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Investigating the factors governing the damage occurrence on buildings exposed to slow-moving landslide risk

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Abstract The paper deals with an ongoing research aimed at investigating the relationships between the kinematic features of slow-moving landslides affecting urban areas and the related effects on exposed buildings. These relationships are expressed in terms of changes of damage severity levels over time also considering the factors governing – in different way – the onset and the development of the damage. The building response to slow-moving landslide was analysed by exploring long-term and multi-temporal monitoring/surveying information gathered from conventional and innovative techniques along with background geological, geomorphological and geotechnical data. To this aim, the analysis starts from a well-documented case study in Calabria Region (southern Italy) and then it extends to four other areas in Italian Apennines with similar geological settings, landslide types and built-up features.

The results achieved can help setting up more reliable models for consequence forecasting to be used in quantitative risk analyses.

Keywords slow-moving landslides, building damage, vulnerability, risk.

Introduction

The interaction between slow-moving landslides and human settlements is a remarkable issue for both scientific and technical communities involved in identifying the most suitable strategies for land-use planning and urban management (Ferlisi et al., 2019; Gullà at al., 2021). In the last years, the interest on the topic is increased by the evidence that several urban areas are affected by active landslides involving complex geological formations and moving along shear zones where fine-grained soils prevail. Although the representative velocities of those landslides usually range from extremely slow to slow classes (Cruden and Varnes, 1996), exposed buildings can suffer damages whose severity increases over time as cumulative displacements increase with high socio-economic impacts (Peduto et al., 2018).

To address this issue, empirical procedures implementing data collected by way of in-situ/laboratory tests and monitoring techniques can help in generating tools able to predict the onset and the development of the slow-moving landslide damage to the exposed buildings (Fell et al., 2005, Corominas et al., 2014).

However, to obtain reliable results, a preliminary effort is required in terms of knowledge on the factors governing – in different way – the response of the above buildings to displacement patterns at foundation level such as: *i)* the landslide mechanism, which includes information about the landslide intensity measure (e.g. a representative velocity or differential displacements cumulated in a reference time period), *ii)* the landslide displacement trends and their evolution over time (e.g. weather-induced reactivations and/or accelerations associated with a permanent or episodic activity); *iii)* the characteristics of the involved soils (in terms of both physical and mechanical properties), *iv)* key building characteristics (structural and foundation typology, geometry, state of maintenance); *v)* the suffered (or expected) building damage severity level joint with their vulnerability; *vi)* the position of a given building with respect to the landslide-affected area (i.e. at the head, body or toe).

In this regard, provided that similar geological and geomorphological features as well as landslide types and urban fabric are considered, the analysis of large dataset of multi-source information gathered from in-situ surveys and monitoring data acquired by both conventional (ground-based) and innovative (remote sensing) techniques can help in the activities aimed to investigate the role played by each of the above governing factors. Following this line of thought and with the general intend to go in-depth on all aspects governing the damage occurrence on buildings exposed to slow-moving landslide risk, this research starts from the analysis of a well-documented case study in southern Italy (Lungro village, Calabria region), where the availability of long-term and multi-temporal monitoring/surveying information along with background geological, geomorphological and geotechnical data, allowed to investigate the relationships between the kinematic features of slow-moving landslides affecting urban areas and the related effects on exposed buildings in terms of changes of damage severity levels over time also considering the building position with respect to the landslide-affected area. Then, the evidences raised from the exploration of the dataset available for Lungro village were jointly analysed with other case studies in the southern Apennine of the Calabria region, wherein a rich sample of slow-moving landslide-induced damage to buildings was collected. The preliminary results provide useful background for activities aimed at generating reliable damage forecasting tools to be used in quantitative risk analyses for built-up environments interacting with slow-moving landslides. These tools can help the decision makers in identifying appropriate structural and/or non-structural measures for risk mitigation.

The case studies

The case studies under consideration are five urban areas (Lungro, Verbicaro, San Mango d'Aquino, Lago and Gimigliano municipalities) located in the southern Italian Apennines (Calabria region, Figure 1), widely affected by slow-moving landslides mainly involving complex-structured and weathered soils. The areas present similar geological and geomorphological features characterized by very steep slopes affected by rotational/translational slides, complex slide/flow and landslide zone where clustering of phenomena is too tight to distinguish different bodies. Urban fabric is composed of masonry objects made up of 2-3 floors with pebbles, or irregular stones on shallow foundations located in the historic centres and reinforced concrete buildings up to 5-6 floors built in the new-developed areas. The best-documented case study is the Lungro village (Fig. 2) for which geological-geomorphological information and geotechnical data with deep and surface displacement monitoring data coming from both conventional (inclinometers and GPS, Fig. 2a) (Gullà et al. 2017; Peduto et al. 2018) and innovative remote sensing (DInSAR) techniques (Peduto et al. 2017), are available. The latter (Fig. 2b) derive from the processing – by way of the SAR tomographic analysis (Fornaro et al., 2009) – of very high-resolution x-band radar images acquired by Cosmo-SkyMed constellation, recently updated within MEFISTO research project to cover a ten-year monitoring interval from May 2011 to September 2021. The comprehensive analysis of the data coming from previous studies carried out in the area through the application of the "*aPosIn*" procedure (Gullà et al., 2017) - which relies on the combination of geological information, geomorphological criteria and both geotechnical and remote displacement monitoring data This allowed typifying the inventoried slow-moving landslides (Fig. 2a) in six categories (Fig. 2b), differing in geometric and kinematic characteristics, involved soils, and type of movement.

Fig. 1 The analysed case studies: Lungro, Verbicaro, San Mango d'Aquino, Lago and Gimigliano municipalities (southern Italy).

This allowed typifying the inventoried slow-moving landslides in six categories (Fig. 2) of different geometric and kinematic characteristics, soil type, and movement mechanism. A multi-temporal building damage surveys were available on the buildings exposed to landslide risk identified by overlapping the typified slow-moving landslide inventory with the built-up map. During the in-situ surveys, information about the building characteristics in terms of structural and foundation typology, geometry, state of maintenance, the building position with respect to the landslide (at the head, body or toe), the interacting landslide typology and the building damage level (DL) were collected via ad-hoc predisposed building fact-sheets (Ferlisi et al., 2015; Peduto et., 2017; Nicodemo et al., 2018). The recorded DLs were categorized by adapting the classification system proposed by Burland et al. (1977) on the basis of the visual interpretation of crack patterns exhibited by the building façades considering six categories (D0 = negligible; D1 = very slight; D2 = slight; D3 = moderate; D4 = severe; D5 = very severe). Figure 3 shows the results of the multi-temporal building damage assessment in Lungro village collected during in-situ surveys in October 2015 (Fig. 3a), June 2019 (Fig. 3b) and October 2022 (Fig. 3c) with two examples of DL evolution over time for both reinforced concrete (Fig. 3d) and masonry (Fig. 3e) buildings. Likewise for Verbicaro, San Mango d'Aquino, Lago and Gimigliano municipalities, remote sensing (DInSAR) displacements data and multi-temporal damage dataset on buildings in slow-moving landslide-affected area are available. The DL and position with respect to the landslide-affected area, collected during in-situ surveys at different time interval, were homogenised using the same ranking scale and damage classification (Burland et al., 1977) adopted for Lungro for the purpose of their cross comparison.

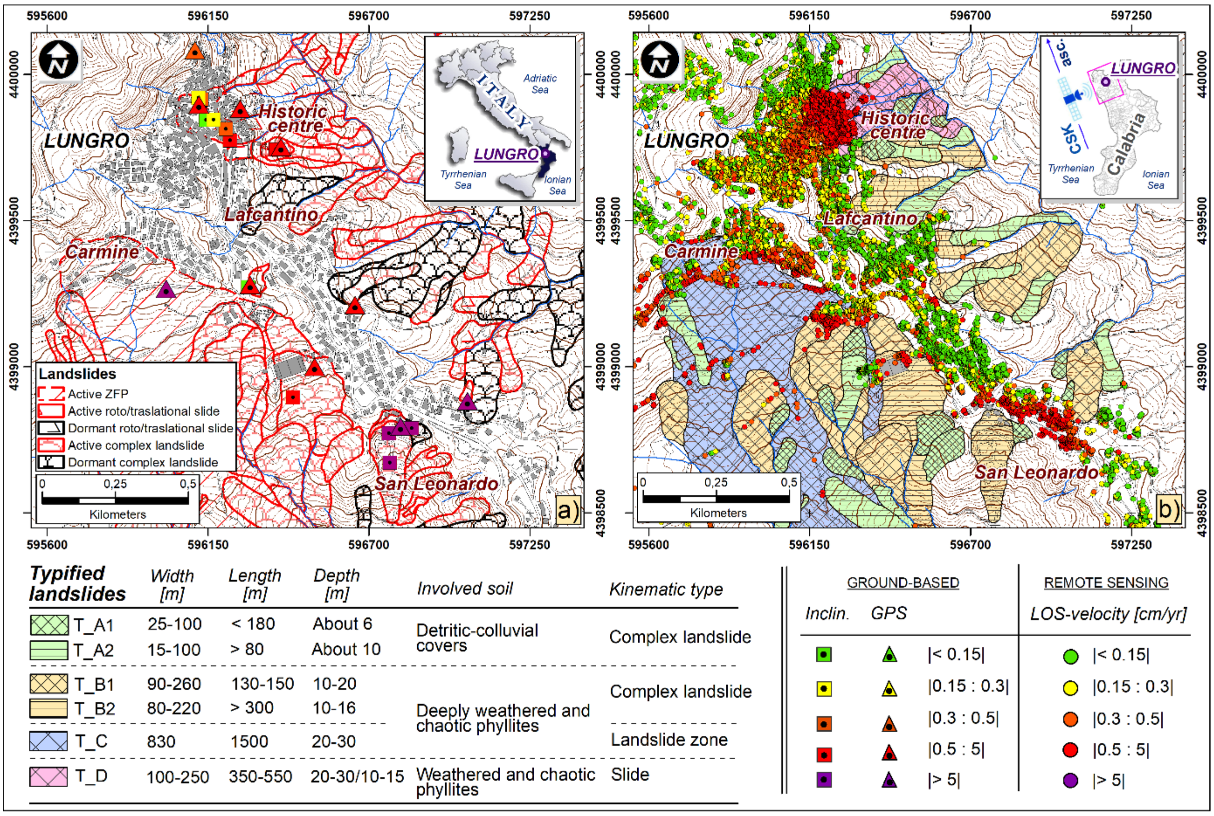

Fig. 2 Lungro village study area: a) landslide inventory map with ground-based (inclinometers and GPS) monitoring network and b) map of typified landslides (from Gullà et al., 2017) with spatial distribution of remote sensing data derived from the DInSAR processing of Cosmo-SkyMed images.

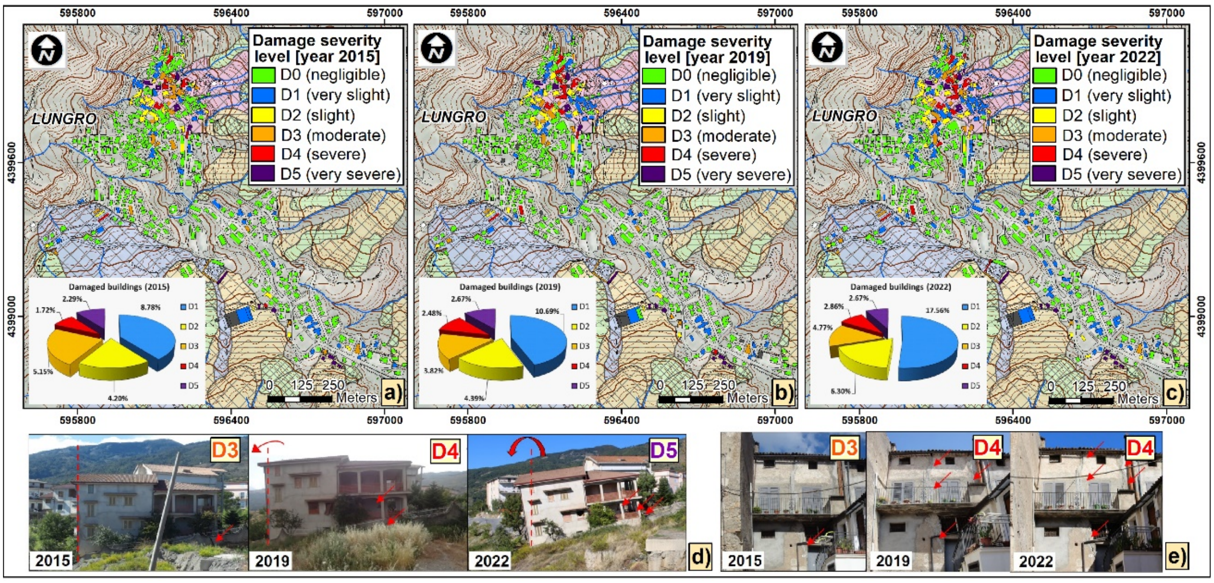

Fig. 3 Multi-temporal damage assessment of buildings in Lungro study area collected during in-situ surveys in a) October 2015, b) June 2019 and c) October 2022 with two examples of damage severity level evolution over time for d) reinforced concrete and e) masonry buildings in slow-moving landslide-affected areas.

Results

As for the Lungro area, the exposed buildings were preliminarily identified by overlaying the topographic map to the landslide inventory map. Out of a total of 470 surveyed buildings, 194 (63 reinforced concrete and 131 masonry buildings) resulted to be located on landslide-affected areas.

Focusing on a sub-sample of 68 masonry buildings composing a homogeneous sample located on landslide-affected areas or close to landslide boundary, a preliminary check of the distribution of damage severity level — ranging from D1 to D5 — was carried out based on the landslide typology and the landslide typified categories (Figure 4).

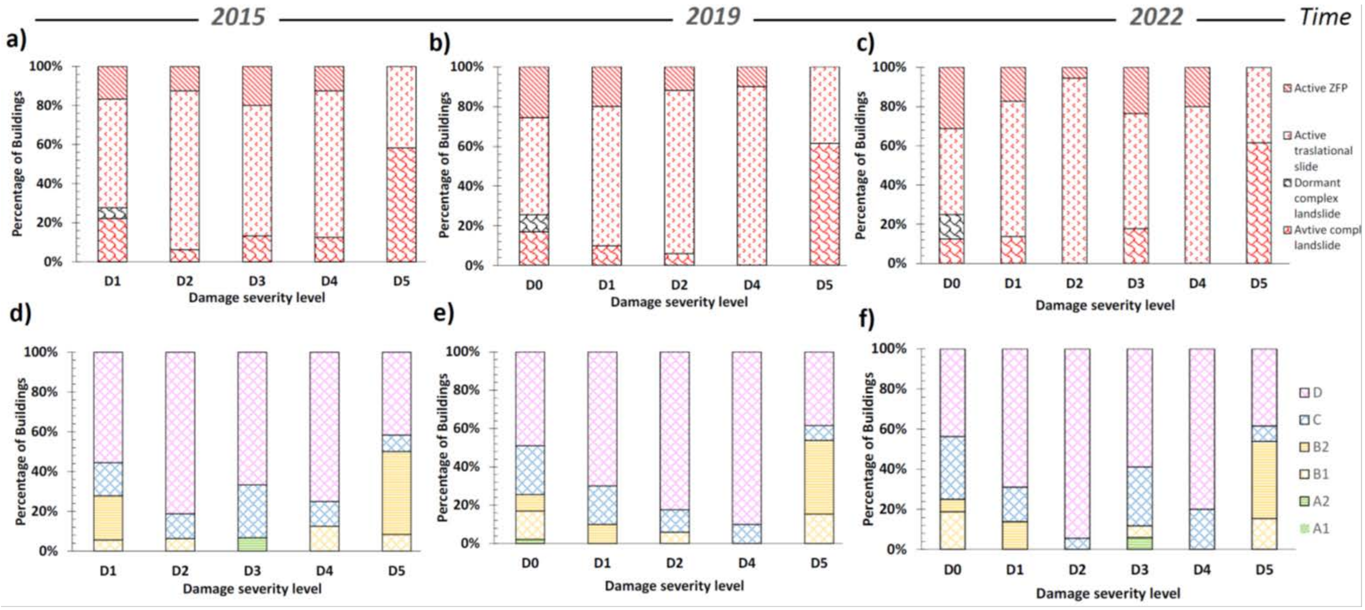

Fig. 4 Distribution of building damage severity level over time recorded in Lungro village in a) 2015, b) 2019 and c) 2022 in-situ damage surveys according to the landslide typology and d) 2015, e) 2019 and f) 2022 according to the landslide typified categories (see Fig. 2 for legend).

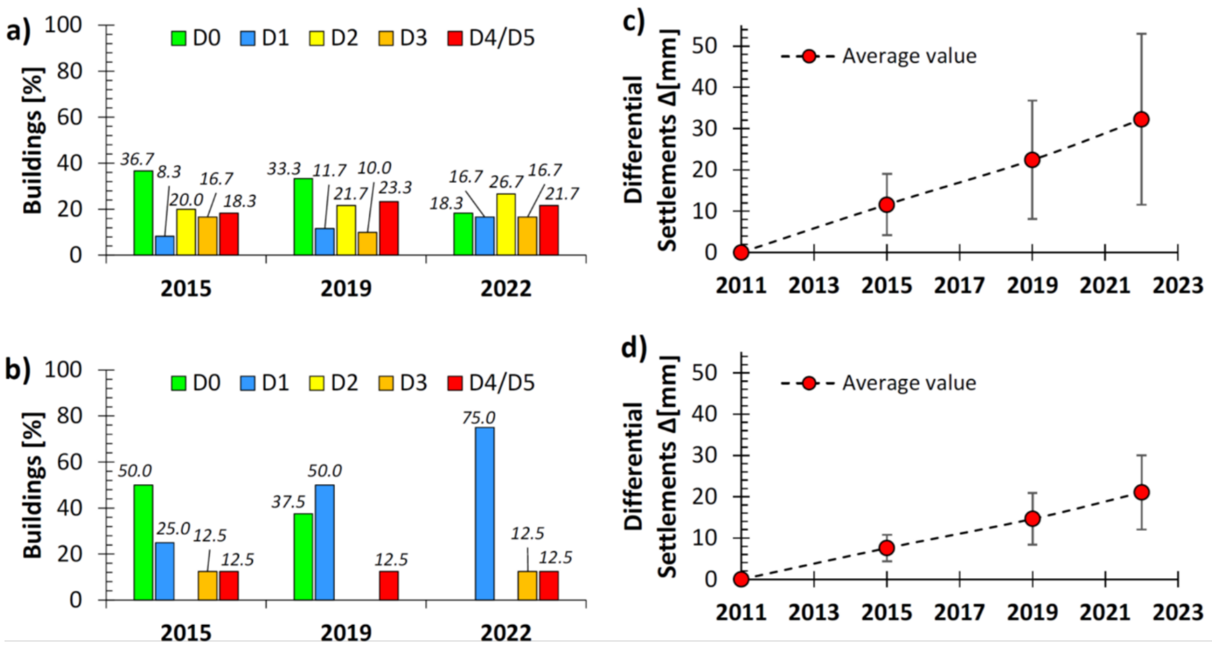

Fig. 5 Multi-temporal damage evolution for masonry buildings in Lungro village located on a) the head or b) the body of a slow-moving landslide and DInSAR-retrieved differential settlement (Δ) trend for buildings located on c) the head or d) the body of slow-moving landslide.

In particular, the analysis of the damage dataset collected in different time intervals (2015, 2019 and 2022) shows that most of the damaged buildings interact with landslide-affected areas mapped as "active" and, as expected, independently of the survey time, those buildings attain damage severity levels that are higher than those located in area mapped as "dormant" landslide. Furthermore, an increasing damage severity level over time is observed for buildings interacting with slow-moving landslides mapped as translational slide.

Referring to the typified landslides, the damage severity level over time seems to keep the same distribution (Figs. 4d, 4e, 4f) with the highest damage severity levels recorded by buildings interacting with the landslides of categories "B2" (medium/large complex landslide involving deeply weathered and chaotic phyllites) and "D" (deep/large translational slide involving weathered and chaotic phyllites) (Fig. 2b).

Additionally, a check of the distribution of damage severity over time was carried out by distinguishing the position of the buildings with respect to the landslide-affected areas (i.e. at the head, Fig. 5a or on the body, Fig. 5b). Figures 5a and 5b highlight that buildings located at the head attain damage severity levels higher than those located on the landslide body. Since damage onset and development relate to the magnitude of building settlements, remote sensing data – previously validated via a cross-comparison with ground-based measurement (Peduto et al., 2021) – were used to derive the differential settlement (Δ) suffered by each building in the different time intervals (i.e. in 2015, 2019 and 2022). First the cumulative settlements were derived by multiplying the average velocity along the vertical direction (i.e. derived from the Line-of-Sight sensor-target direction) for the period of observation of each considered time interval (Peduto et al., 2017). Then, the differential settlement (Δ) value was computed as the maximum difference of the cumulative settlements recorded by the pertaining coherent pixels (Nicodemo et al., 2017).

The above information was merged with the results of the damage surveys (Figs. 5c and 5d) providing a preliminary analysis of the relationship between the differential settlement trend exhibited by the buildings and the recorded damage severity levels according to their position with respect to the landslide-affected areas. Particularly, the average DInSAR-retrieved differential settlement trends for buildings located on the head (Fig. 5c) or on the body (Fig. 5d) of slow-moving landslide show, on average, that buildings located at the head exhibit higher Δ values, which correspond, in turn, to higher building damage severity levels (Fig. 5a and 5b).

In order to better investigate the distributions of building damage severity level over time according to the landslide typology and position within the landslide-affected area, the evidence raised from the Lungro village were merged with the data collected in the Verbicaro, San Mango d'Aquino, Lago and Gimigliano municipalities (Figure 6).

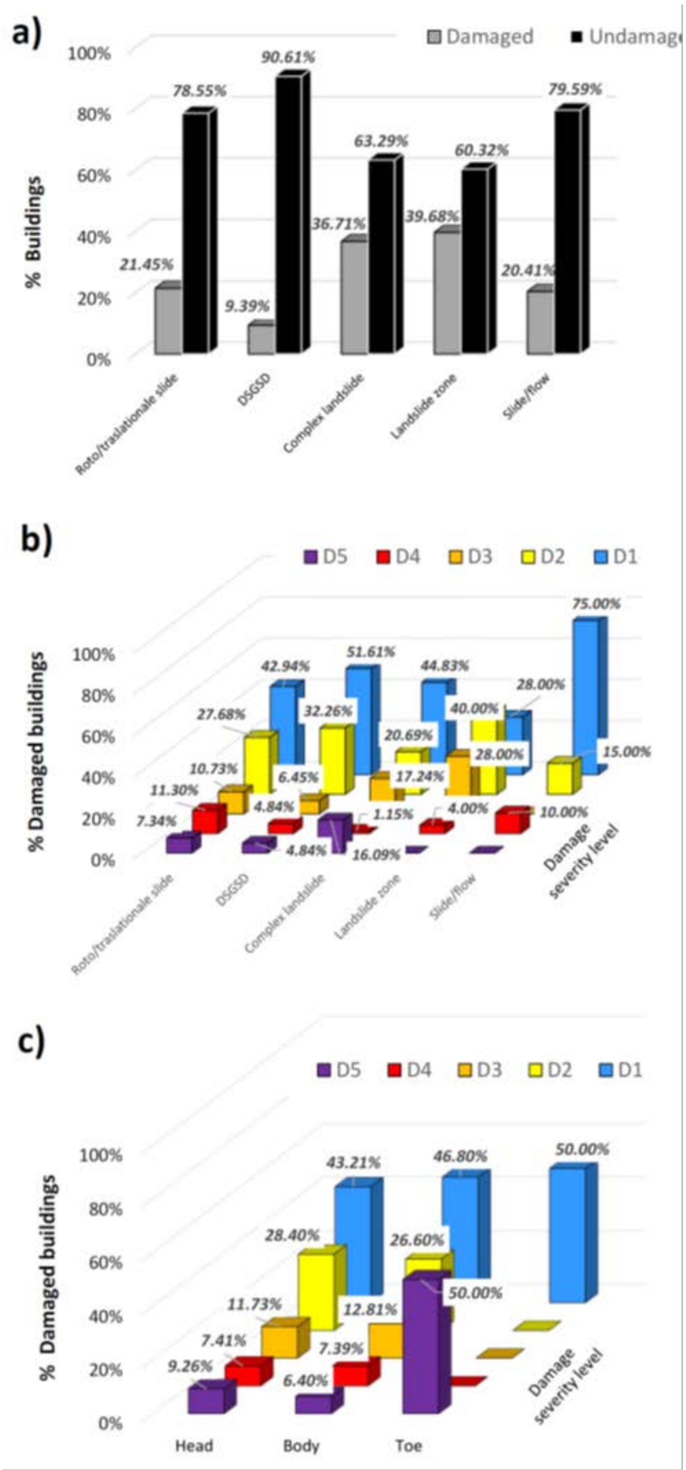

Fig.6 Building damage recorded in slow-moving landslide-affected areas for the five investigated case studies(Lungro, Verbicaro, San Mango d'Aquino, Lago and Gimigliano): a) percentage of damaged and undamaged buildings; b) distribution of the severity level according to the landslide typology; c) distribution of the severity level according to their position with respect to the landslide-affected areas (i.e. head, body and toe).

From the analysis of approximately 1800 buildings it emerges that buildings interacting with landslides classified as roto-translational or complex types (generally shallow) are more susceptible to damage (Fig. 6a) suffering higher severity levels (Fig. 6b). In relation to their position with respect of the landslide-affected area, higher damage severity levels are recorded for buildings located on the head or on the landslide body (Fig. 6c), although in some cases, high damage severity levels are also collected on buildings located at the toe of the landslide.

Discussion and Conclusions

The presented paper shows that the long-term and multi-source settlement monitoring, jointly with multi-temporal assessment of damage affecting the buildings interacting with slow-moving landslides, provide a useful support in activities aimed at investigating the factors governing the damage occurrence on buildings exposed to landslide risk. Nevertheless, this requires the availability of large dataset in homogeneous geo-lithological contexts with relevant information on slow-moving landslide features (e.g. affected-area, state of activity, shape, etc.), the displacement trends and their evolution over time, the exposed facilities (constituting materials, state of maintenance, position within the landslide-affected area) and their damage severity level (generally associated with the attainment of certain serviceability/ultimate limit states).

The preliminary results obtained highlight that monitoring and survey data derived from technological innovation, if jointly analyzed with background data, can provide useful contribution. Moreover, the in-depth knowledge on the factors governing the onset and development of building damage over time is crucial for a proper definition of reliable damage forecasting tools within slow-moving landslide risk mitigation activities.

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