Post-print dell'articolo: *Seismic-induced rockfalls and landslide dam following the October 30, 2016 earthquake in Central Italy.*

In accordo con le politiche editoriali della rivista si riporta di seguito il link della pubblicazione definitiva con il doi.

https://link.springer.com/article/10.1007/s10346-017-0841-8

Seismic-induced rockfalls and landslide dam following the October 30, 2016 earthquake in Central Italy

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Abstract

On October 30, 2016, a seismic event and its aftershocks produced diffuse landslides along the SP 209 road in the Nera River Gorge (Central Italy). Due to the steep slopes and the outcropping of highly fractured and bedded limestone, several rockfalls were triggered, of which themain event occurred on the slope ofMount Sasso Pizzuto. The seismic shock acted on a rock wedge that, after an initial slide, developed into a rockfall. The debris accumulation blocked the SP 209 road and dammed the Nera River, forming a small lake. The river discharge was around 3.6 m^3/s; the water overtopped the dam and flooded the road. By a preliminary topographic survey, we estimated that the debris accumulation covers an area of about 16,500 m^2, while the volume is around 70,000 m^3. The maximum volume occupied by the pre-existing talus mobilized by the rockfall is about 20% of the total volume. Besides blocking the road, the rockfall damaged a bridge severely, while, downstream of the dam, the water flow caused erosion of a road embankment. A rockfall protection gallery, a few hundred meters downstream of the dam, was damaged during the event. Other elastic nets and rigid barriers were not sufficient to protect the road from single-block rockfalls, with volumes around 1–2 m3. Considering the geological and geomorphological conditions, as well as the high seismicity and the socioeconomic importance of the area, a review of the entire rockfall protection systems is required to ensure protection of critical infrastructure and local communities.

Keywords: rockfalls, seismic-induced landslide, landslide dam, Nera River, Central Italy earthquake

1 Introduction

Seismic-induced landslides are characterized by the detachment and rapid downward movement of rock, with the potential to cause economic losses and fatalities (cf. Guzzetti et al. 2005). Rock failures triggered by earthquakes in the last millennium in Italy were catalogued by the database of earthquake-induced ground failures (Italian acronym CEDIT, Martino et al. 2014). Within this framework, Central Italy has been affected by several historical rockfalls related to earthquakes. The more recent one occurred in August–October 2016; at the time of writing the present work (January 2017), this seismic sequence is still going on.

Some previous studies (Antonini et al. 2002; Carro et al. 2003; Gigli et al. 2014) focused on rockfall hazard and risk assessment in the Umbria-Marche Apennines (Central Italy) after the 1997–1998 Umbria-Marche earthquake sequence. That seismic sequence triggered numerous rockfalls along the Nera River Gorge, in the upper Nera

Valley. The 1997–1998 earthquake, with the strongest shock having a moment magnitude (MW) 6.0, is one of the world's best case studies for extensional earthquakes (Barchi and Mirabella 2009 and references within).

The present study describes the seismic-induced rockfalls, and their effects, which occurred on October 30, 2016 along the Nera River Gorge between the Umbria and Marche regional border, close to the little town of Visso. Here (Fig. 1), rockfalls are not rare along about 3 km of the transportation corridor (SP 209 road) southwest of Visso village in the upper Nera Valley (cf. Guzzetti et al. 2004). During the October 30, 2016 seismic event, a new large rockfall interrupted the road and dammed the Nera River. To our knowledge, none of the past rockfalls events was as disastrous and large as those triggered by the 2016 earthquake.

2 Study area

2.1 The seismic sequence of Central Italy, 2016

Countless earthquakes have affected Central Italy in historical times. According to the national catalogue by Rovida et al. (2016), the historical earthquakes affecting the study area (Fig. 1) occurred in the proximity of the Umbria-Marche-Lazio-Abruzzo regional border, roughly coinciding with the water divide of the Apennine chain. Based on instrumental magnitude equivalent to MW by Rovida et al. (2016), since 1328, around ten events have occurred with MW higher than 5.3. The largest occurred in January 1703 (Umbro-Reatino earthquake—MW 6.9).

According to the National Institute of Geophysics and Volcanology of Italy (INGV), the recent seismic sequence started on August 24, 2016, in the Amatrice/Accumoli area (MW 6.0) with thousands of aftershocks which extended for about 40 km from Accumoli (south) to Visso (north): location and magnitude of earthquakes can be downloaded from the INGV website (http://cnt.rm.ingv.it/en). In detail, from August 24, 2016, to January 13, 2017, INGV recorded 55 seismic events with MW $\geq$ 4. Figure 1 shows the location of the study area with epicentres having MW $\geq$ 4, classed by the temporal occurrence. According to the report by INGV (2016), the focal mechanism of the October 30 earthquake is similar to those of previous earthquakes of the sequence, showing the involvement of extensional faults oriented NNW-SSE. At the end of October 2016, the seismic sequence moved north producing the main shocks reported in Table 1.

The s t r o n g - motion n e twork of INGV (h t t p : / /ran.protezionecivile.it/IT/index.php?evid=345980), close to the study area, recorded the maximum PGA (peak ground acceleration) values of 0.26, 0.30, and 0.46 g at Preci, Montecavallo, and Castelsantangelo sul Nera stations, respectively (see Fig. 1 for location). Seismic motions caused several rockfalls and diffuse instabilities along the Nera River Gorge. The most devastating events occurred after the strongest shock of October 30, 2016–6:40:17 UTC (MW 6.5). The largest and most disastrous of these events will be presented and discussed in the following sections.

FIG. 1

2.2 Geological and geomorphological setting

The study area is located in Central Italy, along the border between the Umbria and the Marche Regions and within the Sibillini Mountains, the highest mountain chain in the Umbria-Marche Apennine (the maximum elevation is Mount Vettore, 2478 m above sea level). The Nera River, flowing from NE to SW, crosscuts the study area. On the right side of the Nera River, the elevation reaches 1480 m above sea level, while Mount Forgaletta (1338 m above sea level) is the highest elevation on the left side. The elevation decreases toward the southwest, where two main tributaries of the Nera River occur. The Torso Stream, having a N-S direction, delimits the area on the right side of the Nera River. On the left side, the Morcionara Stream flows from SE to NW.

The morphological setting is the result of a first compressive tectonic phase (Miocene) producing the mountain chains in a fold system elongated in a NW-SE or N-S. Later, since the Upper Pliocene, an uplift phase together with an extensional tectonics raised the topography and segmented the reliefs along the main normal faults (Della Seta et al. in press). In the study area (Fig. 2), the direction of the Nera River follows the conjugated faults direction, along a path with a SW-NE trend.

TABLE 1

Figure 2 shows the geological map of the study area as derived from the official geological map (dataset of Umbria and Marche Regions, http://dati.umbria.it/dataset/cartageologica-dell-umbria and http://www.ambiente.marche.it/Territorio/Cartografiaeinformazioniterritoriali). The area ischaracterized by the outcropping of Umbria-Marche sequence from the Calcare Massiccio (a massive platform limestone) to Scaglia Variegata-Cinerea (marly-calcareous rocks). Slopes in the left bank of Nera River are mainly characterized by the outcropping of the Maiolica Formation (stratified pelagic limestone) with slope angles having values greater than 40° (the highest values are in the SW and NE part of Nera River Gorge, Fig. 2). The amplitude of the relief triggered an active morphogenesis with fast river erosion and strong mass wasting phenomena.

FIG. 2

3 Data and Methods

3.1 Rockfall and diffuse instability

The ground acceleration produced by the 2016 earthquake deeply affected the stability of slopes within the study area. Although the local media reported some rockfalls occurring during the sequence on August 24, 2016 (cf. ANSA 2016), most of the severe rockfalls took place at the end of October 2016, in particular on the morning of October 30, 2016. This paper describes the main rockfalls mapped during a survey carried out a few days after the October 30 main earthquake.

Figure 3 shows the results of our survey. Along the SP 209 road, we located several boulders and debris from diffuse rockfalls, one landslide dam and debris accumulations which in a few cases partially occluded the Nera River.

Most of rockfalls developed in the Maiolica Formation, here highly fractured. Boulders observed along the road have volumes up to about 2 m^3. Rockfall occurrence and distribution depend on several variables such as topographical and geostructural characteristics of the slope, the presence of installed rockfall protection measures, etc. In detail, as shown in Fig. 3, rockfalls are mainly located on steep slopes characterized by overhanging fractured rock masses above the SP 209 road.

It is relevant to point out that the passive protection measures, built after the previous earthquake (Umbria-Marche 1997-1998) along the SP 209 stretch here investigated, were not very effective: most of the elastic nets, rigid barriers, and rockfall protection galleries were severely damaged. Numerous rock impacts seriously damaged the road surface (Fig. 4a, c). Concrete pillars and walls were also damaged (Fig. 4b).Water overtopping the landslide dam also eroded a section of the SP 209 road (Fig. 4d).

Rockfall damages were particularly severe along the road stretch between points g and o in Fig. 3 (about 1 km southwest of Visso). The largest rockfall occurred along the steep-faced north slope of Mount Sasso Pizzuto (elevation between 840 and 910 m above sea level, point p in Fig. 3), which is characterized by highly deformed, stratified, and fractured rocks (Maiolica Formation). Seismic shaking acted on a rock wedge (Fig. 5a, b) and, after an initial slide, developed into a rockfall (cf. Cruden and Varnes 1996), which during the fall caused the erosion and entrainment of the existing debris on the slope. When the detached rock reached the base of the slope, it was further fragmented and the final debris deposit obstructed both the Nera River and SP 209 road (Fig. 5c, d).

The maximum distance and elevation difference between the toe of debris accumulation and rockfall source area are about 200 and 270 m, respectively.

FIG. 3

FIG. 4

FIG. 5

3.2 The *Sasso Pizzuto* landslide dam: description and survey

The Sasso Pizzuto rockfall dammed the Nera River, forming a small lake. Within the study area, ERG Hydro (the company in charge of hydroelectric power plants) manages the Nera River; the company provided unpublished information about the river discharge values.

A few days after the earthquake on October 30, 2016, the river discharge was about 4.4 m^3/s, which later decreased to 3.6 m^3/s.

The water overtopped the landslide dam, flooding the SP 209 road and flowing into a downstream rockfall protection gallery, transforming about 130 m of the road into a water channel (Fig. 3p). The high velocity water flow eroded the road embankment (Fig. 4d) and a bridge. In the second half of January 2017, the water is still overtopping the dam and the road is still interrupted.

To evaluate the volume of rock debris which dammed the Nera River and SP 209 road, a survey with a TruPulse™ 200 laser rangefinder was carried out on December 2, 2016. Since the seismic sequence was still ongoing and quakes could have triggered new rockfalls, it was not possible to carry out any geomechanical investigations for safety reason. The use of techniques for measuring and monitoring of targets without a direct approach to the landslide source area is more and more used in similar conditions (cf., Gigli and Casagli 2013; Allasia et al. 2013; Mazzanti et al. 2015; Di Matteo et al. 2017). The debris accumulation was surveyed standing on the opposite slope (right bank of the Nera River, Lat: 42.927867 Lon: 13.066310 DD, elevation 590 m above sea level). This location was chosen to carry out the survey in a safe condition in the shortest possible time. After the survey, no major earthquakes have been registered; thus, no appreciable changes in size and shape of the debris accumulation occurred. The laser sensor was placed on a tripod allowing the measure of slope distance, horizontal and vertical distance, inclination, or to calculate the elevation of any target.

Thirty points were targeted on the landslide debris that covers an area of about 16,500 m2. For each target, three measurements were taken, and all acquisitions were performed by the same operator. Due to good weather and target conditions (overcast sky and reflective targets) and the instrument levelled on a tripod, according to the instrument specifications, the accuracy of horizontal and vertical distance measurements was ±0.50 m. Considering the overall situation of the survey we believe that this accuracy is acceptable.

4 Results

In order to characterize the morphological conditions of the slope where the Sasso Pizzuto rockfall occurred and the morphometric characteristics of the event, a GIS analysis was defined in ArcGIS 10.1 (Melelli et al. 2016).

In correspondence of the source area, a morphometric analysis of the original slope highlights a steep slope angle (greater than 58°, polygon 4 in Fig. 6a). Moreover, an evident convex curvature area (polygon 5 in Fig. 6a) shows the almost vertical rugged mountains relief. Besides that, the source area is close to the ridge of the slope. All these topographic features are high predisposing factors to rockfalls and landslides induced by earthquakes. The location of the accumulation deposit is not exactly in the perpendicular direction from the source. The wedge shape of the source area has induced an initial movement of the rock mass along a NW direction, immediately followed by the free fall toward the bottom of the slope. The accumulation area covers the foot of the slope; the rockfall mobilized a non-negligible volume of the pre-existing talus too (Fig. 3p-B). It is difficult to estimate the percentage of the volumes of debris deriving from the source area and that from the pre-existing talus along the slope. To estimate the total volume (debris originated by the rockfall plus the mobilized pre-existing talus), the following GIS procedure was used. A digital elevation model (DEM) with a spatial resolution of 5 × 5 m was interpolated starting from the elevation polylines (with a contour interval of 10 m) and points in a vector format available from the regional technical map of Umbria and Marche Regions (scale 1:10,000). The resulting model reproduces the topography before the landslide events. A raster with the same cell size was then interpolated connecting the 30 points targeted on the debris accumulation and using the z values acquired during the surveying. This procedure reproduced the topographic surface after the rockfall event. Matching the cell alignments, the second raster was subtracted from the initial DEM on a cell-by-cell basis. The resulting raster shows the thickness of the landslide body in each cell. With the aim of limiting the analysis to the perimeter of the debris, the polygon representing the accumulation area was used as a mask. The resulting raster with the thickness values was then converted to point features, obtaining a depth for each cell. Each of these points corresponds to the centre of the cell and has a numeric attribute equal to the thickness of the cell. Subsequently, the vector point layer was clipped on the polygon matching the perimeter of the landslide body. Only the points with a positive value of the thickness were selected. This choice assumes that the negative values correspond to those cells where rocks moved away. Points with positive values correspond to the deposition zones of the rockfall. The thickness of the talus at the base of the slope varies between 1 and 15 m with the highest values in the middle-eastern part (Fig. 6b).

Knowing the cell area, it is possible to have an estimation of the total volume resulting in about 70,000 ± 8000 m^3. The uncertainty in the estimation of the volume is mainly due to the accuracy of vertical distance measurements by TruPulse™ (see BThe Sasso Pizzuto landslide dam: description and survey^ section). Assuming a total porosity of blocky talus of about 30% (Sass and Wollny 2001; Moore et al. 2009), the detached rock mass from the source area is estimated in about 50,000 ± 6000 m^3. During the survey, observations by laser rangefinder have shown that the volume of rock detached from the source area is about 40,000 m^3: this estimation is not as reliable as that performed on the total accumulated mass (the overall accuracy of measures are influenced by the colour of rock, the distance between observation point and rockwall, etc.). The difference between the two estimates should not surprise because, as previously stated, the computed volume of debris accumulation incorporates also the volume of the pre-existing mobilized talus. In spite of all the uncertainties, the general picture is self consistent indicating that the preexisting mobilized talus should be no larger than 20% of the total accumulated volume. Finally, according to Rochet (1987) classification, the Sasso Pizzuto rockfall is a mass rockfall (volume between 102 and 105 m^3).

FIG. 6

5 Discussions and conclusions

The survey along the Nera River Gorge has shown the effects of the recent earthquake along a transportation corridor between the Umbria and Marche Regions. The main rockfall (Sasso Pizzuto) produced a debris accumulation having a maximum thickness of about 15 m (with a total volume, including the mobilized pre-existing talus, of about 70,000 m^3) that dammed the Nera River, forming a small lake (surface area approx. 2000 m^2). It is not a particularly large slope failure, but probably is the biggest rockfall occurring in the area during the last two centuries. Indeed, according to a paper which reports a detailed statistics regarding rockfalls in the upper Nera Valley between 1838 and 1997 (Guzzetti et al. 2004), the 1997 earthquake caused rockfalls with volumes in the order not higher than 103 m3. There are no reports about rockfalls with volumes similar to that of Mount Sasso Pizzuto: this absent evidence suggests that the Sasso Pizzuto fall is the greatest since 1838.

The effects of Sasso Pizzuto rockfall on the road network have been severe. This is because the landslide dam occurred in a very narrow section of the Nera River Gorge (width of about 25 m). The water flow (discharge of 3.6 m^3/s) was dammed and currently it overtops the landslide dam (January 15, 2017, Fig. 6a). On November 11, 2016, during a preliminary field survey, most of the overtopping water from the landslide dam was flooding the SP 209 road, and a negligible amount was flowing in the Nera River bed (Fig. 6a). This indicates that the hydraulic conductivity of the debris which filled the river channel is very low, which can be explained by the physical characteristics of the pre-existing debris and fine soils mobilized along the slope (Fig. 3p-B). As the lake level upstream of the rockfall dam was 7 m higher than downstream of the SP 209 road (hydraulic gradient of about 0.12), the hydraulic conductivity of the debris deposited on the road pavement (filtration area of about 50m2) is lower than what one would be expected. These preliminary considerations could be useful for further studies regarding the influence of soil characteristics and mass hydraulic conductivity on the stability of the landslide dam under different hydraulic conditions, considering the maximum peak discharge upstream the landslide dam. In this framework, a careful monitoring and management of river discharge in the next months are urgently necessary also considering the presence of the hydropower plant system upstream and downstream the landslide dam. In the second half of April 2017, the dam is still in place and the overall conditions—both hydraulic and morphological—have not changed.

The seismic-induced rockfalls did not cause any causalities; nonetheless, the earthquake and related rockfalls damage locally the defensive measures installed by National Road Company (ANAS) after the 1997–1998 Umbria-Marche and caused the blocking of about 4 km of SP 209 road (interruption of traffic). Guzzetti (2006), in the framework of research regarding rockfall hazards after the 1997–1998 Umbria-Marche earthquake, carried out a set of numerical experiments. This research considered, among other issues, the efficacy of the defensive measures put in place by ANAS in a zone of the Nera River basin (about 15 km southwest to the study area, including a stretch of SP 209). The research has shown that in similar roads "the 21.0% of the rockfall elastic fences or concrete walls can be either bypassed by high flying rockfalls, or can be damaged or destroyed by fast moving boulders". The rockfall effects after the October 30, 2016 earthquake, described in the present paper, confirm the scenario obtained by Guzzetti (2006). Indeed, the rockfalls due to the recent 2016 earthquake destroyed or damaged several elastic nets and rigid barriers within the study area (cf., Fig. 4a, c), indicating that the current defensive measures have been not sufficient for protecting the SP 209 road. In other words, this indicates that the defensive measures were designed for protecting against events of a minor intensity of those produced by the October 30, 2016 earthquake, which was among the strongest of the last eighth centuries. Extensive damage to some of the defensive measures is coupled with further changes in geomechanical properties of rock masses along the slopes due to seismic shaking.

Since during the last decades, the upper part of the Nera Valley is experiencing emigration and a slow demographic decrease, coupled to the ageing of its population (cf., Desplanques 1969; Piermattei 2013; Lucarini 2016), the choice of how to restore the road conditions should be carefully evaluated. This requires an accurate geological-geomorphological study, a risk assessment, and the comparison of different technical solutions (new measures for securing the slopes, new rockfall protection galleries or a bypass tunnel, etc.) aiming to reduce the rockfall risk within acceptable values. All these aspects, together with socioeconomic evaluation of the territory, will be necessary to policy makers for future planning.

Acknowledgments

Authors wish to thank the ERG Hydro (Production Unit) which kindly provided discharge data of Nera River.

References

Allasia P, Manconi A, Giordan D, Baldo M, Lollino G (2013). ADVICE: a new approach for near-real-time monitoring of surface displacements in landslide hazard scenarios. Sensors. 13: 8285–8302. http://doi.org/10.3390/s130708285.

ANSA (2016). Sisma, distacco massi da parete roccia. URL:http://www.ansa.it/marche/notizie/2016/09/08/sisma-distacco-massi-da-parete-roccia_16d153da-0d37-42ee-8025-1bcbf9efb6a4.html. [Last accessed: 2017.01.10, in Italian].

Antonini G, Ardizzone F, Cardinali M, Galli M, Guzzetti F, Reichenbach P (2002). Surfaces deposits and landslide inventory map of the area affected by 1997 Umbria-Marche earthquakes. Boll. Soc. Geol. It. 1: 843-853.

Barchi M R, Mirabella F (2009). The 1997–98 Umbria–Marche earthquake sequence: “Geological” vs. “seismological” faults. Tectonophysics. 476: 170–179. http://doi.org/10.1016/j.tecto.2008.09.013.

Carro M, De Amicis M, Luzi L, Marzorati S (2003). The application of predictive modeling techniques to landslides induced by earthquakes: the case study of the 26 September 1997 Umbria–Marche earthquake (Italy). Engineering Geology. 69: 139–159. http://doi.org/10.1016/S0013-7952(02)00277-6.

Cruden D M, Varnes D J (1996). Landslide types and processes. In: Landslides: investigation and mitigation, Turner A K, Shuster R L (Eds.). Transportation Research Board, Special reports. 247:36-75.

Della Seta M, Melelli L, Pambianchi G (in press). Reliefs, intermontane basins and civilization in the Umbria-Marche Apennines: origin and life by geological consent. In: Landscapes and Landforms of Italy, Soldati M and Marchetti M (Eds.). New York, Springer ed.

Desplanques H (1969). Campagnen ombriennes. Colin A, Paris, pp 283 (Italian edition by Melelli A, 1975. Campagne umbre. Tipografia Guerra, Perugia, pp 461).

Di Matteo L, Romeo S, Kieffer D S (2016). Rock fall analysis in an Alpine area by using a reliable integrated monitoring system: results from the Ingelsberg slope (Salzburg Land, Austria). Bull. Eng. Geol. Environ. http://dx.doi.org/10.1007/s10064-016-0980-5.

Galadini F, Messina P, Giaccio B, Sposato A (2003). Early uplift history of the Abruzzi Apennines (central Italy): available geomorphological constraints. Quaternary International. 101-102: 125-135. http://dx.doi.org/10.1016/S1040-6182(02)00095-2.

Gigli G, Casagli N (2013). Extraction of rock mass structural data from high resolution laser scanning products. In: Margottini C, Canuti P, Sassa K (eds) Landslide science and practice. Springer, Berlin, pp 89–94

Gigli G, Morelli S, Fornera S, Casagli N (2014). Terrestrial laser scanner and geomechanical surveys for the rapid evaluation of rock fall susceptibility scenarios. Landslides. 11: 1-14. http://doi.org/0.1007/s10346-012-0374-0.

Guzzetti F, Reichenbach P, Ghigi S (2004). Rockfall hazard and risk assessment along a transportation corridor in the Nera Valley, Central Italy. Environmental Management. 34(2): 191–208. http://doi.org/10.1007/s00267-003-0021-6.

Guzzetti F, Colin P, Stark C P, Salvati P (2005). Evaluation of Flood and Landslide Risk to the Population of Italy. Environmental Management. 36 (1): 15-36. http://doi.org/10.1007/s00267-003-0257-1

Guzzetti F (2006). Landslide hazard and risk assessment. PhD thesis at Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen Friedrich-Wilhelms-Universität University of Bonn, Bonn, Germany. http://geomorphology.irpi.cnr.it/Members/fausto/PhD-dissertation. [Last accessed: 2017.01.12].

INGV (2016). Summary report on the October 30, 2016 earthquake in central Italy M_w 6.5. http://doi.org/10.5281/zenodo.166238.

Lucarini C. (2016). Discussione del disegno di legge n. 2567 . Senato della Repubblica Italiana, XVII LEGISLATURA, 729[a] Seduta. Resoconto stenografico, 23 Novembre 2016, p.19-21. https://www.senato.it/3818?seduta_assemblea=851. [Last accessed: 2017.01.15, in Italian].

Martino S, Prestininzi A, Romeo R W (2014). Earthquake-induced ground failures in Italy from a reviewed database. Nat. Hazards Earth Syst. Sci. 14: 799-814. http://doi.org/814.10.5194/nhess-14-799-2014.

Mazzanti P, Bozzano F, Cipriani I, Prestininzi A (2015). New insights into the temporal prediction of landslides by a terrestrial SAR interferometry monitoring case study. Landslides. 12: 55-68. http://doi.org/10.1007/s10346-014-0469-x.

Melelli L, Cencetti C, Cecconi M, Faralli L, Vecchietti A, Pane V (2016). The hermitage of Cerbaiolo (Tuscany, Italy): stability conditions and geomorphological characterization. Environmental Earth Sciences. 75(4): 322. http://doi.org/1-14. 10.1007/s12665-015-5128-6.

Moore J R, Sanders J W, Dietrich W E, Glaser S D (2009). Influence of rock mass strength on the erosion rate of alpine cliffs. Earth Surface Processes and Landforms. 34: 1339–1352. http://doi.org/10.1002/esp.1821.

Piermattei S. (2013). Local farmers vs. environmental universalism: conflicts over nature conservation in the Parco Nazionale dei Monti Sibillini, Italy . In: After anthropocentrism? Environmental conflicts, social movements and power," Koensler A and Papa C (Eds.), special section of the *Journal of Political Ecology.* 20: 255-341. http://jpe.library.arizona.edu/volume_20/Piermattei.pdf

Rochet L (1987). Application des modèles numériques de propagation à l'étude des éboulements rocheux. Bull. Liaison Labo P. et Ch. 150/151: 84-95 (in French).

Rovida A, Locati M, Camassi R, Lolli B, Gasperini, P (2016). CPTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia. http://doi.org/10.6092/INGV.IT-CPTI15.

Sass O, Wollny K (2001). Investigations regarding alpine talus slopes using Ground-Penetrating Radar (GPR) in the Bavarian Alps, Germany. Earth Surf. Process. Landforms. 26: 1071–1086. http://doi.org/10.1002/esp.254.

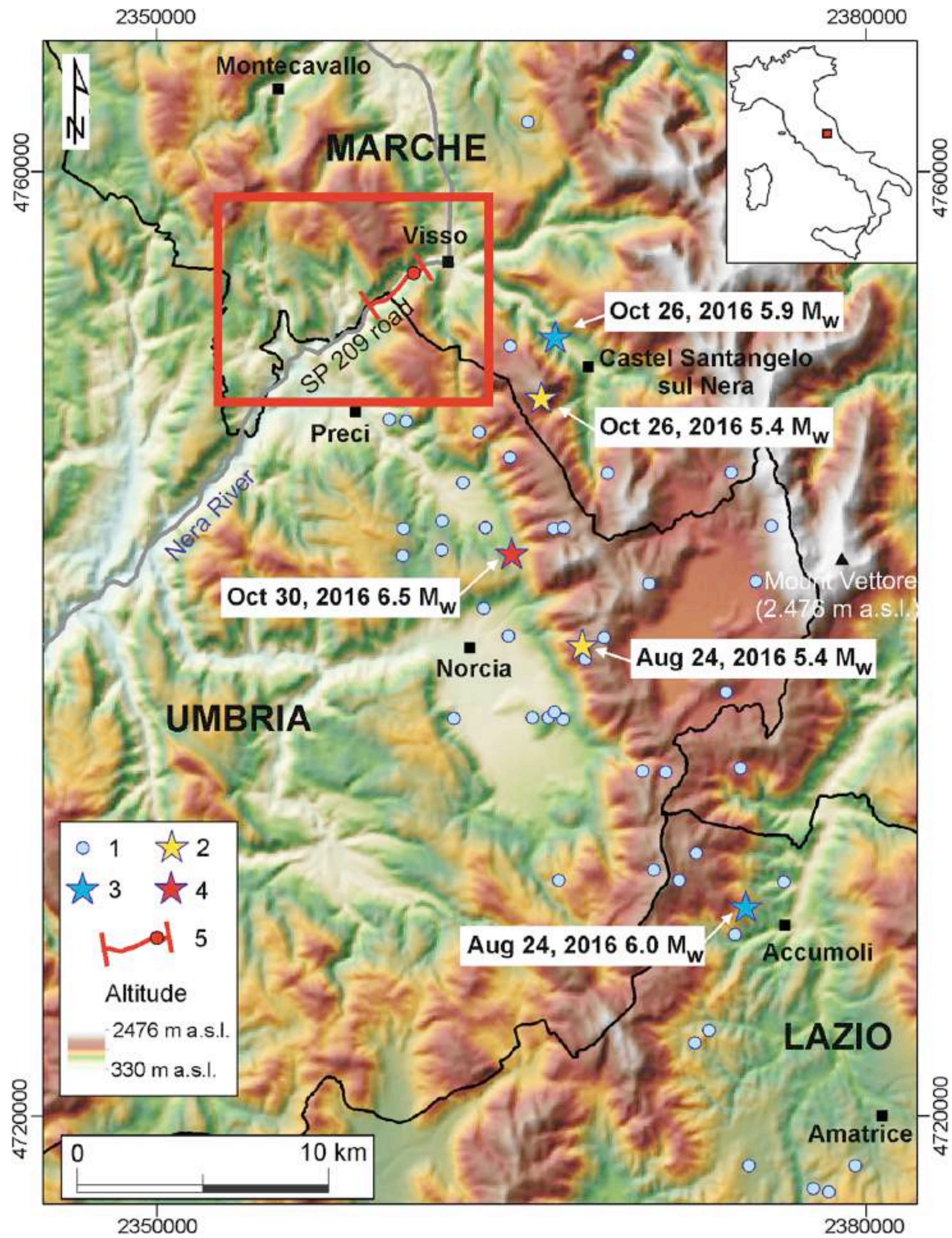

Figure 1 Location map of the seismic sequence in Central Italy (data are referred to August 24, 2016 – January 13, 2017 period). Symbols show the epicentres with: 1) $4 \leq M_w \leq 5$; 2) $5 < M_w \leq 5.5$; 3) $5.5 < M_w \leq 6.0$; 4) $M_w > 6.0$.

Date	Time (UTC)	Magnitude (M_W)	Depth (km)	Latitude	Longitude	Municipality
26/10/2016	17:10:36	5.4	5	42.88	13.13	Castelsantangelo sul Nera
26/10/2016	19:18:05	5.9	6	42.92	13.13	Castelsantangelo sul Nera
30/10/2016	06:40:17	6.5	5	42.84	13.11	Norcia

Table 1 Data of main shocks of October 2016, downloaded from the INGV website (http://cnt.rm.ingv.it/en).

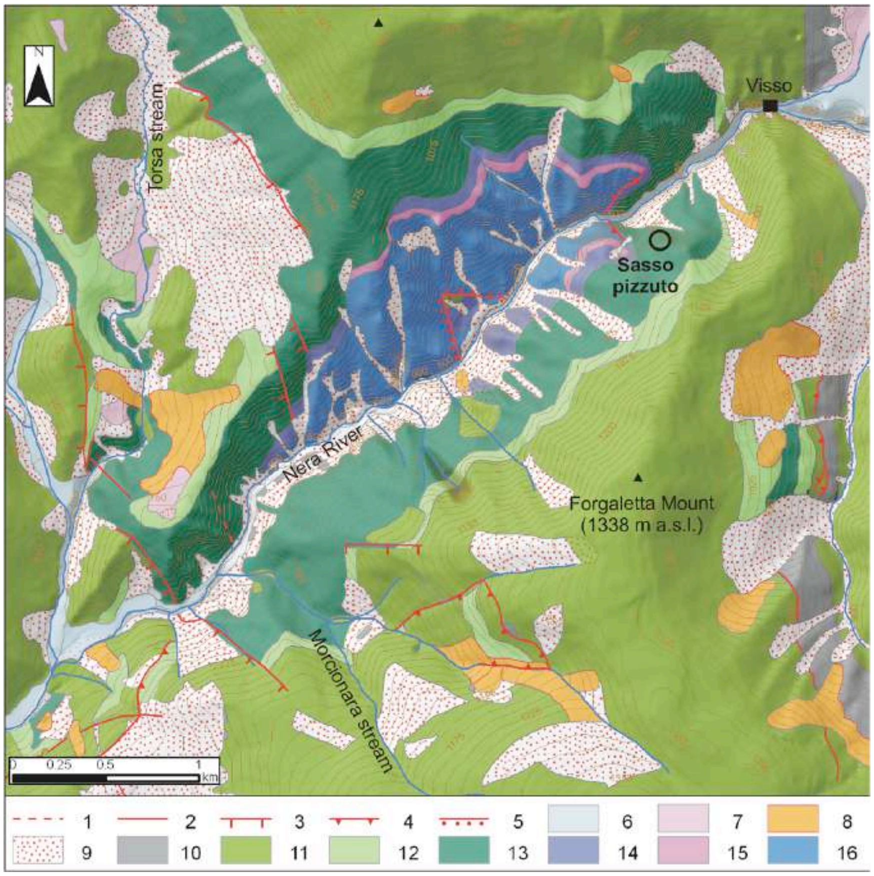

Figure 2 Geological map of the study area. 1) Presumed faults, 2) faults, 3) normal faults, 4) reverse faults and thrusts, 5) syn-sedimentary faults, 6) actual and terraced alluvial deposits, 7) colluvial and eluvial deposits, 8) landslides, 9) talus, 10) *Scaglia Cinerea* and *Scaglia Variegata*, 11) *Scaglia Rossa* and *Scaglia Bianca*, 12) *Marne a Fucoidi*, 13) *Maiolica*, 14) *Calcari Diasprigni*, 15) *Bugarone Group*, 16) *Calcare Massiccio*. Derived by geological datasets of Umbria and Marche Regions (http://dati.umbria.it/dataset/carta-geologica-dell-umbria and http://www.ambiente.marche.it/Territorio/Cartografiaeinformazioniterritoriali/Archiviocartograficoeinformazioniterritoriali/Cartografie/CARTAGEOLOGICAREGIONALE110000.aspx).

Figure 3 Location of rockfalls and diffuse instabilities along the study area with some pictures of the main landslides. Yellow dots represent main detached block falls and mass falls along the SP 209 road and debris accumulation; Red rhombus represent the landslide dam which dammed the Nera River; Blue stars represent debris accumulation which partially dammed the Nera River; Blue triangle shows the location of main damages to infrastructures (erosion of road pavement and pillars breaking of rockfall protection tunnel). A) *Sasso Pizzuto* rockfall source area; B) erosion of existing debris along the slope; C) *Sasso Pizzuto* landslide dam.

Figure 4 Damages to infrastructures induced by seismic activity and related rockfalls within the study area. a) overturning and displacement of elastic nets (point *g* in Fig. 3); b) pillar breaking and distortion of a rockfall protection tunnel (point *i* in Fig. 3); c) breaking of rigid barriers by a rock block (point *d* in Fig. 3); d) erosion of road embankment (point *i* in Fig. 3) by water flow related to landslide dam (point *o* in Fig. 3).

Figure 5 A) Detail of rock mass cut out from the *Sasso Pizzuto* rockwall as consequence of October 30, 2016 seismic main shock; B) detail showing bedding planes cut by two main joint systems; photos of the landslide dam lake taken from downstream (C) and upstream (D). The width of the road is about 7 m. The position of A) and C) pictures is shown in Fig. 3p and Fig. 3o.

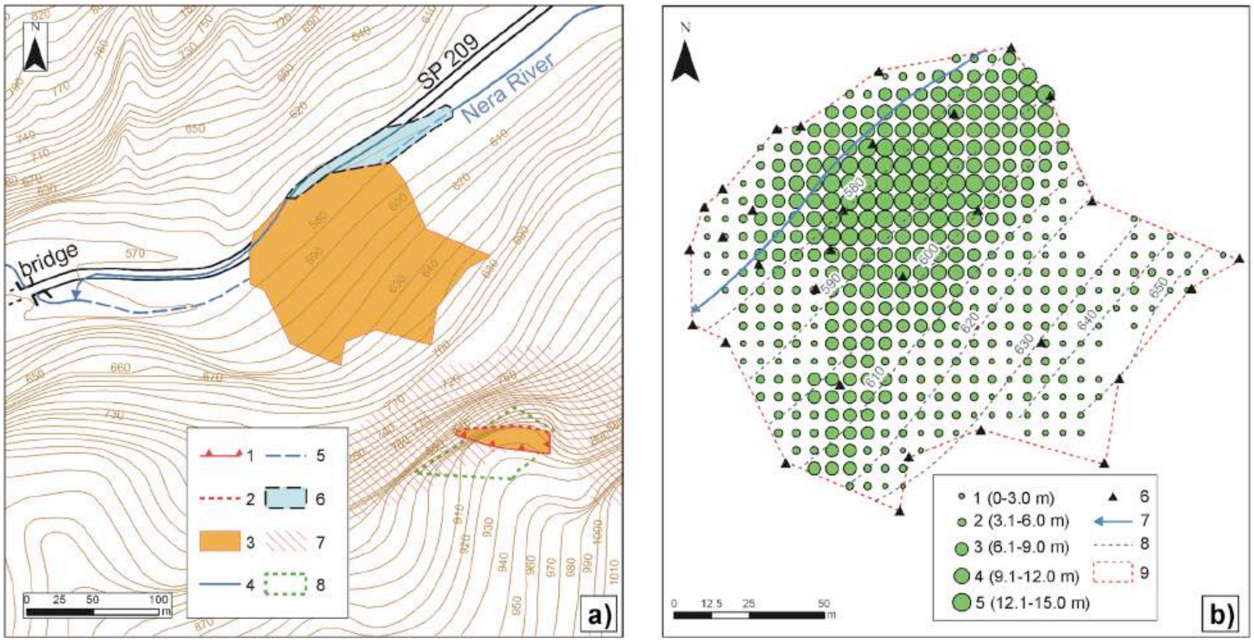

Figure 6 a) the *Sasso Pizzuto* landslide: 1) niche, 2) main joint system delimiting the source area at the bottom; 3) source area and debris accumulation; 4) present Nera River course; 5) Nera River course before the landslide; 6) lake formed by the landslide dam; 7) slope angle values > 58°; 8) curvature values corresponding to steep, rugged mountain morphology. b) Thickness of the accumulated talus as resulted from GIS processing. 1-5) classes of thickness values of talus; 6) points targeted by TruPulse™ 200 laser rangefinder survey; 7) Nera River; 8) contour lines before landslide (available from Regional Technical Map of Umbria and Marche Regions); 9) boundary of the accumulated talus.