6	0
Amplified conditions INTERM	0.073	25.8	8.4	0.2
Amplified conditions MAX	0.088	29.9	10.3	0.4

Minimum (MIN), intermediate (INTERM) and maximum (MAX) PGA values are derived from "bedrock" accelerograms amplified using software STRATA

4.2 Ground Motion Input Data

To estimate the shaking conditions at Caramanico during the 1627 earthquake we first used a procedure proposed by Sabetta and Pugliese (1996), which allows obtaining artificial accelerograms representative of the ground motion expected for the Italian events of defined magnitude and distance at a site characterised by the presence of thick (>20 m) and relatively stiff soil-type lithologies (S-wave velocities > 400 m/s). This is done using GMPE's calibrated on the Italian accelerometer data to define median characteristics of time-dependent ground motion spectra, in order to calculate non-stationary time series simulating realistic accelerograms.

To take into account site amplification effects, the artificial accelerograms were used as input to a 1D layering model to perform a site response analysis in the frequency domain through the code STRATA (Kottke and Rathje 2008), which is available at http://www.gnu.org/licenses/. The program conducts equivalent-linear site response analysis in the frequency domain using time domain input motions or random vibration theory methods, and allows for randomization of the site properties.

To define the non-linear soil shear behaviour under seismic loading, we followed the empirical correlations of Vucetic and Dobry (1991) describing the variation of shear stiffness and damping ratio with shear strain for PI = 0. The soil thickness (30 m), constrained by the boreholes, and a unit weight of 20 kN/m3 were used. The applied shear wave velocity (Vs) values (600 m/s for soil and 1300 m/s for the bedrock) are based on the results of the Refraction Microtremor (ReMi) investigation at Caramanico (Coccia et al. 2010).

For the local bedrock (mudstones) a unit weight of 24 kN/m3 was adopted. The values of damping refer to the results of laboratory tests (G. Lanzo, University of Rome La Sapienza) conducted on one undisturbed mudstone sample obtained from a borehole drilled in the vicinity of the 1627 landslide site.

The amplified accelerograms generated with software STRATA were used for subsequent slope stability analysis. Significantly, the

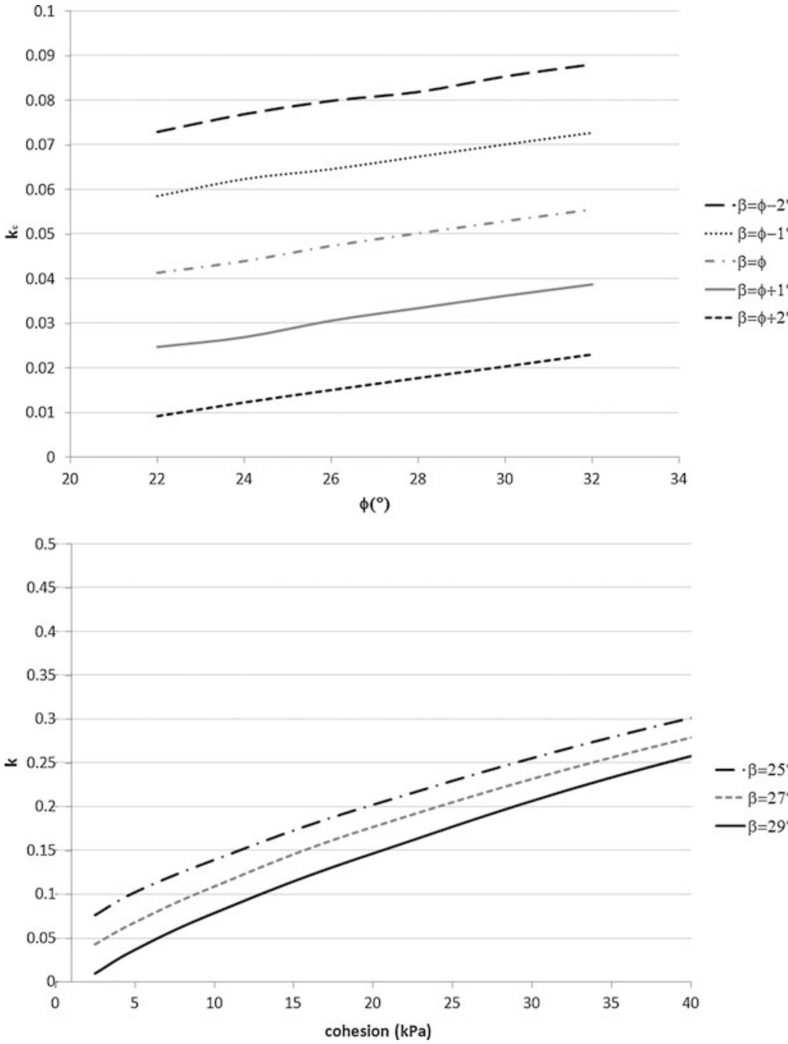

Fig. 2.6 Variation of the seismic critical coefficient (k_c) with respect to: (*upper figure*) friction angle φ, with c = 3 kPa) and (*lower figure*) cohesion c ($\varphi = 27°$), for different values of the slope angle (β)

amplifications (up to ~100 %, Table 2.1) obtained are closely comparable to the amplification factors identified from accelerometer monitoring at Caramanico.

5 Dynamic Slope Stability Analysis Based on Newmark Model

First the assessment of the critical or yield seismic coefficient value k_c (value of seismic acceleration expressed in g that produces a pseudostatic factor of safety = 1) was carried out by applying the upper-bound pseudo-static limit analysis and assuming a logspiral failure mechanism representative of a local slope failure (Chang et al. 1983). Plane strain conditions were assumed for isotropic and homogeneous soil mass (e.g. colluvium) sliding on a failure surface characterised by a rigid-plastic Mohr–Coulomb constitutive law. There is a lack of accurate information on the original, pre-failure slope inclination (β), as well as on the mobilised values of cohesion (c) and soil friction angle (φ) along the failure surface. Therefore, a parametric analysis was carried out with respect to both c (ranging between 3 kPa and 40 kPa; $\varphi = 27°$) and φ (ranging between 22° and 32°; c = 3 kPa), for prescribed values of the slope inclination β. According to the upper-bound limit analysis, for each pair of [φ, β] and [c, β] values, the k_c value was derived by imposing the minimization of k_c with respect to the geometrical parameters. The results of the analysis in terms of k_c values against φ and c are shown in Fig. 2.6 and the corresponding critical acceleration values ($a_c = k_c \cdot g$) were selected for the calculation of the earthquake-induced permanent displacements.

The rigorous permanent-displacement (Dn) analysis, with double integration of the soil mass acceleration over the time intervals characterised by $a > a_c$ (Newmark 1965), was performed using a software developed by Jibson and Jibson (2003). Three amplified accelerograms characterized by the minimum, intermediate and maximum values of PGA, as well as a non-amplified synthetic accelerogram representative of the slope bedrock conditions were used in the Dn analysis. In addition, for comparative purposes we used an accelerogram from a strike-slip event of similar magnitude to that of the 1627 earthquake, (the 1956 M 6.8 El Alamo Baja, California earthquake), registered at El Centro station (with flat ground, deep, stiff soil conditions) positioned at an epicentral distance (121 km) that is about the same as the distance between Caramanico and the 1627 earthquake epicentre.

The results show that significant displacements, that is close to 10 cm, a threshold assumed by Wilson and Keefer (1985) for the occurrence of coherent slide type failures, are obtained by imposing very low k_c values (within 0.02) and amplified conditions (Table 2.1). Such low k_c values are derived if similar values of slope geometry (β) and friction angle (φ) are assumed, along with low values of the soil cohesion (cf. Fig. 2.6). We speculate that by breaking the cementation bonds within the colluvium rich in carbonate clasts, the mainshock might have drastically reduced the cohesion and caused the failure during the strong aftershock that followed 15 min later.

6 Concluding Remarks

This study illustrates how historical earthquake information can be combined with present day in situ accelerometer monitoring for seismic landslide susceptibility assessments. The Caramanico accelerometer monitoring data show that on hillslopes with bedrock covered by thick colluvia, local litho-stratigraphic amplification can generate seismic shaking much higher (one order of magnitude in terms of total shaking energy) than that estimated by ordinary attenuation relationships (with calibration relying on accelerometers typically located on flat ground). This is consistent with the Newmark analysis of the 1627 seismic landslide at Caramanico, which indicates that significant site amplification would have been necessary to trigger the failure.

However, evaluations of seismic stability of slopes relying on Dn estimates require the integration of different types of input data (topographic, geotechnical, hydrogeological, seismological), which are characterized by a certain degree of natural dispersion (e.g. seasonal temporal variability), as well as variable resolution, quality, and reliability (cf. Murphy et al. 2002). The application of Newmark displacement analysis to the 1627 case shows that without accurate knowledge of slope material properties the reconstruction of mechanisms of seismically triggered deep slope failures could be difficult. We also recognize that the Dn results linked to low critical coefficient values (<0.05) can be affected by considerable degree of uncertainty (cf. Strenk and Wartman 2011).

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