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LANDSLIDES INVENTORY MAP OF THE ROADWAY SS103 IN SOUTHERN APENNINES (ITALY)

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EXTENDED ABSTRACT

L'aumento negli ultimi anni delle precipitazioni concentrate in brevi intervalli di tempo come conseguenza dei cambiamenti climatici ha incrementato lo sviluppo di nuove frane e la riattivazione di movimenti più antichi anche nella catena montuosa dell'Appennino meridionale (Italia). Il censimento e la mappatura delle frane in carte di inventario in territori come quello italiano è una prassi comune già da molti decenni e viene realizzato con modalità differenti basate sulla morfologia del territorio, la tipologia di frane, l'intensità delle precipitazioni, al fine di ottenere, grazie ad analisi statistiche mirate, una valutazione della suscettibilità e pericolosità delle aree interessate. La presenza di tracciati stradali di importanza regionale in aree soggette regolarmente a franosità diffusa rappresenta una delle criticità che gli enti territoriali (Comuni, Province, Regioni) devono gestire con maggiore frequenza, principalmente per il rischio di isolamento di aree rurali fino ad interi centri abitati, con conseguenze anche economiche per il corretto ripristino delle sedi stradali. In tale contesto, le carte inventario di frane specificamente realizzata lungo tracciati stradali costituiscono lo strumento base per una successiva razionalizzazione degli interventi e dei costi ad essi correlati. In questo lavoro è presentata la carta inventario delle frane che interessa una importante arteria stradale interna dell'Appennino meridionale, la SS103 "Val d'Agri" che attraversa le regioni Campania e Basilicata, da ovest verso est, per una lunghezza complessiva di 172 km. In particolare, il tratto stradale analizzato è lungo 71 km e si sviluppa da Montesano sulla Marcellana fino a Guardia Perticara con un'ampiezza di 2 km in modo da poter mappare interamente i corpi di frana interferenti con la struttura viaria. Le basi cartografiche geologiche prodotte dall'ISPRA e disponibili online, digitalizzate manualmente in ambiente GIS, hanno portato alla realizzazione della carta dei complessi litologici. Il rilevamento sul campo e l'analisi di foto aeree e di immagini realizzate da drone hanno permesso di cartografare oltre 2300 frane lungo il transetto della SS103 investigato. Considerato l'elevato numero di frane, il tratto stradale è stato suddiviso in 15 segmenti, omogenei per caratteristiche geologiche e morfologiche. Le frane sono state classificate secondo Cruden & Varnes, 1996 e Hungr *et alii*, 2014, prendendo in considerazione il tipo di movimento e lo stato di attività utilizzando la seguente nomenclatura: 1) crolli e ribaltamenti, 2) scivolamenti 3) colamenti, 4) colate rapide, 5) complesse e 6) creep. Nella carta dei complessi litologici sono stati identificati 9 gruppi di litotipi, elencati da C01 a C09, che variano da rocce carbonatiche e silicee a depositi arenacei, marnosi, siltosi e argillosi. I litotipi più abbondanti in percentuale attraversati dalla SS103 appartengono al complesso C04 con il 24%, mentre meno abbondanti sono i complessi litologici C01, C03, che arrivano al 19% e 17%, rispettivamente. Valori inferiori che variano dall'11% al 1% sono mostrati dai restanti complessi litologici. La frequenza di franosità misurata lungo il tracciato investigato della SS103 ha mostrato che il 42% del tracciato è interessato da frane per una lunghezza di circa 30 km. Di questo tratto circa il 66% è interessato da colamenti, che risultano la tipologia di franosità più diffusa, a cui seguono in ordine di abbondanza relativa le frane complesse (13%), gli scivolamenti (7%), i crolli e ribaltamenti (4%), le colate rapide (3%). Le aree interessate da creep occupano, infine, il 7%. Circa lo stato di attività delle frane si osserva che il 58% sono attive, il 42% sono in stato di quiescenza, mentre non sono state osservate frane inattive, a testimonianza di una elevata dinamica superficiale dell'area. L'analisi di dettaglio dei 15 segmenti ha messo in luce che i colamenti sono la tipologia dominante nelle successioni arenaceo-marnoso-argillose mentre i crolli prevalgono nei depositi carbonatici e silicei. Numerose sono le frane complesse e gli scivolamenti che risultano abbondati nel segmento 5 nei depositi arenaceo-conglomeratici. In conclusione, l'analisi della carta inventario delle frane ha identificato le tipologie di frane dominanti e il loro stato di attività e di conseguenza costituisce l'approccio di base su cui sviluppare studi futuri sulla suscettibilità del tracciato stradale e sulle tipologie di interventi che le pubblica amministrazione potrebbe realizzare per garantire la viabilità in sicurezza in questa area dell'Appennino meridionale.

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ABSTRACT

Landslides represent one of the main processes affecting mountainous and hilly landscapes, and within the context of geological hazard, they can cause the damming of many paths and roads, hindering the movement of people and goods. Landslide inventory maps specifically created along roadways, serve as the fundamental knowledge tool for designing interventions. The paper deals with the mapping of landslides distribution along the roadway SS103 "Val d'Agri" which is a relevant thoroughfare crossing the Campania and Basilicata regions, in southern Italy. The mapping is realized in a 71 km long transect, considering a width of 2 km to allow for the complete mapping of landslide bodies intersecting with the road infrastructure. Field surveys and UAV images were used to map landslides, in a landslide inventory map at 1:5000 scale. Lithology and slope features were primarily considered to divide the transect into 15 homogeneous sectors. The investigation allowed us to detect more than 2300 landslides which were classified on movement types and state of activity. Results show that the largest number of landslides occurred in sandstone and clayey lithologies, both in mountain and hill landscapes. This landslides inventory map represents the basic tool for further hazard investigation.

Keywords: landslides, landslide inventory map, road network, southern Apennines, Italy

INTRODUCTION

The recent increase of rainfalls as a consequence of climatic changes has triggered more new landslides in southern Apennines of Italy than the past decades, producing a variety of landform and showing complex spatial distribution and activity than the older ones (Bentivenga *et alii*, 2020). Landslide inventories are crucial for evaluating susceptibility, hazards, and risks, and for devising resilience strategies in mountainous regions. The production of landslide inventory maps, in areas where high landslide hazard exists, was a common activity useful in the evaluation of spatial distribution, typology, magnitude, and state of activity of landslides (Guzzetti *et alii*, 1999, 2012; Hungr *et alii*, 2001; Stark & Hovious, 2001; Schilirò *et alii*, 2018). Landslide inventory maps are a valid tool for local and regional mass movements investigation and can be realized using several approaches such as the location and typologies of landslides (Cardinali *et alii*, 2001; Galli *et alii*, 2008), the rainfall effect and/or the variety of landslides (Guthrie *et alii*, 2004; Guzzetti *et alii*, 2000), and the computation of statistical analyses to produce landslides susceptibility and hazard (Guzzetti *et alii*, 1999; Roth, 1983; van Westen *et alii*, 1999; Conforti *et alii*, 2014). Landslides affecting the road network are one of main critical issues for local municipalities and local authorities, because landslides cause the interruption of connections among countries and isolated villages, the interruption of supplies of goods and services with a confinement of entire communities. The costs of damaging landslide along roadways are mainly covered by public resources based on reports and documents produced by local and regional authorities (Donnini *et alii*, 2017).

In the paper, the investigation of landslide distribution along the roadway SS103 "Val d'Agri", located in southern Italy, was carried out. The SS103 is about 172 km long, and cross-cuts a variety of geological and geomorphological landscapes varying from mountain to hill (Fig. 1). The landslides inventory map was realized along a transect of 71 km long, considering a width of 2 km to allow for the complete mapping of landslide bodies intersecting with the road infrastructure. Coupling field geomorphological surveys, aerial photos, and UAV image interpretation, a lot of landslides were detected and mapped within the GIS environment. The entire area was divided into 15 sectors which are homogeneous from a lithological and morphological point of view. Landslides were classified based on the current landslide classification and differentiated by types of movement, with states of activity identified (Cruden & Varnes, 1996; Hungr *et alii*, 2014). Results of this study will help researchers and municipalities develop effective mitigation plans and reduce costs in roadways connecting isolated mountain areas and villages in low population density regions and to reduce the cost-effective in roadways connecting isolated mountain sites and villages in low population density region.

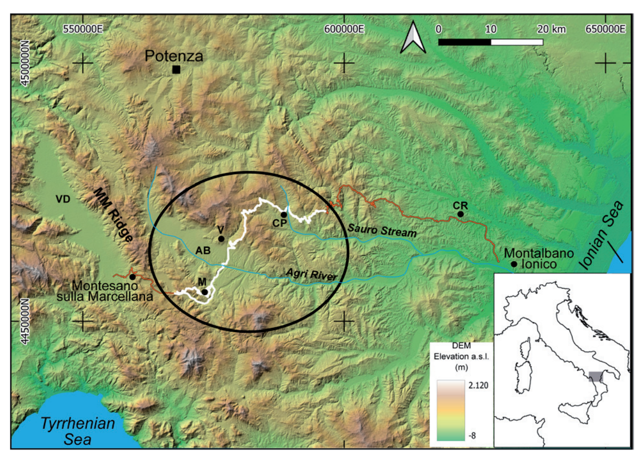


Fig. 1 - Hillshade view and roadway SS103 "Val d'Agri" (red line). White color line in the black circle evidences the investigated 71 km long transect. Black circle is the studied area. Acronyms: MM: Maddalena Mounts; VD: Vallo di Diano basin; AB: Agri intermontane basin; M: Moliterno village; V: Viggiano village; CP: Corleto Perticara village; CR: Craco village

MATERIALS AND METHODS

Starting from the preparation of a basic cartographic dataset composed by the Regional CTR map ("Carta Tecnica

Regionale") and 5m-resolution DTM, available at https://rsdi.regione.basilicata.it/, the geological sketch map of the 71 km long transect of the SS 103 was manually digitized using the QGis application, considering a width of 2 km on the right- and left-sides of the roadway. Polygons, polylines, and points were used in the digitizing process with drawing errors ranging from 0.1 to 0.3 mm. The geological maps was digitalized from the Geological sheets of Italy at 1:50000 scale (https://www.isprambiente.gov.it/Media/carg). The investigated area partially corresponds to the Geological Sheets 489 (Marsiconuovo), 490 (Stigliano), 505 (Moliterno), and 506 (Sant'Arcangelo). Figure 2 shows an example of shapefiles generated after the process of digitization and correction of topological bugs and geological map obtained at the end of the process. Fields were then filled to produce a colored geological map. The next step was the extraction of a lithological map from the previous geological map. It was realized considering as input parameters the lithology, the morphology, and mechanical properties of rocks. According to these parameters, different geological formations were merged into a single homogeneous geological complex, thus forming nine lithological complexes. Lastly, landslides features were obtained merging field survey carried out at 1:5000 scale, interpretation of aerial photos, and UAV images. The drone (DJI Air 2S aircraft machine) features a fully stabilized 3-axis gimbal and 1-inch CMOS sensor camera at different resolutions. The DJI Air 2S was equipped with the DJI RC-N1 remote controller which boasts four built-in antennas and DJI's long-range transmission of 12 km and photos and videos up to 1080 resolution pixels.

The legend of the landslides inventory map was based on the type of movement and state of activity in agreement with the landslide classification proposed by Cruden & Varnes (1996) revised by Hungr *et alii* (2014). Hence, landslides were here classified as follows: 1) rock falls and topples, 2) slides 3) earth flows, 4) mud and debris flows, 5) complexes, and 6) creeping. The rate of movement varies from slow to rapid according the landslide velocity scale as proposed by the literature and the state of activity takes into account inactive, dormant, and active landslides. Two main geomorphological features of a landslide, among all those defined by Cruden & Varnes (1996), were selected and drawn in the GIS application corresponding to 1) the main scarp, 2) the main landslide body and the zone of accumulation. The first feature is a steep erosion surface placed on the upper edge of the landslide generated by movement of displaced material, the second one represents the body of displaced material which overlies the surface of rupture and includes the area where the displaced material lies above the undeformed ground surface. Taking into account both the lithology and slope of the transect and considering the significant length of the investigated roadway equal to 71 km, a separation into 15 segments was carried out. The 15 segments were listed in

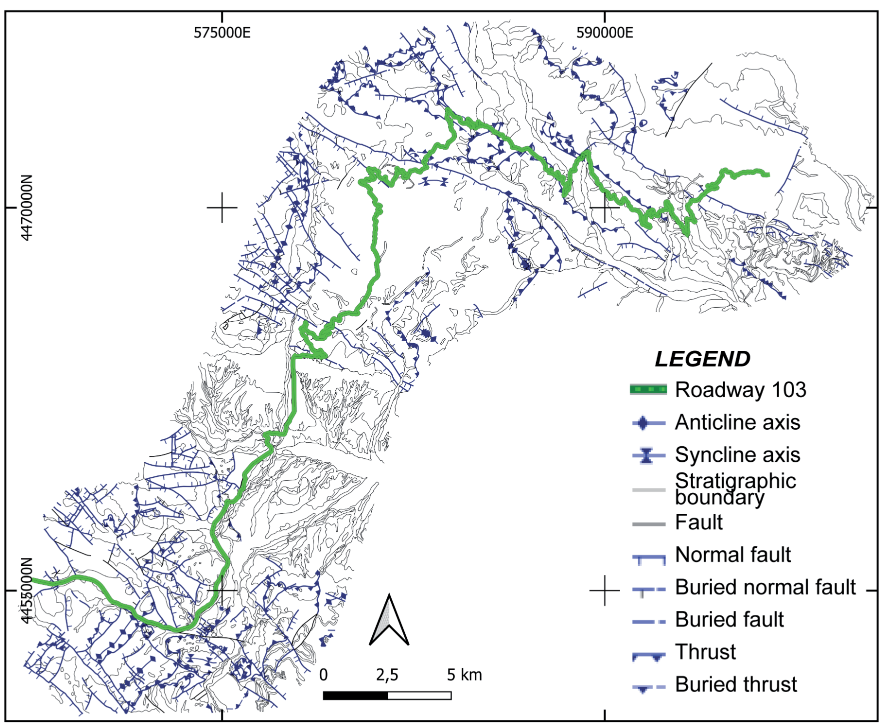
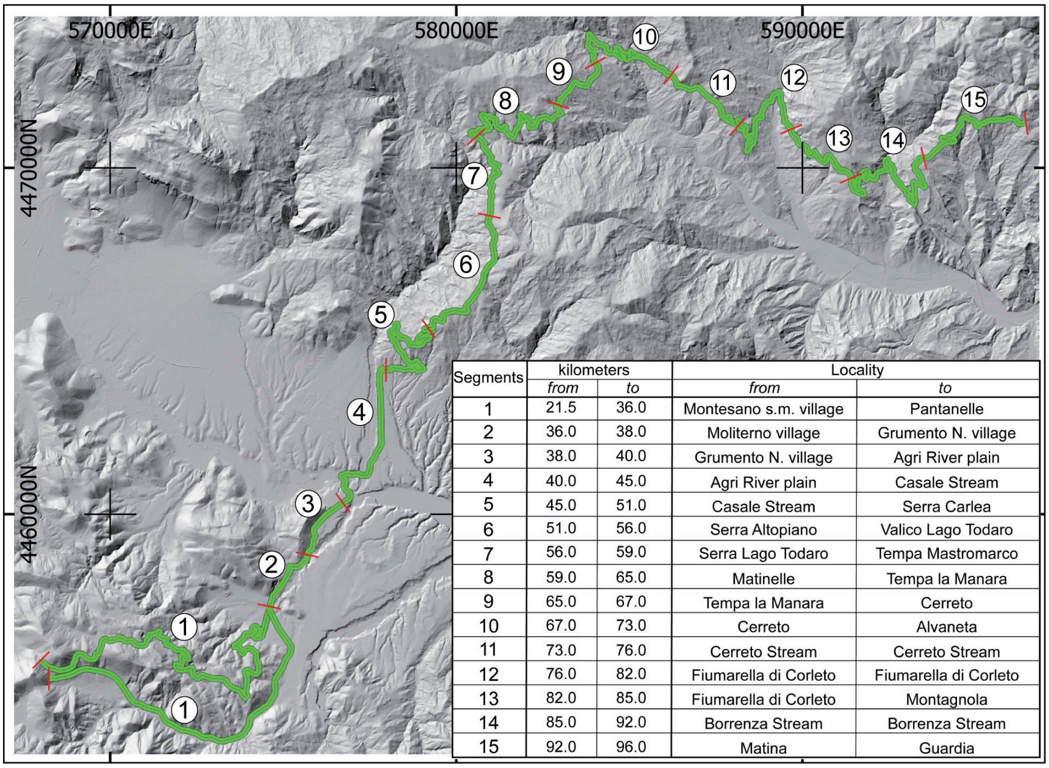


Fig. 2 - Example of shapefile containing digitized polygons and lines used in the geological map



Segments	kilometers		Locality	
	from	to	from	to
1	21.5	36.0	Montesano s.m. village	Pantanelle
2	36.0	38.0	Moliterno village	Grumento N. village
3	38.0	40.0	Grumento N. village	Agri River plain
4	40.0	45.0	Agri River plain	Casale Stream
5	45.0	51.0	Casale Stream	Serra Carlea
6	51.0	56.0	Serra Altopiano	Valico Lago Todaro
7	56.0	59.0	Serra Lago Todaro	Tempa Mastromarco
8	59.0	65.0	Matinelle	Tempa la Manara
9	65.0	67.0	Tempa la Manara	Cerreto
10	67.0	73.0	Cerreto	Alvaneta
11	73.0	76.0	Cerreto Stream	Cerreto Stream
12	76.0	82.0	Fiumarella di Corleto	Fiumarella di Corleto
13	82.0	85.0	Fiumarella di Corleto	Montagnola
14	85.0	92.0	Borrenza Stream	Borrenza Stream
15	92.0	96.0	Matina	Guardia

Fig. 3 - Distribution of the 15 segments along the roadway SS103. Red lines are the boundaries dividing different segments

Figure 3 showing the start-to-end route expressed in kilometers as indicated along the roadway SS103 and the crossed locality.

GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

The investigated area is located in the southern Italy and include different geological and geomorphological landscapes. It extends for about 71 kilometers, crossing the axial and frontal sectors of the southern-Apennine chain and contains rugged mountains and ridges, low elevation hills, flat plains and terraces. The study area corresponds to a segment of the SS103 "Val d'Agri" state road, an important connecting road between Basilicata and Campania regions. It developes from Montesano sulla Marcellana village (40°17′N; 15°42′E) in the Campania Region, at about 850 m a.s.l., to Montalbano Ionico (40° 15' 12"N; 16° 42'19"E) in the Basilicata Region, at about 15 m a.s.l. (Fig. 1). It crosses many rivers such as Agri and Sauro and thorough the Maddalena Ridge (MM in Fig. 1)). Furthermore, the roadway SS103 crosses the floor plain surface of the Agri intermontane basin (AB in Fig. 1) and a large sector of the eastern front of the chain. Elevations in the investigated area range from 532 m to 1835 m and reaching a maximum relief of about 550 m between Viggiano and Corleto Perticara villages. The roadway SS103, between Moliterno and Stigliano villages, is largely developed in a mountainous landscape, running at altitudes greater than 600 m a.s.l. In particular, it runs on the lower part of the Moliterno village and then crosses the high Agri valley floor, and close to Viggiano village follows approximately a N-S orientation. Then, it reaches about 1100 m of elevation a.s.l. and goes down to the Corleto Perticara village. The roadway continues towards many villages reaching elevation of about 900 m a.s.l. The SS103, until the Montalbano Ionico village crosses a hilly physical landscape with elevations falling at few hundred meters a.s.l. at the end of the roadway. In 90's the SS103 crossed through the Craco (CR in Fig. 1) ghost town (Bentivenga *et alii*, 2024; Gizzi *et alii*, 2024; Pescatore *et alii*, 2024) but its course was recently diverted due landslides occurred westward. The mountainous area crossed by the roadway SS103, is largely characterized by steep slopes, narrow and deep river valleys and in correspondence with tectonic structures and lithological variations, abrupt changes in slope are detected. In particular, the steepest slopes are found in correspondence with outcrops of the Apennine Platform and some formations belonging to the Lagonegro Units and sandstones of the Gorgoglione Formation (Fig. 4). These rugged morphologies, largely due to the presence of lithologies with totally different erodibility, give rise to numerous landslides that manifest themselves as rock fall, slides, earth flows and complex landslides which are sometimes active or quiescent and therefore

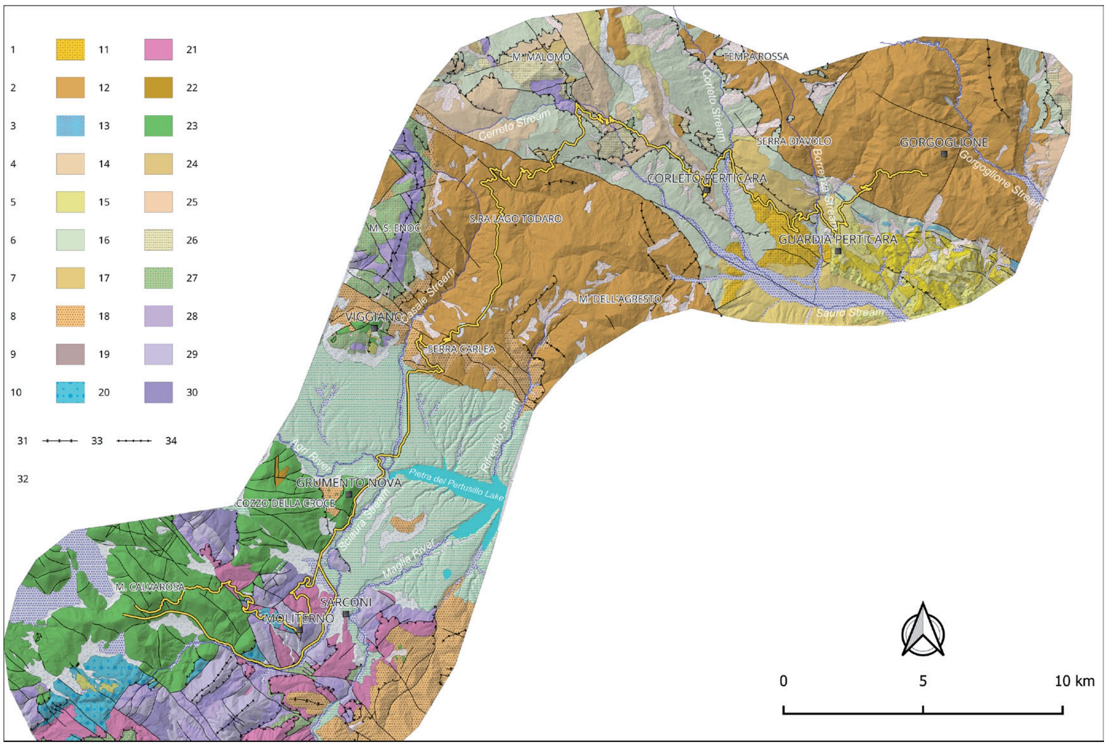


Fig. 4 - Geological sketch map of the study area. Legend: 1) Slope deposits (Holocene); 2) Landslides (Holocene); 3) Alluvial deposits (Holocene); 4) Conglomerates, sands, and clays of the Pertusillo supersynthem (Middle to Late Pleistocene); 5) Galaino breccias (Early to Middle Pleistocene); 6) Castronuovo conglomerates (Early Pleistocene); 7) San Lorenzo clays (Early Pleistocene); 8) Guardia Perticara conglomerates and sands (Early Pleistocene); 9) Difesa Pincia clays (Early Pliocene); 10) Torrente Sauro clays (Early Pliocene); 11) Torrente Racanello conglomerates (Early Pliocene); 12) Gorgoglione Fm (Middle Miocene); 13) Timpone d'Arena conglomerates and sands (Middle Miocene); 14) Tufiti di Tusa Fm (Late Oligocene – Early Miocene); 15) Corleto Perticara Fm (Late Eocene – Early Miocene); 16) Varicolori clays Fm (Late Cretaceous – Oligocene); 17) Monte Sant'Arcangelo Fm (Late Cretaceous – Eocene); 18) Albidona Fm (Early Miocene); 19) Saraceno Fm (Late Eocene – Early Miocene); 20) Monte Foraporta Fm (Late Triassic – Middle Jurassic); 21) Moliterno Fm (Triassic); 22) Bifurto Fm (Early to Middle Miocene); 23) Carbonates of the Apennine Platform Fms (Late Triassic – Late Cretaceous); 24) Torrente Serrapotamo Fm (Late Oligocene); 25) Numidian Flysch Fm (Early Miocene); 26) Flysch Rosso Fm (Late Cretaceous – Early Miocene); 27) Galestrino Flysch Fm (Cretaceous); 28) Scisti Silicei Fm (Jurassic); 29) Calcari con selce Fm (Late Triassic); 30) Monte Facito Fm (Middle to Late Triassic); 31) Faults; 32) Thrusts; 33) synclinal axis; 34) Anticlinal axis. Yellow line is the transect of the SS103 roadway

subject to reactivation during rainfall events. The steepness is significantly reduced in the areas where predominantly clayey lithologies outcrop, however, landslides frequently involve the SS103 and sometimes cause interruption. Between Craco and Montalbano Ionico areas, clayey formations and subordinately sandy and conglomeratic ones are the main lithologies crossed by the SS103 (Fig. 1). As a consequence, landsliding is the main morphogenetic process in the physical landscape as in the case of the well known Craco village that has been interested by a progressive abandonment after the occurrence during time of landslides and earthquakes that caused the disruption of large portions of the urban settlement. In general, the area crossed by the roadway SS103 is affected by many landslide, many of these are present in public database and reports (AVI, 1996; IFFI PROJECT, 1999; RenDiS PROJECT, 2005; Lazzari, 2011). In a recent work, landslides of the Fiumarella di Corleto catchment basin were investigated suggesting a landslide density of about 43% of the entire studied area (Bentivenga *et alii*, 2023). Landslides affecting the Casale Stream in the Agri intermontane basin were investigated by Monaco (1991) suggesting a strong influence of the tectonic activity as triggering factor of landslide activation. In the eastern sector of the Agri intermontane basin, Bucci *et alii*, (2021) suggest the geological setting as factor controlling the type and spatial distribution of landslides.

From a geological point of view, the study area is partially corresponding to the Miocene-Quaternary fold-and-thrust belt of the southern Apennines chain. The latter was developed starting from the Upper Oligocene-Lower Miocene onwards as a result of different Mesozoic-to-Cenozoic paleogeographic domains deformation towards NE and is composed of east-verging tectonic units (Pescatore *et alii*, 1999), overlapping on the Apulian Platform to form a large duplex geometry (Patacca & Scandone, 2007 and references therein). The average direction of the chain axis is approximately N150°, which corresponds to the strike of both the main thrusts and the coaxial normal faults, while extensional tectonics is still active along the axis of the chain deforming Quaternary deposits (Beneduce & Giano, 1996; Bavusi *et alii*, 2004). Such a complex structural setting produced a mountain chain over 2000 m high and a NW-SE-oriented regional divide separating the catchments of rivers draining to the Tyrrhenian Sea (southwest), the Adriatic Sea (northeast), and the Ionian Sea (east).

The investigated area crossed by the SS103 includes different geological and geomorphological domains located in both the axial and the eastern zones of the chain. The western sector of the roadway cross-cuts the Maddalena mountains, a NNW-SSE-oriented Ridge separating the two Pleistocene intermontane basins of Vallo di Diano on the left and high Agri on the right. The Maddalena Ridge is mainly composed of Triassic-to-Cretaceous shallow-water carbonates pertained to the Apennine platform unit and by Triassic-to-Paleogene deep-sea and shallow-water carbonate and siliceous successions of the Lagonegro unit (Fig. 4). Shallow-water carbonate succession of the Monte Foraporta unit, deep-sea siliciclastic succession of the Silentine unit, and Miocene siliciclastic deposits complete the geological and tectonic units shaping the Maddalena mountain Ridge (Palladino *et alii*, 2023) (Fig. 4). Following the roadway SS103 and overcoming the Grumento Nova village, the floor surface of the Agri intermontane basin crops out. It is filled by Early-to-Late Pleistocene coarse-grained and fine alluvial and fan deposits forming several orders of terraced surfaces (Giano, 2016). Continuing towards north-east along the SS103 the S. Enoc and Serra dell'Agresto mountain ridges are crossed. The first ridge is composed of limestones, cherts, and radiolarites of the Lagonegro Unit whereas the second one by arenites, siltites, and clays of the Albidona Fm. Passed the Agri basin watershed, the SS103 comes in the catchment basin of Sauro River mainly composed by the Sannio and Sicilide units with associated Miocene-to-Pliocene thrust-top deposits (Patacca & Scandone 2007; Palladino *et alii*, 2023). The Cretaceous-to-Oligocene Varicolori clays Fm and younger formations pertained to the Irpinian units such as the Gorgoglione Fm are the main successions which outcrop in the area. The Miocene Gorgoglione Fm is composed of conglomerates, sandstones, and clays and represents the main geological unit crossed by the roadway SS103. Furthermore, the SS103 cross-cuts the conglomerates, arenites, siltites, and clay rocks forming different geological units such as the Torrente Racanello, Corleto Perticara, Numidian Flysch, and Torrente Serrapotamo units ranging in a time span including the Late Eocene until to the Pliocene (Prosser *et alii*, 2008).

RESULTS

The SS103 roadway traverses various geological deposits and different rock types in a complex physical landscape varying from rugged mountains to plains and low-angle hills. As a result, the 15 investigated segments revealed significant variations in the type and age of landslides. This necessitated a detailed analysis of landslides within each individual segment, one of which is characterized by peculiar features.

Geolithological map

The geological formations were grouped into nine lithological complexes based on homogeneous mechanical characteristics (Fig. 5a). The carbonate complex (C01) includes all calcareous and dolomite rocks, the siliceous complex (C02) consists of rocks belonging to the Scisti Silicei Fm. The clayey-marly-arenaceous-calcareous complex (C03) includes several geological formations characterized by the alternance of different sedimentary rocks that have a same competence, from an erosional point of view. Someplace, clays and arenites are the dominant lithologies outcropping and consequently a clayey-arenaceous complex (C04) was considered. Conversely, where only marl and carbonate rocks outcrop the marly-calcareous complex (C05) was created. The dominance of arenites and conglomerate levels and banks define the arenaceous-conglomerate lithological complex (C06). The sandy-clayey complex (C07) is composed by fluvial and lacustrine deposits, and the conglomerate-sandy complex (C08) contains mainly the coarse-grained deposits of alluvial and marine systems. Finally, coarse-grained subaerial slope deposits form the detrital complex (C09) also containing colluvial terrains. Along the 71 kilometers-long of the investigated roadway, the maximum percentage of length falls in the clayey-arenaceous lithologies (C04) with 24%, corresponding to about 20.23 kilometers (Fig 5b). The C04 complex is mainly distributed in the central portion of the roadway corresponding to the Gorgoglione Fm. Less frequent are the carbonate (C01) and clayey-marly-arenaceous-calcareous (C03) complexes reaching 19% and 17%, respectively. The first complex is located in the western portion of the roadway and is restricted to the mountainous relief of the Maddalena Ridge (MM in Fig. 1), whereas the second one is evenly distributed along the transect and the reaches are not much longer than 2.8 kms. Less abundant in percentage are the detrital complex (C09), with 11% that is scattered in the whole transect, and the conglomerate-sandy (C08) and arenaceous-conglomerate (C06) complexes, with 10%, the first localized in the flat surface of the Agri floor valley, the second between Serra Carlea and Serra Lago Todaro sites (Fig. 5a). A lower frequence was found for the marly-calcareous (C05), sandy-clayey (C07), and siliceous (C02) complexes with 5%, 3%, and 1%, respectively.

Landslide inventory map

A landslide inventory map was realized through detailed field geomorphological surveys, aerial photos, and UAV image interpretation. The spatial investigation of landslide distribution

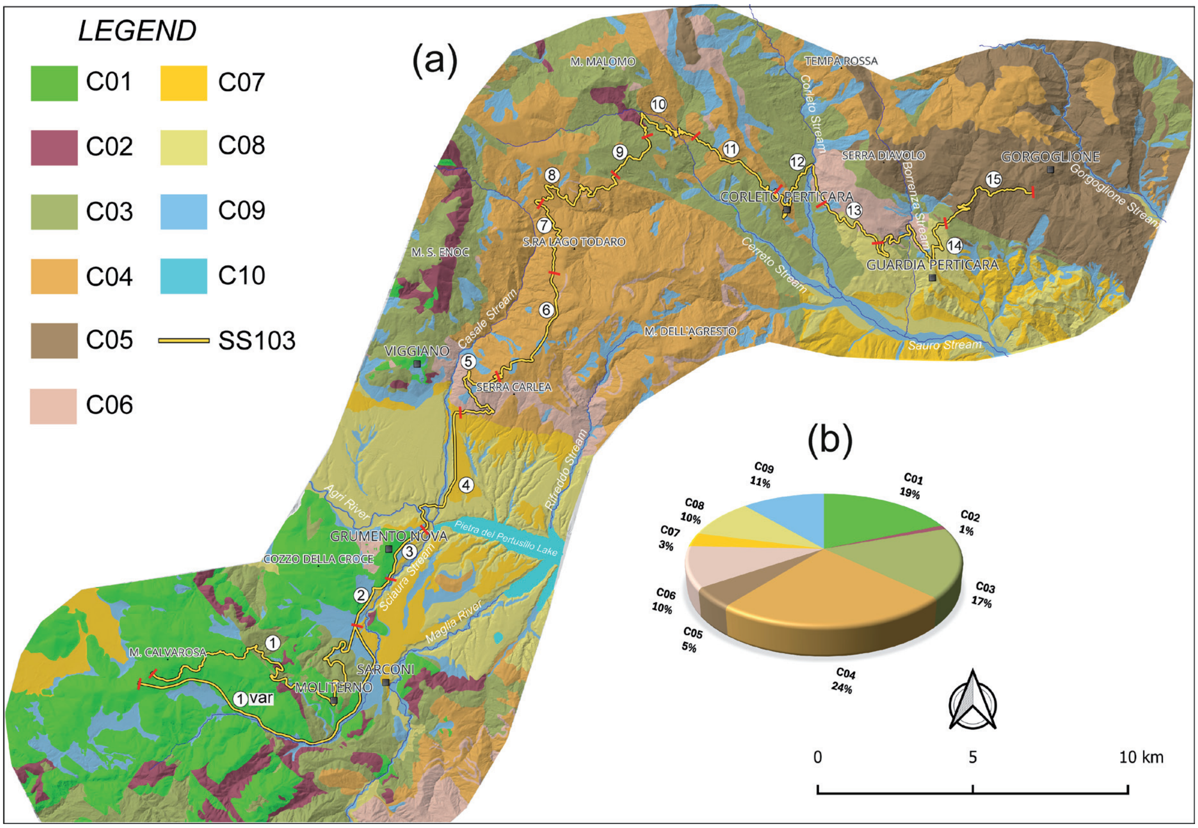


Fig. 5 - Map of the lithological complexes distributed along the roadway SS103 "Val d'Agri"(a). Legend: carbonate complex (C01); siliceous complex (C02); clayey-marly-arenaceous-calcareous complex (C03); clayey-arenaceous complex (C04); marly-calcareous complex (C05); arenaceous-conglomerate complex (C06); sandy-clayey complex (C07); conglomerate-sandy complex (C08); detrital complex (C09). The Pie chart (b) shows the abundance percentage of lithological complexes which cross-cut the roadway. Numbers in the circle are the segments of the roadway

shows a strong control of C01, C04, and C03 lithological complexes and of slope angles on landslides, they can therefore be considered predisposing factors to slope instability. More than 2300 landslides were detected and mapped in the study area (Fig. 6a); they affect about 30 kms of the SS103 corresponding to about 42% of the whole investigated roadway. The detailed analysis of landslide distribution reveals that the fluvial incision of stream valleys such as the Casale, Corleto, and Borrenza streams together with clayey, silty, and arenaceous lithologies are the main landslide predisposing factor. In fact, both the vertical incision and lateral planation processes of streams in the floodplains can give rise to a backward erosion process along the slope valleys and to several generations of superposed landslides bodies. Earth flows are the most abundant landslides which were mainly detected in the transect included between the Viggiano and Guardia Perticara villages, with 66% of the crossed roadway corresponding to about 20 kms (Fig. 6b). The other types of landslides are less abundant, varying from 3% of mud-debris flows to 13% of complex landslides. Furthermore, the analysis of the state of activity of all the landslides, determined by a comparison of old aerial photos and field survey and UAV images, has shown that 58% are active, and 42% are dormant equivalent, whereas no inactive landslides were detected, (Fig 7a, b). Active and dormant landslides are mainly concentrated from the segment 5 to the 15 in which crop out arenaceous, silty, and conglomerate lithologies.

Earth flows, the dominant type of landslide in the investigated area, are characterized by an elongated shape in plain view and a narrower transfer zone than the detachment and accumulation zones (Keefer & Johnson, 1983) . The main landslide scarps are formed of several coalescent smaller scarps with arcuate shapes tens meters wide (Fig. 8). These morphological features are particularly visible in the clayey and silty bedrock belonging to the C03, C04, and C05 lithological complexes (Fig. 5a). Earth flows are mostly active, and recent episodes of landsliding caused the re-incision of thalwegs which were filled with older landslide deposits. Rock falls and rock topples are mainly localized in the western sector of the roadway where the carbonate and siliceous lithological complexes outcrop. Their source areas are strictly related to faults and fracture systems generating single or multiple

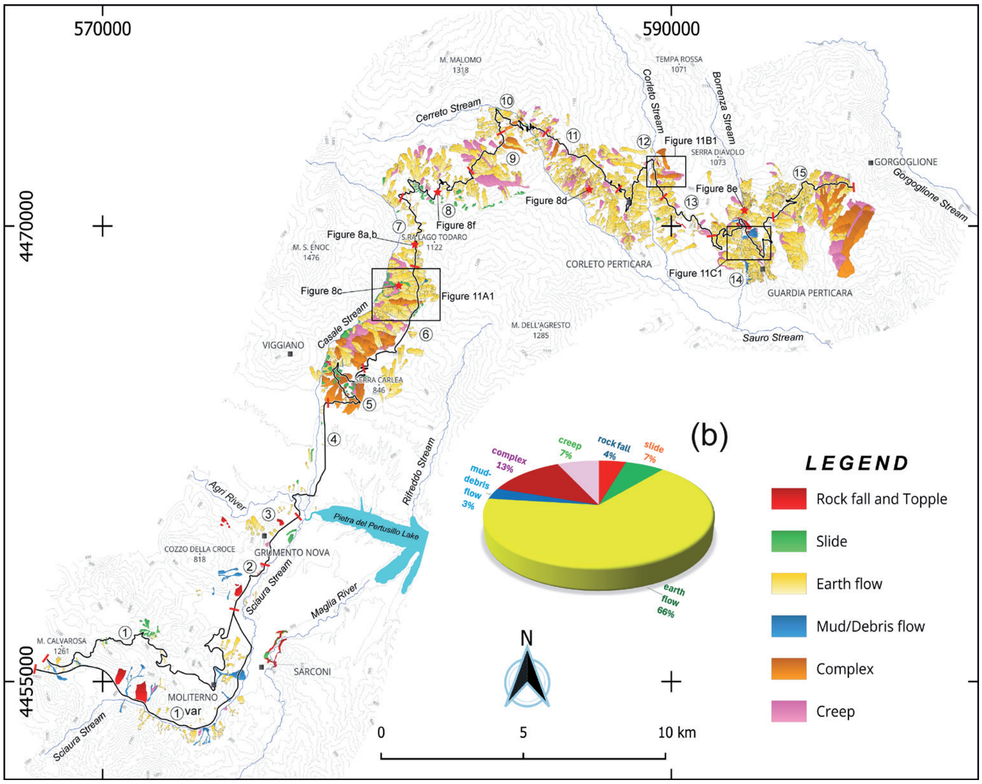


Fig. 6 - Landslide inventory map of the investigated transect along the roadway SS103 (a). The Pie chart (b) shows the abundance percentage of landslide types which cross-cut the roadway. Red stars indicate the location of the photos in figure 8 and black boxes the details of landslides bodies distribution in figure 11. Numbers in the circle are the segments of the roadway

blocks and their deposits form talus and cone debris at the base of scarps. In some cases, the deposits (Fig. 7a) blocked the roadway such as in segments 1, 2, and 3 (Fig. 6a). Complex landslides are mainly formed by earth slide evolving to earth flow types in the middle and lower sectors of the slope. They are mainly localized along the segments 5, 6, 12, and 15 where clays and sandstones are the prevalent lithologies corresponding to several lithological complexes (see Figs. 5a and 10a for details). Both rotational and translational slides involve few areas formed by rocks lithology. Conversely, the slides of the segment 8 are close to the roadway SS103 involving it, directly. In many areas, the creeping process involves large older landslide areas up to the roadway such as the segments 6, 9, and 13 (Fig. 6a).

Segmentation of the S.S. 103 roadway

Below are reported the results coming from the 15 segments identified in the 70 km-long transect of the roadway, illustrating details of each segment, in order to observe differences or similarities among them.

Segment 1 of the roadway SS103 is composed of two different older (1) and younger (1var) road segments (Fig. 3). The old segment crosses the Moliterno village whereas the younger one follows the watercourse of the Maglia River at lower elevations than the older. The elevation profile of the older segment shows an irregular decrease with some reaches quite planar varying from 1040 m to 605 m of elevation a.s.l. and a slope angle less than 2.5°. Conversely, the younger segment presents a regular decrease of elevation, from 930 to 605 m a.s.l. and a slope angle reaching about 2.5° (Fig. 9). Both the two road segment 1var and 1 are stable because they cut the carbonate and siliceous lithological complexes, only two small stretches of the old road show fracturing due to the working in progress of two quarries. Only the last two kilometers of the roadway cross the alluvial deposits of the Agri basin fill. Two areas of rock falls are found in the left-side younger segment whereas several small earth flows are distributed in both the right-sides younger and older segments. Debris flow landslides affect both the two segments and cuts the SS103 until reaching the Sciaura Stream talweg (Fig. 6a). In the older segment, 14.5 kilometer length only 411 meters are affected by landslides corresponding to 2.80% of the total segment whereas with the younger ones, 11.4 kilometer length 2383 meters of the roadway are involved in the mass movement related to 21% of the reach. Furthermore, the 12.8% of older segment is affected by active landslides whereas the 7.6% shows dormant landforms. Conversely, less active landsliding are found in the younger segment up to 0.8% (Fig. 10a, b). No differences

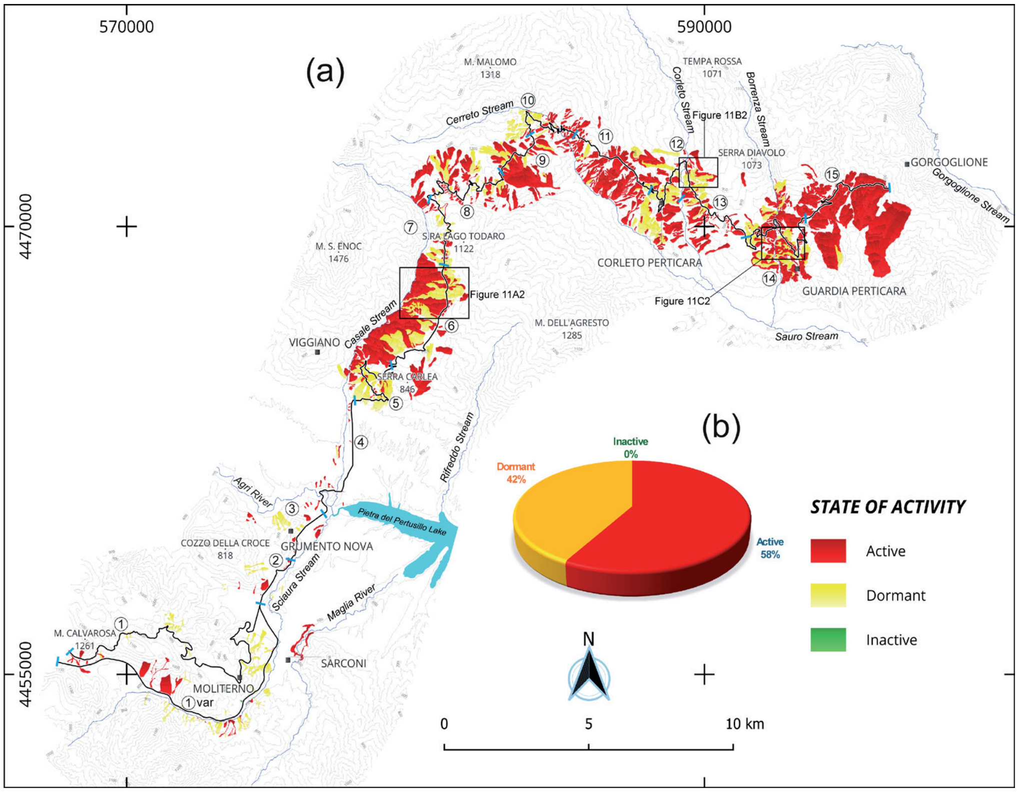


Fig. 7 - Landslide activity map of the investigated transect along the roadway SS103 (a). The Pie chart (b) shows the percentage of active, dormant, and inactive landslides which cross-cut the roadway. Black boxes are details of the landslides bodies distribution in figure 11. Numbers in the circle are the segments of the roadway

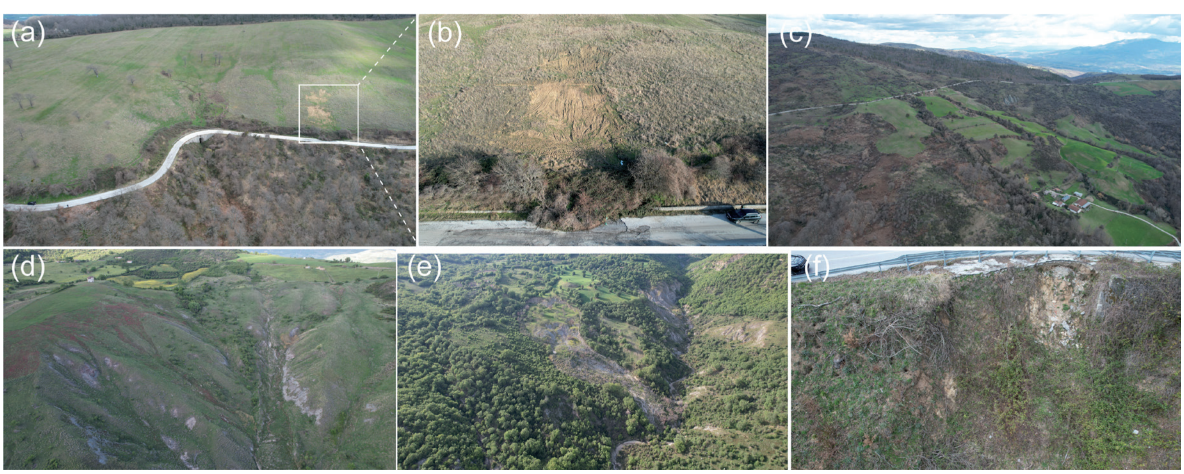


Fig. 8 - Panoramic views of several landslides affecting the roadway SS103. (a) earth flow in clayey-arenaceous rocks of the segment 7 and (b) detail of a recent re-activation of the older landslide body; (c) panoramic view of a complex landslide in clayey-arenaceous rock of the segment 6, affecting the main road in the upside a farm in the downside; (d) earth flow in marly-arenaceous-calcareous rocks of the Varicolori clay Fm placed in the segment 11 and close to the Corleto Perticara village, note how all the talwegs are filled by the landslide bodies which flow toward the main channel; (e) rotational slide evolving to flow in conglomerate-sandy lithologies of the segment 14, note the landslide body filling the talweg thus producing a damming of the channel; (f) detail of a recent rock fall in clayey-arenaceous rocks of the segment 8, close to the main road. Geolocalization of photos was reported in figure 6

in elevation are found in the segment 2 which vary from 605 m to 593 m a.s.l. and a slope angle of about 3° is only present in100 m-length segment whilst the slope average that is less than 1° (Fig. 9). Segment 2 unfolds from the km 36 to the km 38 in the carbonate complex (C01) and shows small active scarps in the right-side of the road toward the Sciaura Stream. In the 2 km-length of the reach, 325 meters involve active rock fall scarps equal to 16% of the segment length that are placed close to Il Monte site (Fig. 10a, b). Segment 3 follows the NE-SW-oriented piedmont sector of the Grumento Nova hill from the km 38 to the km 40 and is placed mainly on detrital (C09) and conglomerate-sandy (C08) complexes. The segment shows low slope angle less than 2° and elevation range from 593 m to 576 m a.s.l. (Fig. 9). It presents 16% in length of the reach which are affected by rock falls and 4.5% of earth flows in a total segment of 2 kilometers long; moreover one active scarp close to the right-side of the roadway is found at km 38. The deepening of the Sciaura Stream channel induces a backward erosion of the valley side toward the roadway. In the segment, the 11.4% of landsliding is active and the 4.5% is dormant whereas no inactive landslides are present (Fig. 10a, b).

Segment 4 crosses the Agri River from km 40 to km 45 and develops its reach mainly on the sandy-clayey complex (C07) and secondary in the conglomerate-sandy complex (C08) corresponding to the floor valley of Agri basin. Its vicinity to the left-side fluvial valley of Casale Stream is congruent with earth flow as main landslides. In fact, only 37 meters of the whole 5 km-long segment are involved in landsliding corresponding to 0.7% of the total segment length. The segment crosses the two floodplains of Agri River and Casale Stream and runs on the Agri terraced surfaces attaining the piedmont area at 650 m of elevation a.s.l. (Fig. 9). Several reaches show slope angle of about 2° as a consequence of the crossing stream valleys. In the segment 5, the roadway SS103 start from the Agri valley floor plain at km 45 until to the Serra Carlea Ridge at km 51 and change its elevation from 650 m to 943 m a.s.l., thus producing a relief of 293 m. The segment firstly crosses the arenaceous-conglomerate complex (C06) where slope angle is higher, up to 3° and then the sandy-clayey lithologies (C04) at the hilltop where the slope angle is lower than 2° (Fig. 9). The area is strongly affected by complex (40.5%) and slide (13.2%) mass movements affecting reaches of 2.4 and 0.8 kms-length, respectively, in a segment of 6 kms-length. Moreover, a few earth flows (2.5%) are also found with 151 meters of length. Dormant landslides are the most abundant percentage with 49.5% affecting about 2.9 kms of the roadway, whereas the active ones are 10% occupying about 0.6 kms. Take into account that landslides were activated mainly in the arenaceous-conglomerate complex than the sandy-clayey ones as a consequence of the geological arrangement and higher slope angle. Finally, a typical feature of the reach is that the main landslide bodies contain small recent landslides that directly affect the road.

Segment 6 of the roadway is developed on the fluvial divide of the right-side valley of Casale Stream from the km 51 to the km 56 and get up from 942 m to 1086 m showing low-angle slope with only three points reaching about 3°; more frequent are the reaches with a flat planar trend (Fig. 9). The segment 6 is entirely formed by the arenaceous-conglomerate lithological complex (C06) and all landslides are located in the left-side roadway because of the slope move towards the Casale stream valley and decrease in elevation from about 1000 m to about 750 m. The earth flow is the main landslide typology distributed along the entire 5 kms-length segment, achieving 1.5 kms corresponding to 30.3% of the total length. Less percentages show the complex

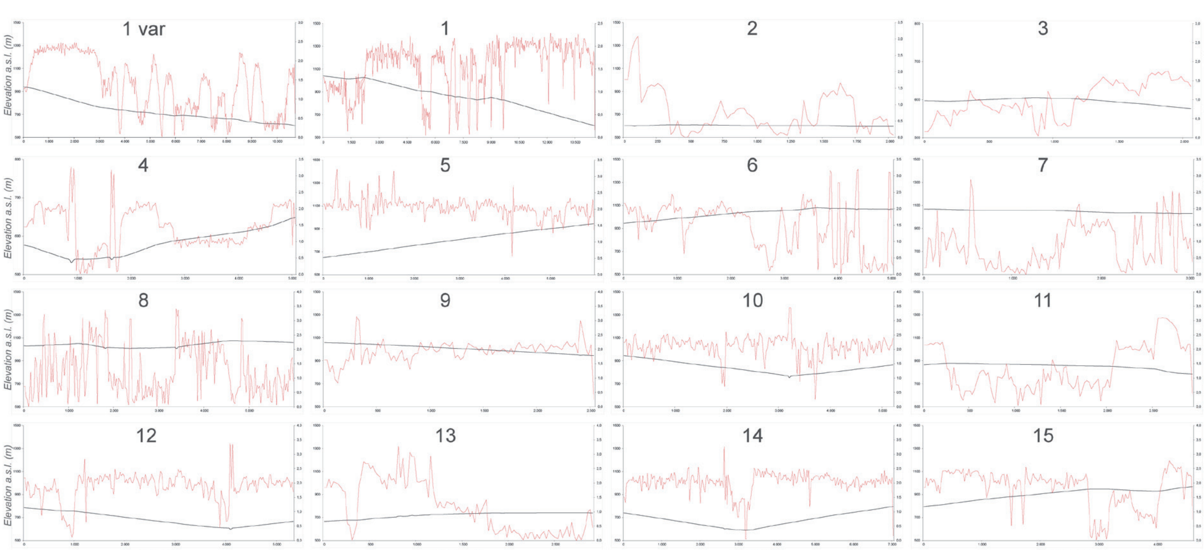


Fig. 9 - Elevation versus slope diagrams of the 15 roadway segments. Black line is the altitudinal profile realized along each of the 15 segments, red line is the slope angle measured along each segment of the roadway

(1.7%) and the slide (1.2%) involving about 140 meters of length, overall. Locally, in the scarp edge of landslides also the creeping is present affecting 35 m of the roadway. It is worthy to note that from the km 51 to the km 54 the roadway is not directly affected by landslides because they are placed in the left-side and out of the road. They are located in the left-side of the Casale stream valley and flow to northwest directly in the thalweg (Fig. 6a). The active landslides are dominant with 27.6% of the total length of the segment whereas the dormant are 5.2% (Fig. 10a, b). The next segment 7 starts from the km 56 up to the km 59 and corresponds to a flat reach and is run along the upper side-valley of Casale Stream. It runs in the same lithological complex of the previous segment 6, the C06 which is composed of arenite and conglomerate lithologies. The segment is 3 kms long and runs in the upstream valley of the Casale Stream showing six points with slope angle up to 2° (Fig. 9). Earth flow is the only typology of landslide which interests the segment covering a distance of about 1.4 km, with a percentage of 45,5% that include 20.2% of active and 25.4% of dormant landslides (Fig. 10a, b). Segment 8 changes in elevation from 1030 m to 1070 m a.s.l., the latter reached in the last kilometer and cross three small stream valleys running from km the 59 to the km 65. Consequently, slope angle shows several peaks up to 3° (Fig. 9). The lithologies crossed by the segment which is 6 kms long corresponds to the arenaceous-conglomerate complex (C06) and the main landslide typology is the earth flow with 23.8% covering 1.4 kms in length. Less percentage distribution shows mud-debris flows (2.7%) and slides (4.2%) typologies reaching about 164 and 251 meters of length, respectively. More consistent is the percentage of creeping that achieves 6.9% affecting up to 400 m of the segment. Finally, among all the mass movements of the segment 8, 12% are active and 12.9% are dormant whereas no inactive are present (Fig. 10a, b). Segment 9 decreases its elevation from 1057 m to 973 m a.s.l., starting from the km 65 up to the km 67 with a mean slope angle of about 2° (Fig. 9). It crosses 2 kms-length in the clayey-marly-arenaceous-calcareous complex (C03) where earth flows are the dominant feature affecting both the left- and right-side of the roadway. Note that despite the change in lithologies with regard to the previous segment 8 the dominant landslide remains the earth flows with a percentage of 57.6% covering 1.1 kms in length. An other types of mass movement is the complex landslide with 7.8% and the creeping with 11.7% affecting 155 and 233 meters in length, respectively. Within the 2 km in length of the whole segment has been possible to observe 711 m of active (35.6%) and 829 m of dormant (41.5%) mass movements (Fig. 10a, b). Segment 10 passes through the Cerreto Stream valley and changes its elevation from 973 m to 872 m a.s.l., starting from the km 67 up to the km 73; in fact, the Cerreto fluvial thalweg firstly decrease and after increase its elevation with a slope angle ranging from 2° to 2.5° (Fig. 9). The segment crosses mainly the clayey-marly-arenaceous-calcareous (C03) and clayey-arenaceous (C04) complexes and secondary the siliceous (C02) one and is entirely affected on both the left and right sides valleys by mass movements. Earth flows with 32.8% is the main landslide typology covering about 2 kms in length of the total segment which is 6 kms long. Less frequent are the complex (4,3%) and slide (1.1%) features that are 323 m long, overall. Creeping is also present with 2.8% affecting 167 m of the segment. The state of activity in the segment can be associated to active (26.3%) and dormant (14.6%) typologies which cover 1,5 and 0.9 kms, respectively (Fig. 10a, b). Starting from the km 73 up to the km 76, segment 11 firstly through 1 km in the clayey-arenaceous (C04) and 2 kms in the clayey-marly-arenaceous-calcareous complex (C03). It passes from 872 m to 785 m of elevation across a flat reach of the roadway; slope angle is quite constant between 0.5° and 1° and increase at the end of the segment achieving about 3° (Fig. 9). Also in this segment the earth flow is the dominant typology of landslide with 40.7% of landslides affecting 1.2 kms in length. The creeping is less frequent with 12.6% covering 378 m in length. A reach of 1.5 kms is affected by active landsliding (50.1%) corresponding to the half of the entire segment whereas only 96 meters are dormant (3.2%) (Fig. 10a, b). Segment 12 starts from the km 76 up to the km 82 and crosses the right- and left-side valleys of the Corleto Stream. A first segment through the clayey-arenaceous complex (C04), a second one crosses the clayey-marly-arenaceous-calcareous complex (C03) up to the thalweg of Corleto Stream, and a third segment crosses the arenaceous-conglomerate complex (C06) from the thalweg to the end of the segment (Fig. 5a). The segment changes

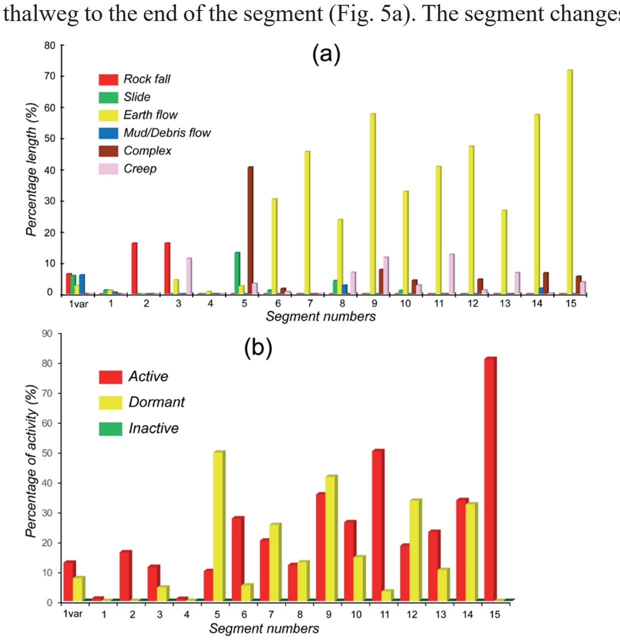


Fig. 10 - Percentage length of landslide types (a) and percentage activity of landslides (b) in the 15 roadway segments

its elevation from 785 m to 665 m and attains the maximum slope angle in the thalweg of the stream with 3.5° whereas a flat sector has less than 0.5° (Fig. 9). Similarly to the previous segment 11, the main landslide type affecting the reach is the earth flow with 47.3%, corresponding to 2.8 kms in length. Complex landslides and creeping are also present in 4.7% and 1.3%, respectively, affecting about 355 m of the segment. Less activity of landslides was observed in the segment with 33.5% of dormant landslides and 18.5% of active ones (Fig. 10a, b). Different lithological complexes are crossed by the segment 13 which unfolds from the km 82 up to the km 85. They are the arenaceous-conglomerate lithological complex (C06) and the conglomerate-sandy complex (C08). Elevation change from 665 m to 740 m and high slope angle close to 3° are found in the first reach of the segment whereas the final sector shows less than 0.5° and a quite flat surface (Fig. 9). Earth flow is the main landslide type and with 26.7% and 802 meters in length are more abundant in the C06 complex than the C08. Furthermore, a few reach of the segment with 203 meters in length is affected by creeping with 6.8%. The activity of mass movements shows a dominance of active processes with 23.1 % covering a sector of about 0.7 kms in length and less frequence of dormant ones with 10.4% and a length of 312 meters (Figs. 6a,7a). Segment 14 is developed from km 85 to km 92 and crosses two main lithological complexes, the arenaceous-conglomerate (C06) and the conglomerate-sandy complex (C08), and one secondary detrital complex (C09). Elevation starts from 737 m a.s.l., and finishes to 798 m a.s.l., passing through the fluvial valley of the Borrenza Stream placed at 581 m a.s.l. Slope angles are constantly around the 2° except in the thalweg of the Borrenza Stream where are less than 0.5° (Fig. 9). Also in this case, the earth flow is the dominant type of landslide which transversely crosses the roadway with 4 kms of length corresponding to 57% of the segment and affecting all the lithological complexes. A few distribution is that of complex (6.7%) and mud-debris flow (1.8%) landslides occurring at 467 m and 124 m of length, respectively. Creeping is not meaningful achieving 13 m of length (0.2%). All mass movements are equally distributed in active (33.7%) and dormant (32.2%) typologies covering 2.4 kms and 2.3 kms in length, respectively (Fig. 10a, b). The last segment 15 unfolds from the km 92 to km 96.68 and firstly passes about 500 m of clayey-marly-arenaceous-calcareous lithologies (C03) and then develops entirely in the marly-calcareous complex (C05). It changes the elevation starting from 798 m until to 966 m a.s.l., and shows a quite constant slope angle of about 2° except two sectors less than 0.5° coincident with two small creeks at the Fosso della Pietra site (Fig. 8). The spatial continuity of the earth flow is detected also in this segment affecting 3.3 kms of the roadway which correspond to 71,6% of the total segment. It is the main percentage of length recognized in all the investigated 15 segments suggesting an increase of the earth flow landslides typology. Less presence of complex landslides (5.6%) and creeping (3.8%) is also found in the segment occurring 432 m of length, overall. Finally, only active landslides were observed in that segment covering about 3.8 kms in length (80.9%) (Fig. 10 a, b).

Along the whole transect of 71 km-long of the roadway (Fig. 6a), earth flows are the more frequent landslides whilst rock falls, slides, mud-debris flows, complexes, and creeps are generally less abundant reaching 34% of the total length (Fig. 6b). The spatial distribution of landslides in the study area reveals that lithology and structure of rocks together with fluvial incision processes are the main predisposing factors in controlling the evolution of the SS103 roadway segment. The role of lithology and the attitude of geological structures as predisposing controlling factors of landslides in the Casale Stream were already recognized by Monaco (1991) arguing that thin horizons in stratified rocks facilitated the triggering of mass movements. The importance of slope gradient in landslide activity was discussed by Conforti *et alii*, (2014b) that consider it as the main parameter influencing the slope stability. Conversely, in the SS103 was recognized that contribution of slope angle fluvial valleys in landslide activity is low because the spatial distribution of landslide bodies suggested the absence of a link to slope gradients. In fact, landslides are largely distributed in areas with different slope gradients, from low to high. The current high state of activity in large sectors of the roadway is connected with the superposition of more landslide events that re-activate older landslide bodies (Fig. 11). Earth flows in figure 11(A1, C1) evidence that younger and smaller landslide bodies were generated from the older and larger landslide and in some circumstances they evolved as complex bodies. Furthermore, the upside of some landslide scarps shows the presence of a creeping process (Fig. 11(B1)).

CONCLUSIONS

The landslide inventory map realized along a transect of 71 km in the roadway SS103 "Val d'Agri" has considered a buffer of 2 km wide along the roadway. The geological maps at 1:50000 scale edited by ISPRA were redrawn in the QGIS application with the aim to create nine lithological complexes, grouping rocks with similar mechanical properties (Fig. 5a). The field survey along the roadway and the interpretation of aerial photos and UAV images permitted to detect up to 2300 landslides (Fig. 6a). According to Cruden & Varnes (1996) revised by Hungr *et alii* (2014), the landslides were classified as: 1) rock falls and topples, 2) slides 3) earth flows, 4) mud and debris flows, 5) complexes, and 6) creeping and the state of activity distinguished into inactive, dormant, and active landslides. Because of the high density of landslides, the roadway transect was divided in 15 segments (Fig. 3). The main lithologies affected by landslides belong to the clayey-arenaceous rocks of the C04 complex

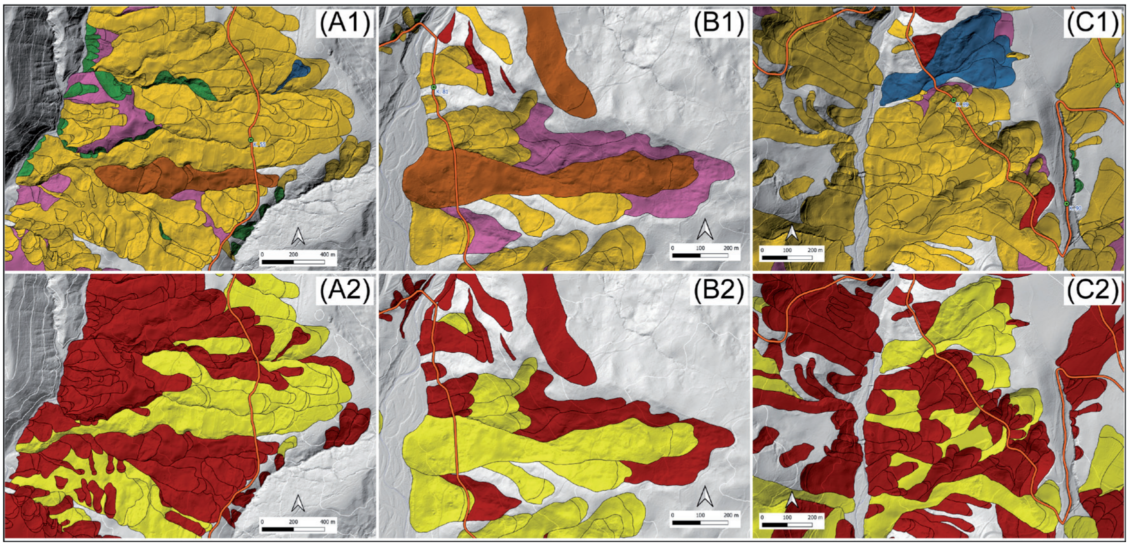


Fig. 11 - Detail of landslide bodies distribution which affect the roadway. (A1), (B1), and (C1) show different typologies of landslides and each color indicates a different landslide typology as follows: Yellow: earth flow; brown: complex; green: slide; blue: mud/debris flow; violet: creep. (A2), (B2), and (C2) are the activity state of landslides in the same above areas whereas red and yellow colors suggest active and dormant landslides, respectively. See figures 6 and 7 for location area

for 24% while in the C01 and C03 complexes landslides are less abundant, representing 19% and 17%, respectively. The remaining lithological complexes show a low abundance of landslides, ranging from 11% to 1% (Fig. 5b). Earth flows are the dominant landslides which affect the roadway, reaching 66% of the total, and placed mainly in the eastern sector for about 20 km in length. The lower the percentages of complexes (13%), slides (7%), rock falls and topples (4%), mud and debris flows (3%) landslides, the creeping is scattered in the whole transect reaching about 7% (Fig. 6b). Concerning the landslides activity state, the 58% is active and the 42% is dormant, whereas no inactive landslide bodies were observed. Details analysis of the data from the 15 segments have shown that earth flow is the dominant process in the segments 6 to 15, whereas rockfall is the primary type in segments 1, 2, and 3. Furthermore, both the complexes and slides typologies are significant in segment 15. In conclusion, the landslide inventory map carried out along the SS103 "Val d'Agri" will be instrumental in mitigating hazards and managing landslide events along this roadway and the findings will aid researchers in advancing the understanding of landslide processes and assist municipalities in reducing roadway maintenance costs, thereby preserving connectivity between sites and villages in this sparsely populated areas of the southern Apennines.

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