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ORIGINAL PAPER

A multi-scale methodological approach for slow-moving landslide risk mitigation in urban areas, southern Italy

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Abstract
Several urban areas in Euro-Mediterranean countries are affected by slow-moving landslides that, even if rarely associated with the loss of human life, can cause damage to structures and infrastructure. In such contexts, the progressive decay of the built environment can bring along a generalized increase of the physical vulnerability and, as a result, slow-moving landslide risk increases over the time. Under these conditions, as long as suitable risk mitigation measures are lacking, the level of risk (also related to earthquakes) could turn out to be no longer acceptable within an a priori unknown time interval. This problem has a relevant social-economic impact, thus requiring the adoption of risk mitigation strategies that need to be effective and, at the same time, sustainable for the involved stakeholders. In this regard, this paper proposes a multi-scale methodological approach—based on the joint use of satellite-derived displacement monitoring data and the results of building damage surveys—whose applicability is tested with reference to urban areas affected by slow-moving landslides in Calabria region (southern Italy).

Keywords Slow-moving landslides · Building damage · DInSAR · Risk mitigation

Introduction

Landslides moving on shear zones that involve fine-grained soils are generally characterized by velocity values that, in the paroxysmal stage of movement, do not exceed 1.8 m/h (Hungr et al. 2005). For this reason, their kinematics is defined as "slow" in order to distinguish them from "fast" landslides that, on the contrary, can generally reach velocity values significantly higher than 1.8 m/h (Hungr et al. 2001, 2005). According to Cruden and Varnes (1996), the above distinction among slow- and fast-moving landslides strongly relates to the severity of damage on the exposed elements. Focusing on slow-moving landslides affecting urban areas, they generally cause neither direct nor follow-on/indirect damages (Roberds 2005) on the exposed people, such as casualties (injuries and fatalities). However, they can cause direct damages on the exposed facilities (e.g., buildings and infrastructure) whose functionality or even stability might be seriously compromised, with social and economic costs (Corominas et al. 2014; Mansour et al. 2011; Peduto et al. 2018).

To address this issue, the adoption of strategies aimed at mitigating the slow-moving landslide risk to facilities is required (Fell et al. 2005); on the other hand, these strategies need to be effective and, at the same time, sustainable for the involved stakeholders (Leroi et al. 2005). In this regard, a perspective is offered by the development of multi-scale methodological approaches—which also make use of information gathered from satellite monitoring techniques—allowing for the optimization of decision-making processes in (1) planning (medium-long term goals), (2) scheduling, with a proper allocation of available economic resources

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(short-term goals) and (3) designing risk mitigation measures. The latter may include structural and/or non-structural interventions. In particular, the structural interventions can (1) pursue the reduction of the slow-moving landslide intensity measure (e.g., the displacement rate) to values that are compatible with the functionality of exposed facilities (hazard reduction) and/or (2) consist of ordinary (painting, crack repair) and extraordinary (retrofitting/strengthening) maintenance works of exposed facilities (conservation and physical vulnerability reduction). On the other hand, the non-structural interventions includes (Ho 2004; Fell et al. 2005): avoidance (e.g., household relocation), transferring (e.g., by insurance policies), and monitoring/warning (for the temporary evacuation of people at risk). Finally, risk communication strategies (e.g., public education campaigns and information services) can be used to address the issue of risk tolerance by general public and involved stakeholders.

Following this line of thought and referring to Gullà et al. (2017a), in this work a methodological approach is proposed and its applicability is tested in study areas of the Calabria region (southern Italy). Furthermore, benefits deriving from a systematic use of the above approach are discussed focusing on the outcomes that can be achieved for the slow-moving landslide risk mitigation at different scales. These benefits are also strengthened by the observation that the increase of damage progressively suffered by the exposed facilities leads to an increase with time of their vulnerability to slow-moving landslides and, more in general, to other natural hazards, such as earthquakes (Negulescu et al. 2014).

The proposed multi-scale methodological approach

The main goal of the proposed multi-scale methodological approach is mitigating the risk to urban areas affected by slow-moving landslides by way of the progressive and integrated planning (at medium scale, 1:25,000), scheduling (at large scale, 1:5000) and design (at detailed scale, > 1:2000) of structural/non structural interventions. Given a scale of analysis, the above approach generally involves (1) characterizing the slow-moving landslides that are representative of a homogeneous geological context (Gullà et al. 2017b) and (2) retrieving the relationships between the cause (changes in value of the adopted landslide intensity measure) and the effect (severity of damage suffered by buildings and infrastructure at risk) (Ferlisi et al. 2018; Nicodemo et al. 2017; Palmisano et al. 2018; Peduto et al. 2017, 2018).

With reference to the latter relationships, the estimation of values to be associated with the landslide intensity measure can derive from the processing of data gathered from conventional monitoring techniques (e.g., inclinometers, topographic leveling, GPS systems) and/or innovative

Table 1 Spatial representation of the facilities at risk according to the scale of analysis (modified from van Westen et al. 2008)

Scale of analysis	Buildings	Infrastructure
Small (1:100,000)	By municipality	General location of transportation networks
Medium (1:25,000)	Mapping units	Road and railway networks
Large (1:5000)	Building footprints	All transportation networks
Detailed (> 1:2000)	Building footprints	All transportation networks

monitoring techniques such as those based on the use of synthetic-aperture radar (SAR) sensors. In this regard, a rich archive of SAR data (i.e., images) covering a long time interval (more than 25 years) is currently available, with a spatial resolution ranging from high (e.g., the first generation radar sensors such as ERS1-2, ENVISAT, RADARSAT1, those still in orbit as RADARSAT2 and the Sentinel-1 mission operating at C-band) to very high (e.g., the COSMO-SkyMed and TerraSAR-X missions, both operating at X-band). The images acquired by the two sets of radar sensors and processed by way of differential interferometric (DInSAR) techniques (Bianchini et al. 2013; Calò et al. 2012, 2014; Calvello et al. 2017; Cascini et al. 2013a; Gullà et al. 2017b; Herrera et al. 2013; Peduto et al. 2017; Tofani et al. 2014; Wasowski and Bovenga 2014) are, respectively, suitable for analysis at small/medium scale (high resolution) and large/detailed scale (very high resolution) at affordable costs if compared with conventional monitoring systems (Peduto et al. 2015).

As for the estimation of the effects on the exposed facilities, in situ surveys aimed at generating damage inventories for a defined category of elements at risk (e.g., masonry buildings) are required at medium and large scales. The recorded damage severity can be classified according to qualitative systems, such as the one based on ease of repair of the visible damage (Burland et al. 1977), and can be used in the generation of empirical fragility curves showing the probability of reaching or exceeding a certain damage severity level for a given value of the landslide intensity measure (Shinozuka et al. 2000). On the other hand, at detailed scale, the damage severity levels can be associated with limiting values of parameters (e.g., the tensile strain on load-bearing walls) to be introduced in semi-empirical damageability criteria (Son and Cording 2005; Burland 1995).

It is worth noting that the spatial representation of the elements at risk (buildings and infrastructure) should adapt to the scale of the analysis, as synthesized in Table 1 and highlighted by van Westen et al. (2008).

Figure 1 shows the flowchart of the proposed multi-scale methodology that, based on suggestions provided by Fell et al. (2008) and preliminarily following a top-down

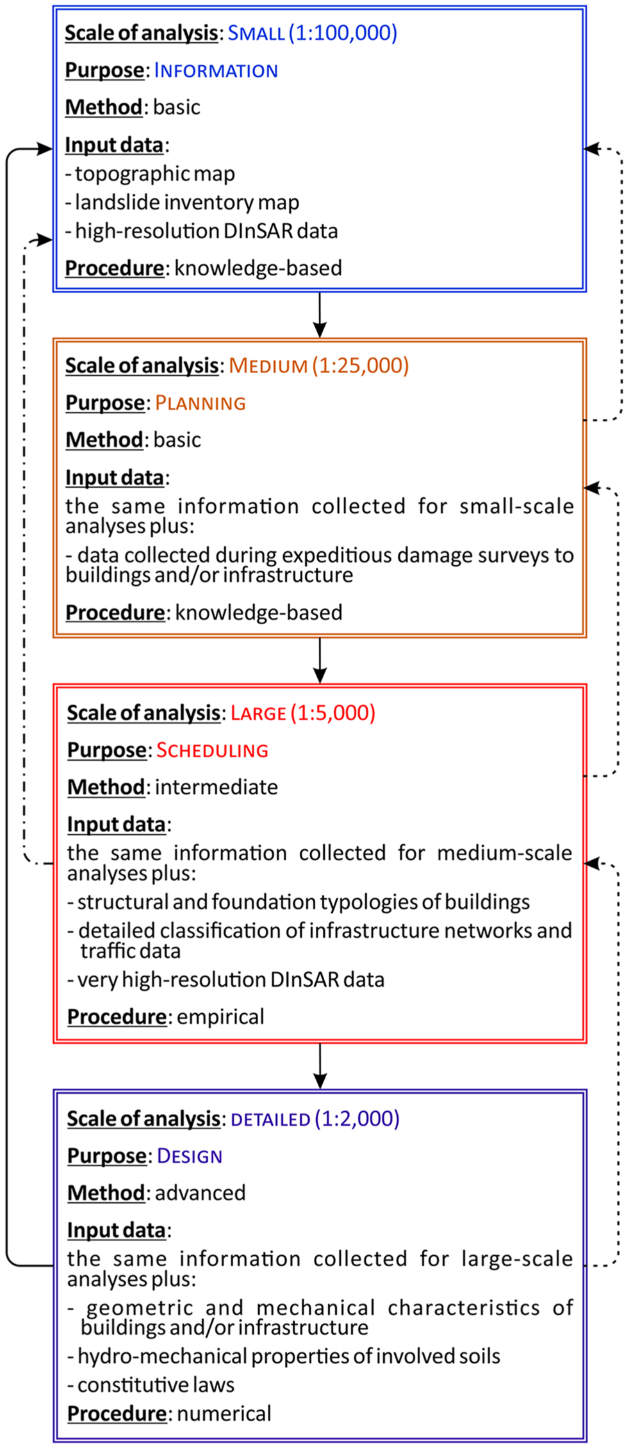

Fig. 1 Flowchart of the proposed iterative multi-scale methodological approach

approach (Cascini 2015), includes three levels of analysis methods (basic, intermediate, and advanced) according to the adopted procedures (knowledge-based, empirical, numerical) and the used input data (available or to be acquired).

First, activities have to be carried out at small scale to inform regional authorities about the municipal territories whose urban areas are exposed to slow-moving landslides. These activities involves combining high-resolution DInSAR data with information gathered from landslide inventory/urban maps in a geographic information system (GIS) environment.

Referring to the urban area of a given municipality (selected among the most exposed ones to slow-moving landslides on the basis of results achieved at small scale), the activities at medium scale deal with the phenomenological interpretation of landslide mechanisms based on the joint use of high-resolution DInSAR data and information collected during expeditious damage surveys to buildings and/or infrastructure. The obtained results can help regional and local authorities in planning well-defined categories of risk mitigation measures (e.g., slope stabilization works) to detected portions of the above urban area.

The activities at large scale are aimed at facilitating local authorities and technical officers in selecting and scheduling the most suitable structural/non-structural interventions (among the categories planned at medium scale). This can be done by analyzing and predicting the damage severity levels—by way of empirical fragility curves—pertaining to homogeneous (in terms of structural and/or foundation typologies) buildings and infrastructure covered by very high-resolution DInSAR data and interacting with slow-moving landslides typified based on their geometric and kinematic characteristics (Cotecchia et al. 2016; Ferlisi et al. 2018; Gullà et al. 2017b; Peduto et al. 2017, 2018).

Finally, the activities at detailed scale—carried out by technicians (e.g., engineers) for properly designing the most suitable interventions scheduled at large scale—consist of numerical simulations (i.e., stress–strain analyses), based on a geotechnical slope model, for predicting both the maximum value of considered slow-moving landslide intensity measure and the damage severity that might be suffered by interacting buildings/infrastructure whose structural features are selected according to the results obtained at large scale.

As shown in Fig. 1, the proposed methodological approach is iterative and should be updated periodically as information gathered from monitoring and in situ surveys becomes available. On the other hand, results obtained at larger scales can be used to improve specific procedures to be applied at smaller scales (Gullà et al. 2017a). This allows for the adoption of preliminary work hypotheses that subsequently can be modified/integrated based on the outcomes progressively achieved and facilitates a fast implementation of the decision-making process, also guaranteeing its effectiveness according to the scales of analysis and related purposes.

Applications of the proposed methodological approach

Small scale

The analysis at small scale (1:100,000) focused on the Cosenza province (Calabria region, southern Italy) for which available input data deal with: the "Landslide Inventory Map" drawn up at 1:10,000 scale within the Hydro-geological Setting Plan—Landslide Risk excerpt (Italian Law 365/2000) by the former Basin Authority of the Calabria region (HSP-LR 2001); the "Map of Urban Areas" at 1:10,000 scale (Greco et al. 2010); and the "Map of DInSAR data" collected within the Piano Straordinario di Telerilevamento Ambientale, which is a project supported by the Italian Ministry of the Environment and Protection of Land and Sea covering all the Italian territory (MATTM 2010). In particular, for the study area, the above DInSAR data derive from processing via the persistent scatterers interferometry (PSI) technique (Ferretti et al. 2001) the following high-resolution C-band ERS1-2 sensor images: 218 images on ascending orbit (period May 1992–November 2000) and 451 on descending orbit (period May 1992–December 2000).

In order to pursue the goal recalled in the section entitled "The proposed multi-scale methodological approach", slow-moving landslides were preliminarily identified (excluding first-time landslide source areas) in the Landslide Inventory Map. Overlapping the derived slow-moving landslide inventory map with the Map of DInSAR data allowed us to identify (1) the slow-moving landslides covered by DInSAR data (map A) and (2) the slow-moving landslides not covered by DInSAR data (map B). Then, moving and not moving coherent pixels (persistent scatterers—PS) were distinguished by setting a threshold value on the velocity recorded along the sensor-target line of sight (V_{LOS}) equal to 1.5 mm/year. This threshold represents a conservative value of the accuracy on V_{LOS} estimated by way of quantitative validation tests that make use of conventional ground measurements (Casu et al. 2006; Lanari et al. 2007); it has been widely used in similar applications to slow-moving landslides (Cascini et al. 2009, 2010).

Based on the V_{LOS} threshold, two output maps were generated, namely: (1) the map C of moving PS with $|V_{LOS}| > 1.5$ mm/year and (2) the map D of not moving PS with $|V_{LOS}| \leq 1.5$ mm/year. Then, the maps A and C were overlapped to derive the "map of moving landslides" (map E); similarly, the overlap of maps A and D allowed us to obtain the "map of not moving landslides" (map F). On the other hand, by overlapping the Map of Urban Areas with, separately, the maps E, B, and F it was possible to generate the "map of moving urban areas" (map G), the "map of potentially moving urban areas" (map H), and the "map of stable urban areas" (map I), respectively. Finally, the "map of vulnerable areas" (map L) was obtained by merging the maps G and H, where the vulnerable areas are defined as the portions of the urban area—pertaining to a given municipality—which are affected by landslides that are moving or that, even if not covered by PSI data, may be moving (adapted from Cascini et al. 2013a).

Once detected the municipalities with vulnerable areas, an index of exposure (IE_i) was computed as:

$$IE_i = \frac{VA_i}{VA_{tot}} / \frac{UA_i}{UA_{tot}}, \quad (1)$$

where VA_i is the total size of vulnerable areas of the i-th municipality, VA_{tot} is the total size of vulnerable areas of all the municipalities, UA_i is the size of the urban area of the i-th municipality, UA_{tot} is the total size of the urban areas of all the municipalities.

The achieved results were plotted at 1:100,000 scale in order to obtain, as a final product, the Map of the Municipalities of Cosenza province with either stable urban (or without vulnerable) areas or vulnerable areas, the latter distinguished according to the value assumed by IE_i (Fig. 2). The municipalities requiring priority studies at larger scales in order to plan and successively schedule the risk mitigation measures are those with an IE_i not lower than one in value.

Medium scale

The study area selected for the analysis at medium (1:25,000) scale corresponds to the urban area (of about 2 km^2) of Verbicaro municipality ($IE_i = 10.16$, Fig. 2). From the geological point of view, the prevailing Frido Unit, constituted by low-grade metamorphic rocks usually marked by extensional brittle-ductile shear zones, includes metapelites, phyllites, shales and metalime-stones; it tectonically overlays the Lungro-Verbicaro Unit that outcrops in correspondence of the historic centre (Amodio Morelli et al. 1976; Borrelli et al. 2018; Ferlisi et al. 2015; Nicodemo et al. 2017, 2018). At the top of the units, locally covered by colluvial deposits, blocks and fragments of metamorphic rocks in a prevalently clayey matrix can be found. The whole study area (Fig. 3) is affected by slow-moving landslides—involving the colluvial deposits and portions of the degraded phyllites—that have been causing damage of different severity levels to both buildings located in the historic centre (mainly of masonry) and in newly developed areas (mainly of reinforced concrete, r.c.) built-up since the 1960s.

According to the proposed methodological approach (Fig. 1), the analyses involved acquiring a topographic map (scale 1:5000) for the identification of the buildings located

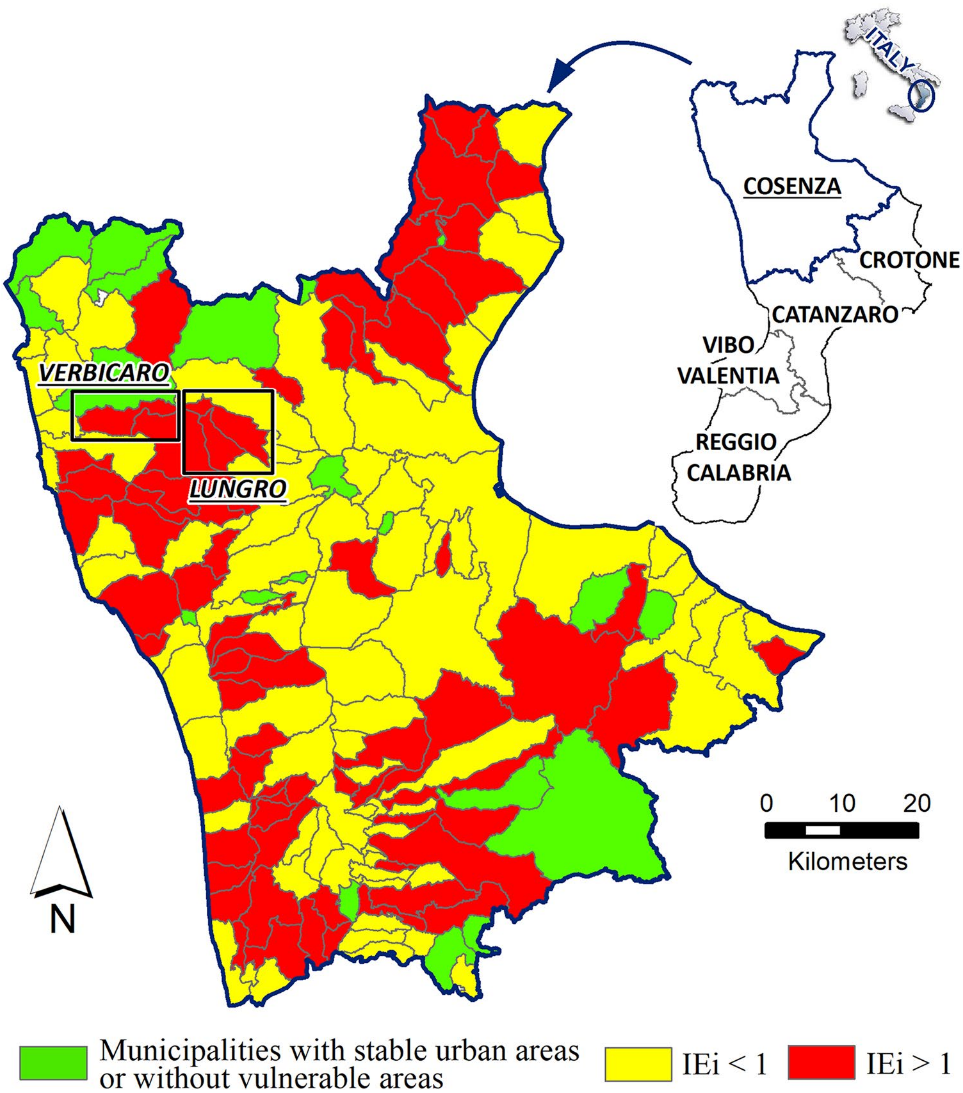

Fig. 2 Map of the municipalities of Cosenza province distinguished according to the value assumed by the index of exposure (IE_i)

in the urban area as well as the slow-moving landslide inventory map, drawn up by Borrelli et al. (2018) at 1:5000 scale. Based on the outcomes of previous studies concerning the Calabria region (Sorriso-Valvo 1993; Antronico et al. 1996; Greco et al. 2007; Gullà et al. 2017b), the mapped landslides are classified as: roto-translational slides, complex landslides, and landslide zones (Fig. 3). The latter class represents areas where clustering of landslides is so tight that it is difficult to distinguish the different bodies (Antronico et al. 1996, 2015; Greco et al. 2007). Moreover, the mapped landslides are distinguished in active or dormant (Cruden and Varnes 1996) on the basis of geomorphological criteria—which make use of field recognition and freshness of the topographic signatures typical of gravity-related landforms—and information gathered from damage surveys to the exposed buildings as well (Borrelli et al. 2018).

The damage surveys were carried out from April 2013–October 2014 using ad hoc predisposed building fact sheets (Ferlisi et al. 2015; Nicodemo et al. 2017) that, among other things, allow for collecting information on (1) the location of a given building and its description in terms of geometric and structural characteristics as well as (2) the damage severity level detected by visual observation of exterior walls and categorized according to six classes (D0: negligible; D1: very slight, D2: slight, D3: moderate, D4: severe and D5: very severe) by adapting the damage classification proposed by Burland et al. (1977) (Table 2). The collected information, jointly with (already available) evacuation/repair/demolition ordinances promulgated by the Verbicaro municipal council for a large number of buildings in the period between 1998 and 2000, was used to generate the building damage map shown in Fig. 4a. The distribution of different structural typologies and recorded damage severity levels in four sub-areas—centre, historic centre, newly developed area (north-west), newly developed area (east)—composing the urban area of Verbicaro (Fig. 4a) are

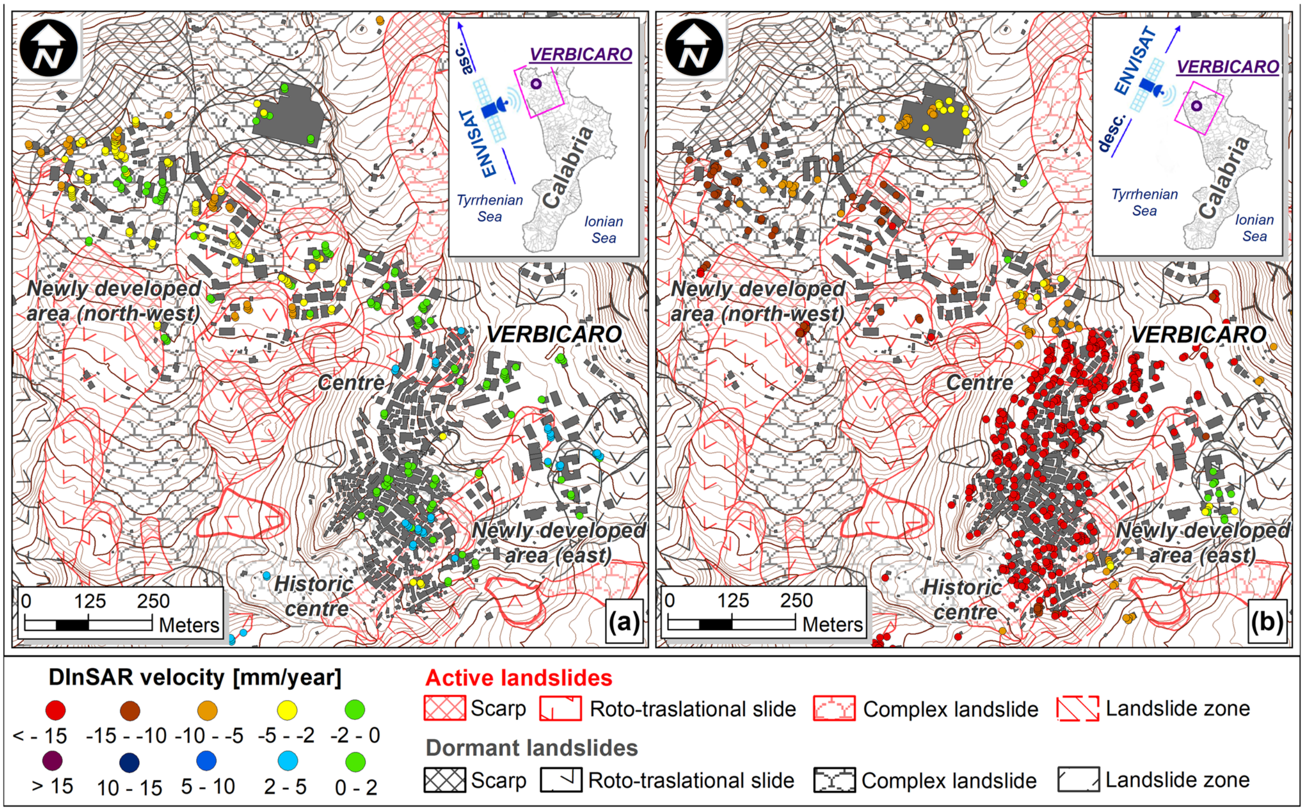

Fig. 3 The Verbicaro study area with inventoried slow-moving landslides (Borrelli et al. 2018) and spatial distribution of DinSAR velocities recorded on ascending (**a**) and descending (**b**) orbits by ENVISAT radar sensor (period 2003–2010)

Table 2 Levels of damage severity along with their description (adapted from Burland et al. 1977)

Level of damage severity	Damage description
D0 (negligible)	Hairline cracks are mainly caused by shrinkage and thermal gradients. Typical widths are less than 0.1 mm
D1 (very slight)	Cracks are fine and rarely visible; they can be easily treated via normal decoration. Typical crack widths are up to 1 mm
D2 (slight)	Visible cracks can be masked by suitable linings or easily filled. Doors and windows might stick slightly. Typical crack widths are up to 5 mm
D3 (moderate)	Cracks are much visible; they require some opening up and can be patched by a mason. Doors and windows might stick; whereas service pipes might fracture. Typical crack widths are 5–15 mm
D4 (severe)	Widespread cracks and extensive damage that requires breaking-out and replacing sections of walls, especially over doors and windows. Settlement might cause slight tilt to walls and onset of fractures to structural elements. Typical cracks widths are 15–25 mm, but also the number of cracks is to be taken into account
D5 (very severe)	Extensive cracking with structural damage that requires a major repair job involving partial or complete rebuilding. Settlements might cause tilt to walls and instabilities requiring the building evacuation. Typical cracks widths are greater than 25 mm, but also the number of cracks is to be taken into account

respectively shown in Fig. 4b, c; whereas the distribution of the recorded damage severity levels based on the building structural typology is synthesized in Fig. 4d.

As for the DInSAR data, they derived from 69 C-band SAR images acquired by the ENVISAT radar sensor (Table 3) with a ground resolution of 10 × 10 m and processed according to the SAR tomographic analysis (Fornaro et al. 2009) that provides a high quality of information on reflective targets. The spatial distribution of DInSAR-derived velocities on both ascending (Fig. 3a) and descending (Fig. 3b) orbits, overlapped to both the topographic map and the slow-moving landslide inventory map, highlights that 453 DInSAR coherent pixels on ascending orbit and 582 on descending orbit cover the whole study area, with

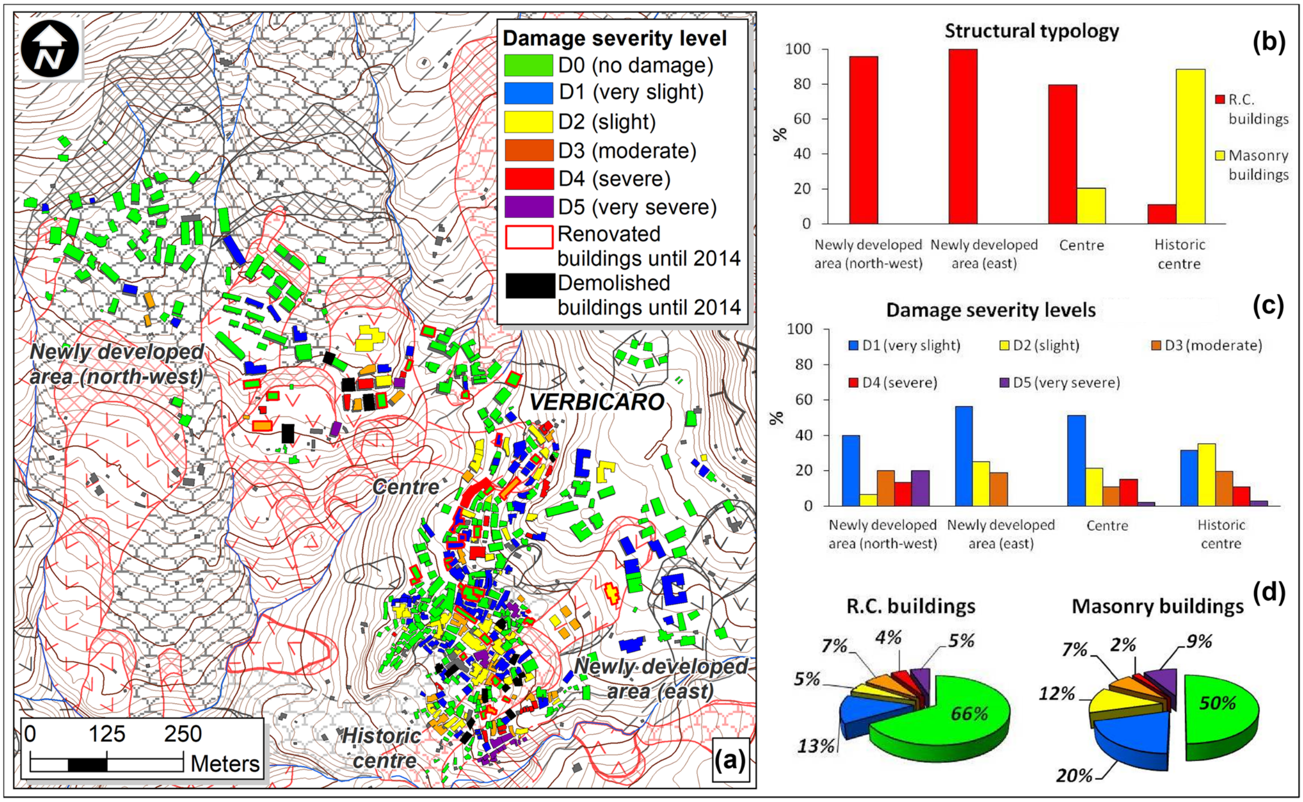

Fig. 4 **a** Map of surveyed buildings distinguished according to the damage severity levels recorded by way of in situ damage survey (for the legend of the landslide inventory see Fig. 3); (**b**) distribution of building structural typologies and (**c**) recorded damage severity levels in the four sub-areas composing the urban area; (**d**) distribution of the recorded damage severity levels based on the building structural typology (modified from Nicodemo et al. 2017)

Table 3 SAR image dataset used for the analysis at medium scale (1:25,000)

Radar sensor	Resolution	Orbit	No of images	Observation period
ENVISAT	High	Ascending	29	from August 2003 to January 2010
		Descending	40	from May 2003 to February 2010

higher velocities recorded in correspondence of the landslides mapped in the central part of the historic centre of Verbicaro.

The availability of remote sensing information on both orbits allowed us to distinguish the velocity components (Cascini et al. 2010, 2013b; Manzo et al. 2006) in the vertical (V_z) and in the horizontal (V_o) directions that, in turn, were interpolated using the inverse distance weighting (IDW) method on cells of 5 × 5 m. For each cell, the ratio between the moduli of the velocity components along the vertical ($|V_z|$) and the horizontal ($|V_o|$) direction was calculated and it was assumed that (Cascini et al. 2013a): (1) the velocity component in the horizontal direction is prevailing when the value of the velocity ratio is lower than 0.57 (equal to the tangent of a 30° angle between the direction of movement and the horizontal axis); (2) the components of the velocity in the vertical and horizontal directions are comparable if the value of the velocity ratio ranges between 0.57 and 1.73 (equal to the tangent of a 60° angle between the movement direction and the horizontal axis); (3) the velocity component in the vertical direction is prevailing for values of the velocity ratio higher than 1.73.

The results of the analysis (Fig. 5) show that in the historic centre, where the masonry buildings exhibit damage severity levels ranging from D1 to D5 (Fig. 4c), the prevailing velocity component is the horizontal one; in the newly developed areas the two velocity components (vertical and horizontal) are comparable in northwest area where damage severity levels from severe (D4) to very severe (D5)—which led to the demolition of some 5–6 storey buildings—are recorded (Fig. 4c); whereas the horizontal component prevails in the eastern portion of the newly developed area where the buildings suffer from damage severity levels not exceeding D3 (Fig. 4c). Finally, in the area of the

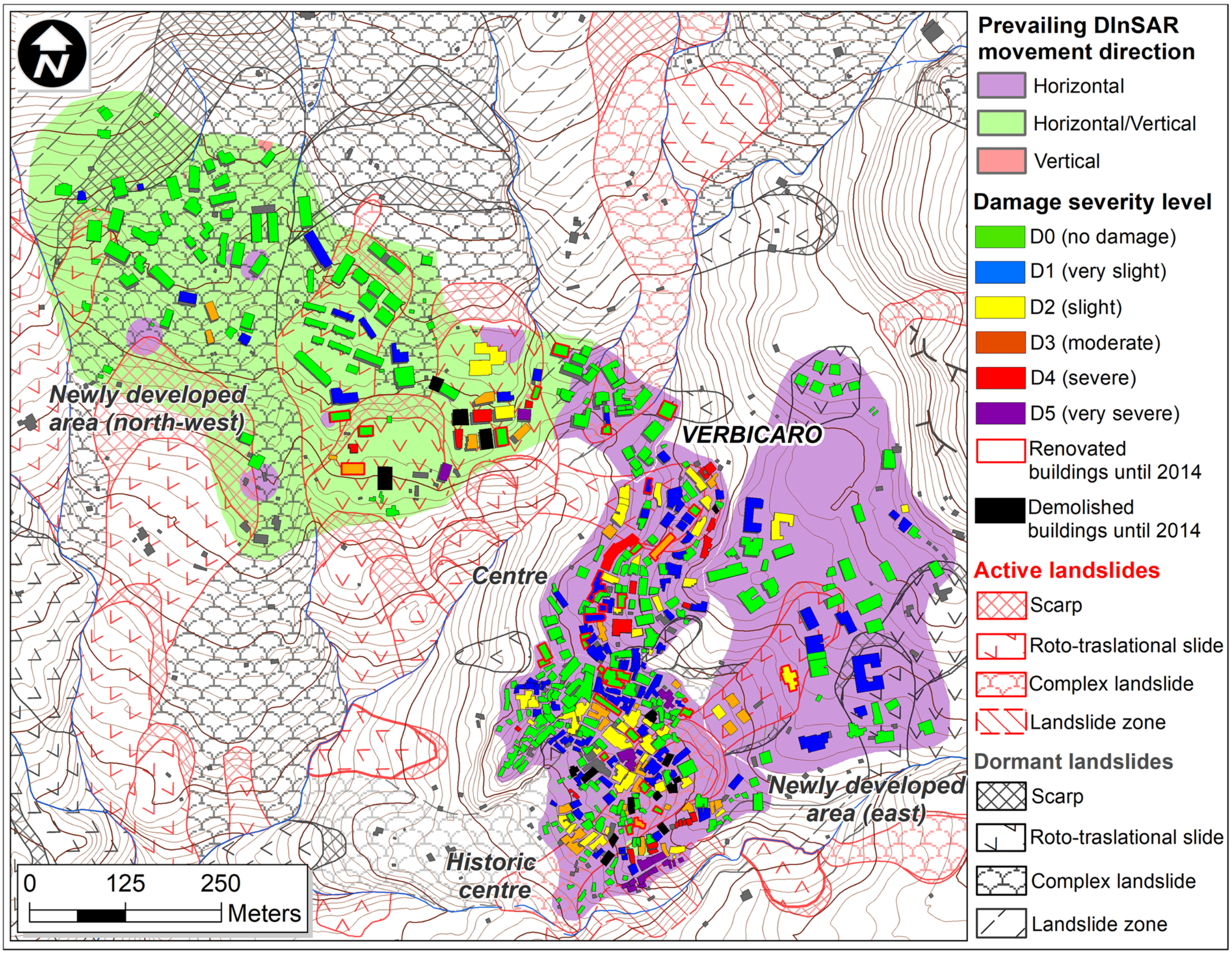

Fig. 5 Map of prevailing DInSAR movement directions in the four sub-areas composing the urban area of Verbicaro

centre—where both masonry and reinforced concrete buildings exhibit damage severity levels ranging from D1 to D4 (Fig. 4c)—the horizontal velocity prevails.

The achieved results (plotted at 1:25,000 scale) provide a useful support for decision makers in charge of planning risk mitigation measures that, in such a case, might involve the stabilization of landslide bodies (structural interventions) located in the newly developed area (north-west) where the highest number of buildings with very severe damage was recorded. In the historic centre, the risk mitigation measures to be implemented can be aimed at recovering masonry buildings and assuring their conservation by way of ordinary maintenance works (structural interventions). In the other two sub-areas, it could be enough using suitable techniques to monitor those parameters (such as surface displacements, also derived from DInSAR techniques) whose variation might prelude to the generation of risk (non-structural interventions); this should be carried out all over the urban area of Verbicaro municipality.

The advices coming from the studies at medium scale allow for addressing intermediate and advanced levels of analysis—to be carried out, respectively, at large and detailed scale—thus objectifying the complex interactions between the slow-moving landslides and the exposed facilities.

Large scale

The case study selected for the analysis at large scale deals with the urban area of Lungro municipality ($IE_i = 3.38$, Fig. 2) that, from the geological point of view, is within the Lungro-Verbicaro Unit (Gullà et al. 2017b; Peduto et al. 2016a). The inventory map (1:5000) of slow-moving landslides typified based on the procedure proposed by Gullà et al. (2017b) shows that slope instabilities can be distinguished in six categories (Table 4). The used DInSAR data derive from the processing via SAR tomographic techniques (Fornaro et al. 2009) of high- and very high-resolution SAR images respectively acquired on ascending orbit by ENVISAT (35 images) radar sensor with a ground resolution of 10 × 10 m and Cosmo-SkyMed (39 images) radar sensor with a ground resolution of 3 × 3 m (Table 5).

Figure 6a, b shows the spatial distribution of the DInSAR coherent pixels derived, respectively, from the processing of ENVISAT and COSMO-SkyMed images. The figure highlights the highest coverage provided by very high-resolution

Table 4 Main features of the typified landslides in Lungro urban area (modified from Gullà et al. 2017b)

Typified landslide	Width (W) [m]	Length (L) [m]	L/W	Depth [m]	Velocity [cm/year]		Involved soil	Kinematic type
					Ordinary	Critical		
T_A1	25–100	≤ 180	≤ 2.5	About 6	2–4	> 200	Detritic-colluvial covers	Complex landslide
T_A2	15–100	≥ 80	> 2.5	About 10	5–7	> 20		
T_B1	90–260	130–550	< 2.5	10–20	0.5–5	> 80	Deeply weathered and chaotic phyllites	Complex landslide
T_B2	80–220	> 300	≥ 2.5	10–16	4–20	> 100		
T_C	830	1500	1.8	20–30	0.5–5	> 40	Deeply weathered and chaotic phyllites	Landslide zone
T_D	100–250	350–550	2.2–3.2	20–30/10–15	0.2–0.5	2–5	Weathered and chaotic phyllites	Slide

Table 5 SAR image dataset used for the analysis at large scale (1:5000)

Radar sensor	Resolution	Orbit	No of images	Observation period
ENVISAT	High	Ascending	35	From August 2003 to January 2010
COSMO-SkyMed	Very high	Ascending	39	from October 2012 to April 2014

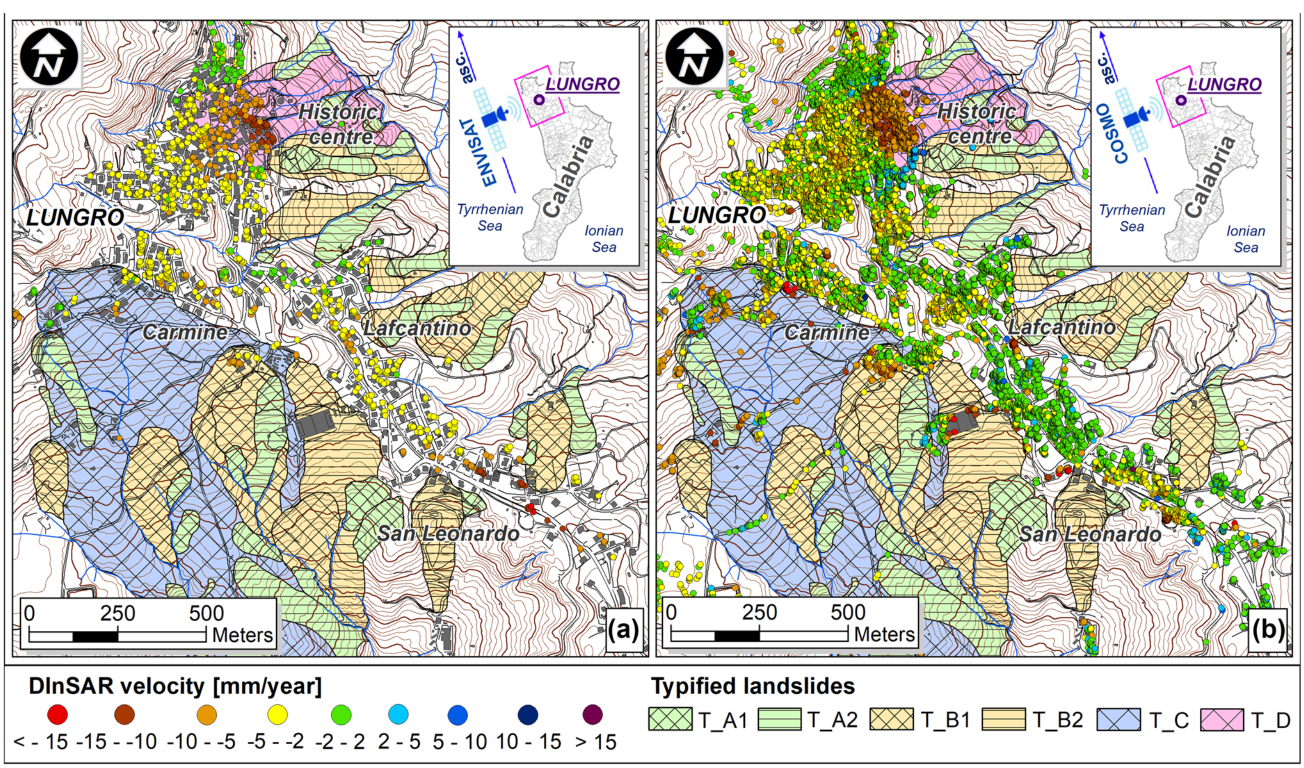

Fig. 6 Map of typified landslides (modified from Gullà et al. 2017b) and DInSAR data distribution (modified from Peduto et al. 2017) over the study area of Lungro derived from processing (**a**) ENVISAT and (**b**) COSMO-SkyMed images

COSMO-SkyMed images (15,252 DInSAR coherent pixels) compared with high-resolution ENVISAT images (7299 DInSAR coherent pixels) and the highest velocity values recorded in the central-eastern portion of the historic centre where the T_D landslides prevail. In detail, the DInSAR data provide evidence of widespread movements on different portion of the urban area (Fig. 6a, b) that, based on geomorphological criteria, are mapped as slow-moving landslide-affected area. Moreover, from the spatial distribution of the DInSAR coherent pixels, some landslide features corresponding to the main scarps exhibiting higher velocities can be identified.

The available information about the damages suffered by buildings (from 1812 to 2011) pointed out that the historical centre of Lungro municipality was systematically affected by damages induced by slow-moving landslides (Antronico et al. 2015; Gullà et al. 2017b). Furthermore, a building damage survey carried out in October 2015 revealed that 111 damaged buildings are located within the landslide-affected areas (Fig. 7a). Figure 7b, c shows the distribution of the different damage severity levels recorded during in situ damage surveys distinguished, respectively, on the basis of structural typology (reinforced concrete and masonry) and typified landslides with them interacting (Peduto et al. 2017).

Among the 111 damaged buildings within landslide-affected areas, 49 (including 12 of reinforced concrete and 37 of masonry) that are covered by at least two coherent pixels for both the ENVISAT and COSMO-SkyMed datasets were considered for the analysis purposes. In particular, for each of the 49 buildings, the differential settlement Δ (assumed as slow-moving landslide intensity measure) was obtained as the maximum difference between the cumulative settlement values pertaining to two generic coherent pixels within the footprint area of the considered building. In particular, the cumulative settlements were computed by multiplying the value of the average velocity along the vertical direction (derived from the LOS) for the observation period of each available dataset. Moreover, for the period February 2010–October 2012 in which DInSAR data are not available, an average constant velocity value equal to the one associated with the longer image dataset (ENVISAT) was considered (Peduto et al. 2017).

Merging this information with the results of the damage survey allowed us to derive the relationships (according to a black-box model) between the differential settlement and damage severity level for both reinforced concrete (Fig. 8a) and masonry (Fig. 8b) buildings. As expected, for both structural typologies, the recorded damage severity level—on average—increases as the differential settlement increases.

Finally, with reference to the sample of (37) masonry buildings, the empirical fragility curves were generated. In particular, based on the frequency of occurrence of each damage severity level referring to different classes of DInSAR-derived differential settlements (Fig. 9a), the log-normal distribution function was adopted as probabilistic model (Ferlisi et al. 2018; Mavrouli et al. 2014; Nicodemo et al. 2017, 2018; Peduto et al. 2016b, 2017). Accordingly, the fragility curves (Fig. 9b) were obtained using the equation:

$$P(Damage \geq Di|\Delta) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{\Delta}{\Delta_m}\right)\right] \quad (i = 1, \ldots, 5) \tag{2}$$

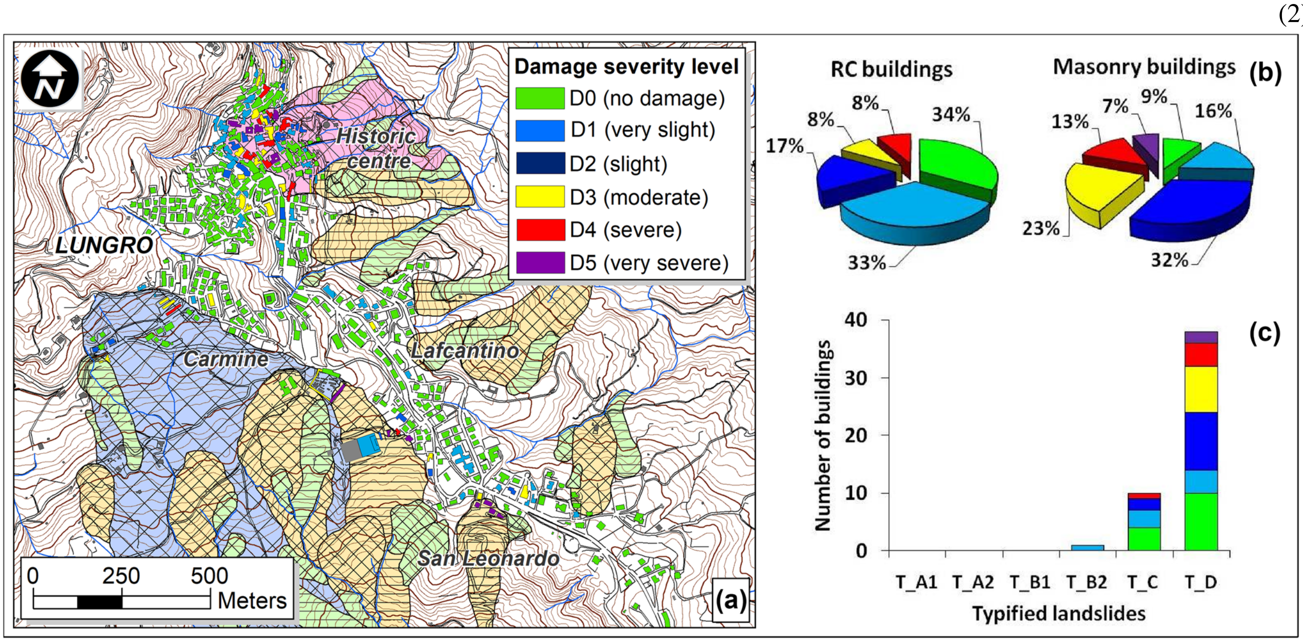

Fig. 7 **a** Map of surveyed buildings distinguished according to the recorded level of damage severity and their distribution based on **b** building structural typology and **c** typified landslides (modified from Peduto et al. 2017)

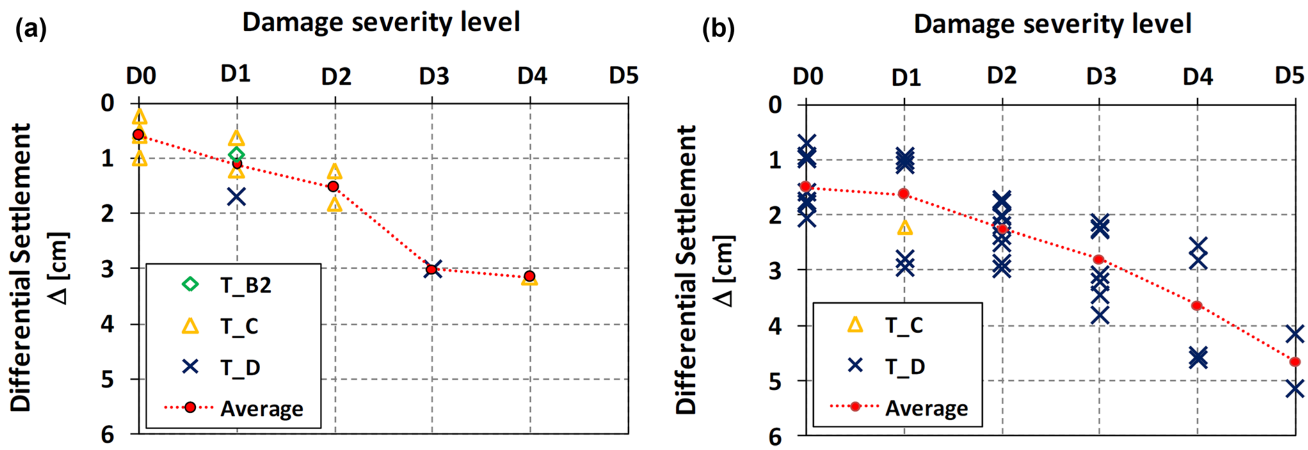

Fig. 8 Damage severity level vs. differential settlements for **a** reinforced concrete and **b** masonry buildings in Lungro study area (modified from Peduto et al. 2017)

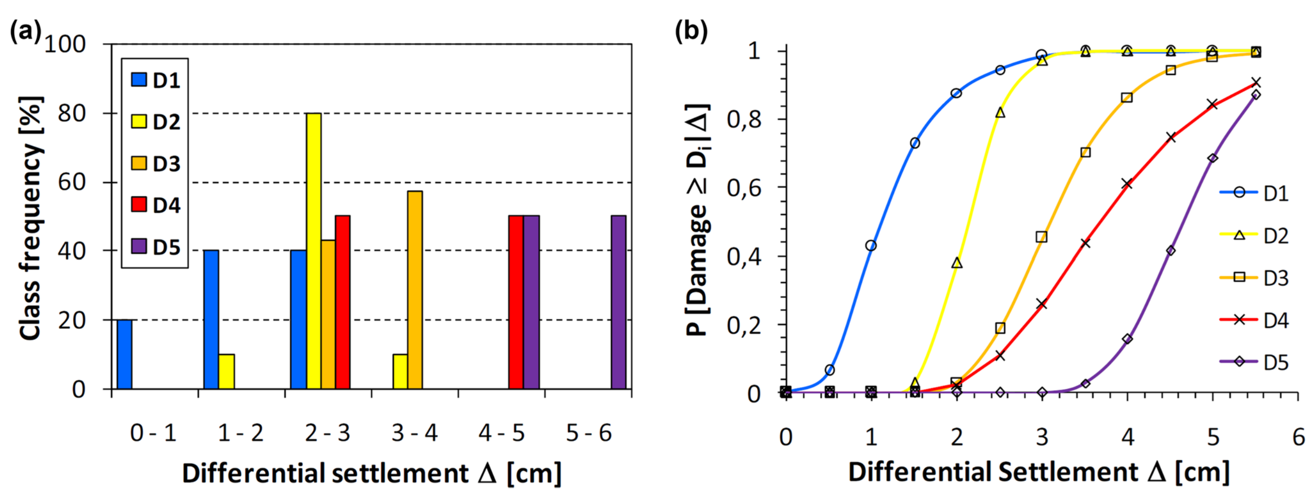

Fig. 9 **a** Class frequency of occurrence for each damage level Di ($i = 1, \ldots, 5$) and **b** empirical fragility curves for masonry buildings in Lungro study area (modified from Peduto et al. 2017)

where Φ [•] is the standard normal cumulative distribution function; Δ_m is the median value of Δ at which the building reaches a given damage severity level (ranging from D1 to D5); and β is the standard deviation of the natural logarithm of Δ.

The achieved outcomes represent the cognitive basis required to (eventually) schedule—taking account of operational and economic constraints—the implementation of risk mitigation measures that first would concern the stabilization of the slow-moving landslide bodies (structural interventions) where very high-resolution DInSAR data (Fig. 6b) show the highest velocity values and for which the most detrimental damage to buildings is expected.

The selection of the most suitable structural interventions could benefit from information about the geometric/kinematic characteristics of typified landslides and the empirical fragility curves, provided that the latter have been validated. For example, the interventions may be aimed at transferring the forces to structural elements connected with a stable underlying deposit (e.g., bedrock); their design—to be performed at detailed scale—could derive from the adoption of a performance-based approach that involves reducing the evolution of slope displacements within an estimated time interval, by limiting their magnitude to a target value—for example, associated with the probability of exceedance equaling the 5% (Zhang and Ng 2005) in the empirical curve related to D3 damage severity—in order to guarantee the functionality of exposed facilities (Galli and di Prisco 2013). This can be beneficial if a large number of slopes to be stabilized and a homogeneous sample of exposed facilities (in terms of age, state of maintenance, geometrical features, and material properties) are accounted for.

Detailed scale

The design of risk mitigation measures at detailed scale (> 1:2000) requires input data of high quality and quantity. In particular, with reference to a given typified landslide, the knowledge of (1) the geometry and kinematics of the landslide, (2) the hydraulic and geotechnical properties of involved soils along with their stratigraphic asset, (3) the pluviometric characteristics of the area and the groundwater regime, is a prerequisite for the generation of a reliable geotechnical slope model and, therefore, for a correct application of limit equilibrium and/or numerical methods (e.g., Finite Elements Methods implementing suitable constitutive laws) aimed at modeling the different processes governing the slope stability (Cotecchia et al. 2016; Gullà et al. 2018). Once the triggering factors are known, the choice of the most suitable stabilization work can be associated with the evaluation of the increase of the factor of safety that, with respect to the occurrence of a failure mechanism, occurs in the transition from the condition of pre- to post-intervention (Ng et al. 2002). On the other hand, whether an approach based on the performance of the geotechnical system including the landslide and the stabilization work is preferred, the design requires the comparison of the expected maximum value of the considered intensity measure (e.g., absolute displacement or differential settlement at the foundation level of a given building) with its limiting value (Galli and di Prisco 2013). The latter can be fixed taking account of the results of (deterministic) numerical analyses aimed at investigating the building response—in terms of damage occurrence and development—of buildings undergoing settlements induced by a slow-moving landslide to be interpreted with well-adopted damageability criteria (Son and Cording 2005; Burland 1995). This study may benefit from the combined use of conventional (i.e., inclinometers) and innovative (i.e., DInSAR) monitoring techniques in reconstructing credible settlement patterns to be used as input in the numerical analyses, as recently showed by Nicodemo et al. (2020). The same monitoring techniques would be used to verify the effectiveness of the selected structural intervention during its life-cycle.

Conclusions

In this paper, a multi-scale iterative methodology for the risk mitigation of urban areas exposed to slow-moving landslides was proposed. It allows planning slow-moving landslide risk mitigation measures based on priority levels (first established at medium scale) in turn leading to the scheduling and the final design of the most suitable interventions—either of structural or non-structural type—on single slopes under the perspective of a proper allocation of the available economic resources. By the way, it may also contribute to reduce the seismic risk in areas where buildings and infrastructure are suffering from damage whose severity level increases over the time due to the interaction with slow-moving landslides.

The results of applications carried out with reference to study areas located in Calabria region (southern Italy) following a top-down approach, highlighted the real possibility to develop increasingly effective tools for the analysis of both slow-moving landslides and the damage induced to the facilities at risk based on integrated procedures that make use of different input data according to the scale of the analysis. In this regard, it must be observed that the results obtained at small scale for information purposes are sensitive to the SAR velocity threshold (i.e., 1.5 mm/year on the line of sight) adopted to distinguish "moving" from "not moving" landslides; however, investigating this effect is beyond the scope of this paper.

Further developments may concern framing the sequential phases of the proposed methodological approach for the landslide risk mitigation in a wider landslide risk management process (Fell et al. 2005, 2008). The latter should include the risk analysis (either qualitative or quantitative, according to the scale of analysis), the risk evaluation (based on agreed risk tolerability criteria), and the risk mitigation (which could benefit from cost–benefit analyses for the proper selection and design at detailed scale of structural and/or non-structural interventions provided that quantitative risk analyses are carried out). This is also a challenge for the Euro-Mediterranean countries and, particularly, for Italy where the official practice involves analyzing and evaluating the landslide risk only on a qualitative basis at medium/large scale (Ferlisi and De Chiara 2016). From this point of view, the development of the activities related to the proposed multi-scale methodological approach (such as, for example, landslide typifying, data collection on the progress of damage with time, monitoring) stands as necessary background for the identification of representative situations over large areas that can be taken as reference—as real on-site laboratories—to improve the analysis procedures and develop innovative technologies aimed at supporting the most advanced landslide risk management processes.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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