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Time evolution of landslide damages to buildings: the case study of Lungro (Calabria, southern Italy)

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Abstract In the last decades, building damage caused by landslides in urban areas has increased due to the rapid growth of urbanization even on landslide-prone slopes. This work presents the analysis results of landslide damage evolution by means of a macrodamage index in relation to the characteristics of landslides. The study area is located in southern Italy, and is affected by slow-moving landslides, which, over time, have caused relevant effects on the buildings. A series of geological and geomorphological studies and field surveys, supported by monitoring via conventional geotechnical techniques, allowed us to classify four categories of landslides based on the following criteria: landslide movement, type of material and estimated depth. Detailed field surveys aimed at evaluating distribution and evolution of the damage to buildings located within and near the unstable area were carried out in 2005 and 2011. The evaluation of the macrodamage index in two different years enabled us to directly correlate the features of the landslide categories and their effects on the urban fabric.

Keywords Urbanized areas · Landslide · Building damage · Monitoring · Calabria · Italy

Introduction

The interaction between landslide phenomena, urban areas and infrastructures has become increasingly relevant over the last decades in many areas of the world, with relevant

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social and economic impact on the affected areas. The diffusion of urban centres and transportation networks on landslide-prone areas is increasing the socio-economic impact of landslide (Schuster and Highland 2007). With reference to the Italian territory, if on one side in the past, several neighborhoods have been built on areas that have turned out to be unstable, on the other, several urban centres have been developed—in particular since the mid 1950s—in areas known to be affected by landsliding phenomena (Guzzetti et al. 2005; Luino 2005; Trigila et al. 2010; Antronico et al. 2013a). In the period between 1300 and 2002, of the 8,103 Italian municipalities, 1,328 (16.4 %) suffered landslides with human consequences (Salvati et al. 2003).

It is well known that during the landslide event, a building may be completely destroyed, partially damaged or affected by deformation or inclination. The factors that influence the degree of impact are: (1) the type of movement, its location, and its magnitude (in terms of volume and velocity); and (2) the building category, age, height/size, and type of foundation. Another important factor affecting the vulnerability of a building is its location relatively to the landslide body (IUGS/WGL 1995; Flageollet 1999; Glade and Crozier 2005; Papathoma-Köhle et al. 2007).

Damage to buildings and infrastructures can be estimated using various methods (Kaly et al. 1999; Blong 2003a): (1) monetary loss; (2) percentage loss estimate, i.e. the cost of the damage/repair as a percentage of the construction cost; (3) an index value on a categorical scale that provides an estimate of damage, with a single value in the index normally representing a range of percentage losses; (4) numerical values standardised to a 0–1 scale; or (5) a macrodamage category that utilises a range of damage characteristics or indicators in an area (indicator values on a categorical scale).

Regarding the approach based on the costs, some Authors (Schuster and Fleming 1986; Middelmann 2007) distinguished three typologies of cost: (1) direct or direct tangible costs (the costs of replacement, repair, or maintenance of the property or facilities); (2) indirect or indirect tangible costs (that is, the reduced real estate values, the loss of productivity, etc.); and (3) intangible costs, due to the stress and to the worse quality of life of the persons affected by the events. In an Australian context, Blong (2003b) developed a damage scale, also relatively inflation-free, constructed in such a way that damage occurring in various locations and caused by various events could be compared and/or summed.

Swiss Re (1998) did not deal with the costs, but only defined: direct damage, indirect damage, and intangible damage. Petrucci et al. (2010) proposed a Total Damage Index, which is the sum of Direct, Indirect and Intangible Damage Indices. The Total Damage Index was also introduced in a tool, called Support Analysis Framework (SAF), which converted descriptions of landslide effects into numerical indexes expressing direct, indirect and intangible damage.

As for the classification of the damage to buildings caused by landslides, which is the object of this analysis, several proposals are present in the literature even if a universal methodology has never been adopted. Alexander (1986) proposed an intensity scale for structural damage caused by subsidence, compression or extension of the ground during landslides. The proposed scale included eight grades, from 0 ("intact building") to 7 ("total collapse"). Geomorphological Services Ltd (1991) introduced a very simple graduation: "negligible", "slight", "moderate", "serious", and "severe". Chiocchio et al. (1997) defined a classification of landslide damage to buildings in urban areas, distinguishing between the two main building typologies of the territory investigated (southern Italy): masonry and reinforced concrete. For each of the eight grades of damage, as Alexander (1986) proposed, the Authors added suggestions regarding immediate and rehabilitation measures suitable to the different damage levels.

Generally, if the landslide is very slow as defined by Cruden and Varnes (1996), damage can be tolerated by the structures whose conditions can be periodically improved by means of structural maintenance or definitely solved by control works (Urciuoli and Picarelli 2008). Mansour et al. (2011), by examining 50 cases of slow-slides in the literature, pointed out that the expected degree of damage to urban areas, highways, bridges and dams can be related to slide velocity or displacement accumulation.

In this study, the analysis results of the relationship between the characteristics of landslides and the building damage evolution are presented with reference to a territory of southern Italy (municipality of Lungro in Calabria) affected by different types of landslides. With this aim, a macrodamage index was introduced and its time evolution was analysed, enabling us to directly correlate the features of the movements to their effects on the urban fabric.

Firstly, to collect the data necessary to investigate the mentioned relationship, the landslides were classified on the basis of characteristics derived through in situ and observation analyses. Moreover, the urban expansion was estimated considering two time spans, while the damages to buildings, classified using the method proposed by Geomorphological Services Ltd (1991), were evaluated in two different years (2005 and 2011). The approach used in this work can be useful for monitoring the damage in single areas of an urban settlement affected by slow landslides, and for planning measurements and actions to mitigate and/or to reduce the risk.

Methodology

Since the aim of this analysis is to study the impact of landslides on the buildings, only direct damages were considered. Detailed field surveys aimed at evaluating distribution and evolution of the damage to buildings located within and near the unstable area have been carried out in the period 2005–2011. The damage assessment was based on site observations (the presence of cracks and/or disjunction in the outer walls, distortion of structures and walls out of perpendicular, as well as partial or total collapse of buildings), and classified as proposed by Geomorphological Services Ltd (1991). Five classes of damages were considered: "negligible", "slight", "moderate", "serious", and "severe", as defined in Table 1. In the analyses, other factors, such as

Table 1 The damage recording scheme proposed by Geomorphological Services Ltd (1991)

Class	Description
Negligible	Hairline cracks to structures with no appreciable lipping or separation
Slight	Occasional cracks. Distortion, separation or relative settlement apparent. Small fragments of debris may occasionally fall onto roads and structures, causing only slight damage. Repair not urgent
Moderate	Widespread cracks. Settlement may cause slight tilt to walls and fractures to structural members
Serious	Extensive cracking. Settlement may cause open cracks and considerable distortion to structures. Walls out of plumb and the road surface may be affected by subsidence. Repairs urgent to safeguard future use of structures
Severe	Extensive cracking. Settlement may cause rotation or slewing of ground. Gross distortion to structures. Repairs will require partial or complete rebuilding and may not be feasible. Severe movements leading to the abandonment of the site or area

Modified from Cooper (2008)

building category, age, height/size, and type of foundations, were not considered.

A simple macrodamage index has been introduced: the Aggregated Damage Index (ADI), which is a weighted average of damaged buildings through the following simple equation:

$$\text{ADI} = \frac{\sum \alpha_i \cdot B_i}{\sum B_i} \qquad (1)$$

where B_i is the number of buildings located in the area belonging to a class of damages and α_i is the weight corresponding to the damage class: 0 for no damage; 0.2 for negligible damage; 0.4 for slight damage; 0.6 for moderate damage; 0.8 for serious damage; 1 for severe damage or destroyed building. According to its formula, the ADI may vary from 0 (area without any damage) to 1 (completely destroyed or severely damaged area).

The data used to classify the landslides were derived from fieldwork, aerial photograph interpretation and geotechnical monitoring. The lithological types cropping out in the study area were obtained through detailed field surveys. A landslide inventory map using 1:25,000 and 1:33,000 scale black-and-white and colour aerial photographs (shot from 1955 to 2001), has been produced. The photo interpretation was validated through several field surveys in 2005–2011, which also allowed to better define type, activity, and estimated depth of phenomena on a morphological basis. Data deriving from inclinometers, installed inside some landslides during a geotechnical campaign carried out in the area since 2006, have been used to acquire indications on the geometric and kinematic features of the landslides types (depth of the sliding surface, involved volumes and mean velocity). Finally, on the basis of the above-mentioned data, four landslide categories were individuated. All the elements acquired have been mapped on a 1:5,000 topographic scale (Technical Regional Map), digitalised and stored in an ArcGIS database to make territorial analysis and graphic rendering more efficient.

Study area

General setting

Lungro, located in the northwest area of the Calabria region, is a small town composed of a historical centre (dating back to the second half of the fifteenth century BC) and a newly developed urban area. The study area, which includes the two urban centres, has an extension of about 5 km² and elevations between 400 and 650 m a.s.l.

From a geological point of view (Fig. 1), the northwestern portion of the area is characterized by the presence of the Lungro–Verbicaro Unit (LVU), dating back to the Middle Trias, made up of metapelites and metacarbonates (Iannace et al. 2005). The LVU, lying next to the dwelled area of Lungro, moves towards the Ophiolitic Unit of Diamante–Terranova (Lower Jurassic–Cretaceous), with a clear extensional tectonic contact. In particular, the cover of the Diamante–Terranova Unit (DTU), made up of phyllites and slate, crops out in the study area. Overall, these lithotypes form a sort of "melange structure" made up of blocks and fragments of different natures in a prevalently clayey matrix, derived from the degradation of phyllites. The metasediments of the DTU are overlain by an Upper Tortonian–Messinian sequence made up of coarse sandstones, clays with gypsy sandstones and gypsum. The early Miocenic succession, then, ends with sediments dating back to the Middle Pliocene–Pleistocene, represented by sandy-conglomeratic successions. Some detrital deposits formed by stony elements of calcareous and/or dolomite origin, immersed in a sandy and/or muddy matrix, are present on the calcareous–dolomite slopes and at their base. Moreover, some debris–colluvial covers and landslide debris, with maximum thickness of about 10 meters, are prevalently present on the DTU phyllite.

The morphology of the area attests to the difference in the mechanical resistance of the outcropping rock units. The study area is bounded to the north by steep slopes made of intensely jointed calcareous–dolomitic rocks. The remaining portion of the area, where extremely deformed and/or chaotic phyllites, clays and shales diffusely crop out, is characterised by a milder morphology with gentle slopes. As can be observed from Fig. 2, the slopes are characterised by a very high landslide incidence; the majority of the phenomena show evidence of recurrent activity (Guerricchio et al. 1993; Gullà et al. 2006; Antronico et al. 2013b).

The instability of the area has been well documented for a long time (Almagià 1910). The analysis of historical data collected over the study area (Gullà et al. 2006) has highlighted that the old centre of Lungro and the newly built up areas have been recurrently affected by landslide phenomena, usually slow ones. Prior to the urban expansion, a portion of the historical centre was affected by severe building stability problems; this situation led the Authorities to include Lungro in the list of the centres that had to be relocated to more stable areas (Law 9 July 1908, No. 445). Towards the second half of the last century, like many other Calabrian centres, Lungro experienced a fast expansion of its urban area; in fact, a considerable urban and road infrastructure development took place in the area southward of the historical centre, between the Tiro and Pantano torrents. In particular, Fig. 2 shows the evolution of the urban fabric, obtained by comparing topographic maps of 1955, 1983 and 2001. Fortunately, at present, the
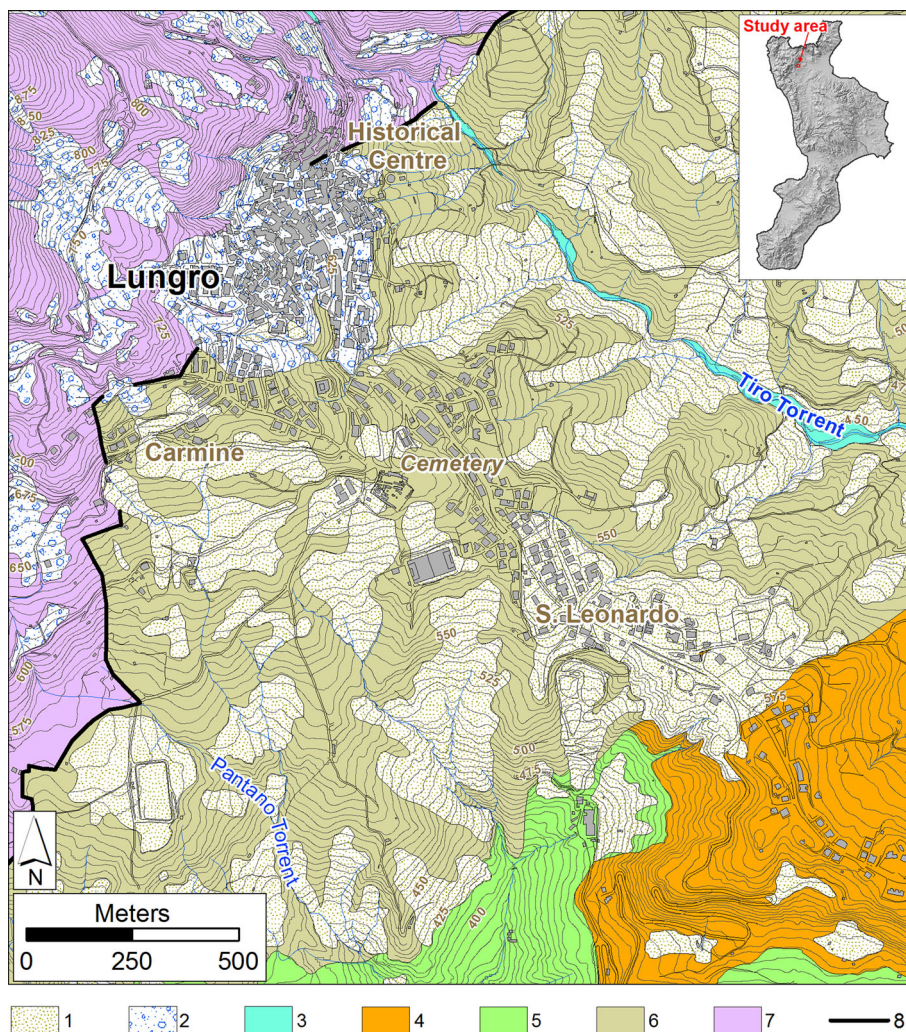
urbanization process does not appear to have increased compared to 2001. Despite the past awareness of slope instability, several private houses, public buildings, and facilities, as well as road networks, have been built up in this area. As a consequence, the instability problems, which initially affected the buildings located in the historical centre, have progressively involved newly developed constructions.

Landslide categories

The prevailing types of mass movement in the study area are: slides, complex slide/flow (Varnes 1978) and landslide zones. The landslide zone represents an area where clustering of phenomena is so tight that it is impossible to distinguish the different bodies, but sometimes mass movements can be mapped inside it (Greco et al. 2007). This type of mass movement is present on the left slope of the Pantano Torrent, characterized by the presence of a large amphitheater-shaped

landslide zone inside which some active mass movements have been mapped.

Moreover, for the aim of this paper, landslides in the study area were classified into four categories on the basis of geomorphological studies and field surveys (Table 2; Fig. 3). Geotechnical measurements confirmed the depths estimated on a geomorphological basis and provided estimates of displacement velocities.

The first category (A) includes landslides affecting detritic-colluvial covers, whose type can be ascribed to the complex landslides with a depth, detected on the basis of geomorphological studies, no greater than 10 m. This category interests most of the study area. From a dimensional point of view, almost all of the landslides in this category were smaller than 5 ha (average length about 250 m; average width 60 m) and occurred on slopes with an inclination lower than 30°.

The second category (B) includes landslides affecting deeply weathered and chaotic phyllites, belonging to the complex landslides type with a depth, also detected on the

Fig. 2 Landslide inventory
map of Lungro (updated to
April 2010) with the indication
of urban area expansion from
1955 to 2001. *1* Ancient rock
slide with uncertain boundary,
2 main scarp of active landslide,
3 main scarp of dormant
landslide, *4* boundary of active
slide-flow, *5* limit of dormant
slide-flow, *6* boundary of active
slide, *7* uncertain boundary of
active slide, *8* limit of dormant
slide, *9* boundary of active
landslide zone, *10* fall/topple,
11 buildings in 1955,
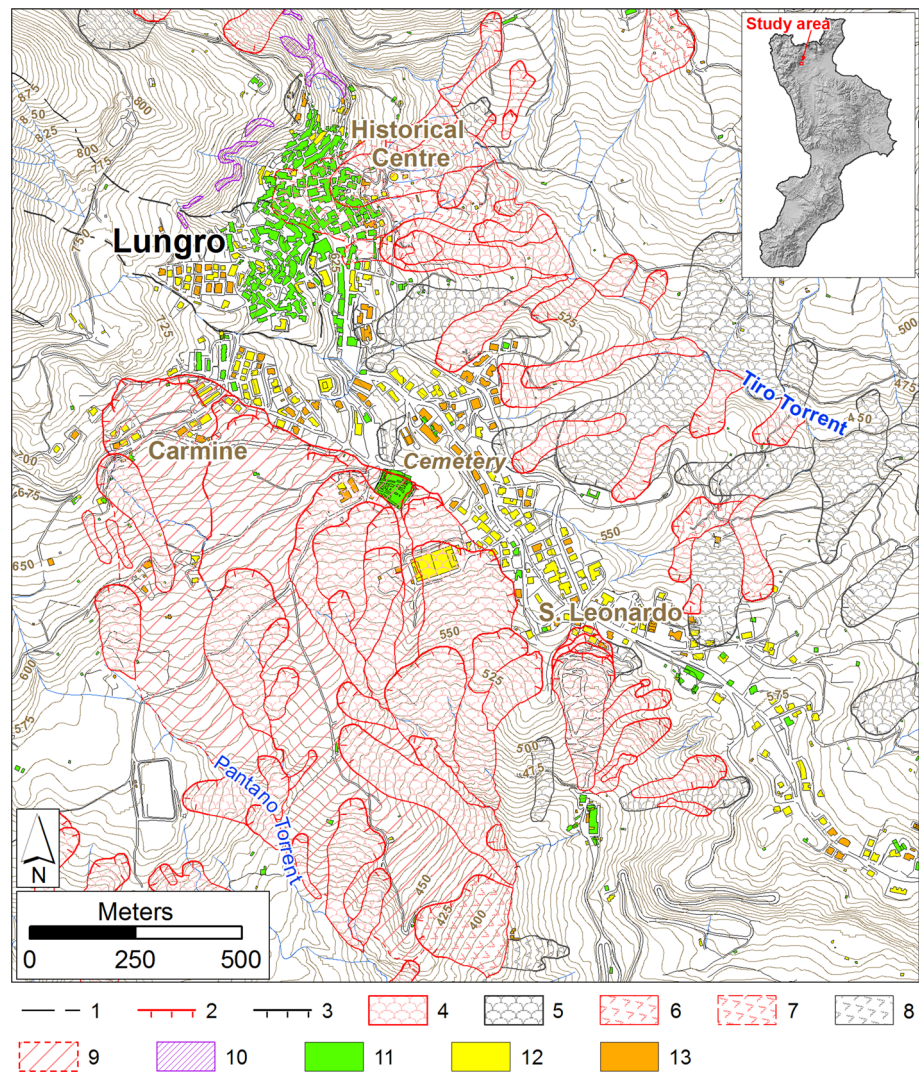*12* buildings in 1983,
13 buildings in 2001

Table 2 Characteristics of landslide categories on the basis of geomorphological studies and field surveys

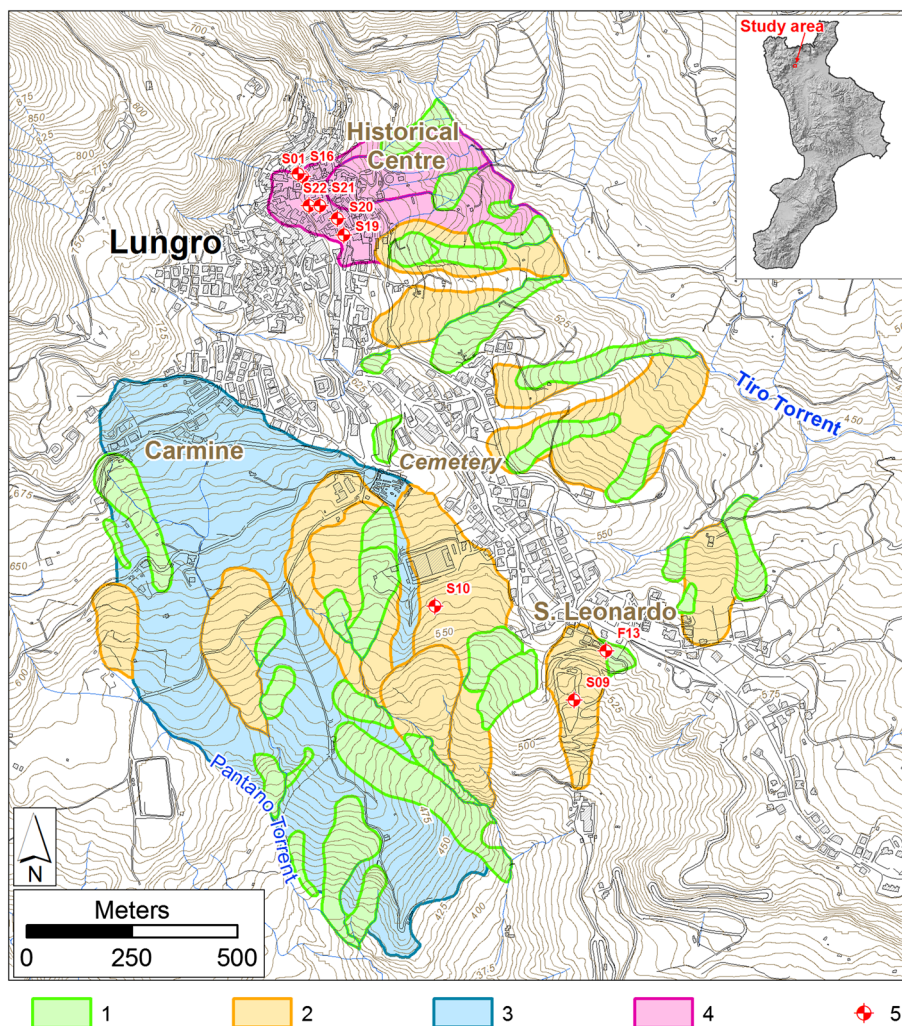| Landslide category	Lithological type	Landslide type	Estimated depth (m)	Typical area (ha)
A	Detritic-colluvial covers	Complex landslide	< 10	5
B	Degraded and chaotic phyllites	Complex landslide	10–20	10
C	Degraded and chaotic phyllites	Landslide zone	20–30	80
D	Degraded and chaotic phyllites	Slide	20–30	14

basis of geomorphological studies, between 10 and 20 m. This category also affects most of the study area. Almost all of the landslides in this category were smaller than 10 ha (average length about 350 m; average width 150 m) and occurred in slopes with an inclination lower than 15°.

The third category (C) includes those landslides affecting deeply weathered and chaotic phyllites, belonging to the landslide zone type with an estimated depth between 20 and 30 m. In the study area, this category of landslide affected the left slope of the Pantano Torrent with a gradient of 11° and an area of ∼80 ha.

Finally, the fourth category (D) includes landslides affecting degraded and chaotic phyllites, belonging to the slide type with a depth between 20 and 30 m. In the study area, this category of landslide affected the historical centre and extended over an area of 14 ha (average length about 490 m; average width 270 m) on a slope with a gradient of ∼15°.

On February 2006, the monitoring of deep seated displacements along some inclinometers, in correspondence to the areas of interest pertaining to more diffused landslides (historical centre, San Leonardo and Cemetery area), was started (Gullà et al. 2006) (Fig. 3). Monitoring results, carried out from 2006 to 2011, were used to validate the

Fig. 3 Landslide categories interfering with structures present in the study area and the location of inclinometric *vertical lines*. *1* Category A, *2* category B, *3* category C, *4* category D, *5* inclinometric *vertical lines*. For an explanation of landslide categories, make reference to the Table 2

depth of the unstable volume detected on the basis of geomorphological studies, and to acquire indications of the displacement velocities for two (categories B and D) of the four landslide categories identified. Table 3 shows minimum, medium and maximum velocity values as compared with available inclinometers for the measurements taken at one meter from ground level. By examining the values for each inclinometer related to its location, the following data emerge: in the area of San Leonardo, affected by a landslide falling within the B category, the highest velocities have been registered (average values of 10–18 cm/year); in the Cemetery area, also affected by a landslide falling into the B category, the average velocity is about 7 cm/year; finally, in the historical centre, affected by landslides falling within the D category, a group of inclinometric vertical lines shows average velocities from about 0.5 to about 2 cm/year, with a minimum value of 0.03 cm/year and a maximum value of about 5 cm/year. These sets of data globally confirm the slow-moving nature of the B and D landslide categories. Following the Cruden and Varnes (1996) landslide

Table 3 Values of displacement velocities, measured in the monitoring period considered (2006–2011) at 1 m from ground level, for the inclinometric vertical lines available

Landslide category and site	Inclinometer	v (cm/year)		
		Min	Max	Average
D	S01	0.13	2.50	0.68
Historical Centre	S16	0.10	1.55	0.54
	S19	0.48	4.97	1.99
	S20	0.03	1.88	0.72
	S21	0.17	1.62	0.64
	S22	0.05	0.35	0.18
B	S10	4.65	9.17	6.66
Cemetery area				
B	S09	5.85	16.21	9.95
San Leonardo	F13	3.60	51.10	18.45

classification based on velocity, the mentioned categories fall within the very slow (16 mm/year–1.6 m/year) and extremely slow (<16 mm/year) classes.

Evaluation of damage and assessment of the damage index (ADI)

Detailed field surveys, aimed at evaluating distribution, degree and evolution of the damage to buildings located within and near the active landslides, have been carried out using the landslide damage classification of Table 1. This classification includes six classes of damage based on the structure damage description, and does not consider the type of building technique. The assessment of building damage has also been extended to a "buffer zone" about 20 m wide, which represents an external belt of influence with respect to the landslide area. When the "buffer zone" of a landslide, belonging to one of the categories indicated above, falls within an area with a different classification, the buildings developed in such area are considered as belonging to the category of maximum extension. In the assessment of the index, only damages to buildings have been taken into account, without considering damages to infrastructures, facilities, etc.

By starting from a damage evaluation obtained through surveys carried out on buildings in 2005, after 6 years (in 2011) the framework damage was outlined both for the buildings that had suffered damages, and for those buildings that, in 2005, had displayed no signs of damage, despite the fact that they were located within a damage affected area. This calculation was possible both thanks to surveys directly carried out on such structures, and to photographic documents collected in the period considered.

The results obtained, grouped for historical centre and newly developed urban area (including the areas of San Leonardo, Cemetery and Carmine), are indicated below.

With respect to the investigated period and the damage distribution, the landslide category A is not included in the analysis.

Historical centre of Lungro

Several structures of the historical centre of Lungro are characterized by severe cracks and deformations as a consequence of the slow-moving phenomena affecting the built up area since earlier times. In particular, historical research and field surveys carried out so far highlight that the portion of the inhabited area most affected by such movements is that which was built within a landslide. This is classified as slide with uncertain boundary, including some minor sliding and sliding-flow phenomena (Fig. 2), and falls within the D category. The vast majority of the buildings falling within this area are made of masonry. The comparisons made through the use of the maps dating back to the 1950s highlight that this area shows no increase in urbanization level. Some important buildings are located

in this area, such as the Town Hall and a school. After the survey that ended in 2011, some of the damaged buildings underwent works to increase their level of safety and reduce the risk of collapse. The analysis of the available data has pointed out that, in the 2006–2011 period, an increase in the degradation of the buildings was registered in the left portion of the landslide classified as slide with uncertain boundary (Figs. 4, 5).

The damage index (ADI) for 2005 and 2011 has been calculated based on these sets of data, Table 4. In the time set considered, data indicates an increase in the number of buildings showing serious and severe damage, leading the ADI to increase by 6 %.

Newly developed urban area

The urban expansion of Lungro started in the second half of last century in the area south of the historical centre, Fig. 2. The slopes in this area—as already highlighted by the historical survey and the interpretation of aerial photos of 1954—have been affected by landslide since earlier times. Recurring remobilisations and, therefore, landslide activity, are witnessed by severe cracks and deformations in structures located on the landslide bodies or in the vicinity of the main scarps. Some buildings show severe structural degradation, others are not serviceable yet.

In particular, most buildings with severe increase in cracks and therefore in degradation, over the period considered, lay within the areas of Carmine, Cemetery, and San Leonardo.

For example, Fig. 6 shows damage evolution on a building located in the Cemetery area. In 1980, a football ground had been built here, but, successively, due to the severe damage suffered in 2000, it has been substituted by a car wash area. Another example is represented by the area of San Leonardo: over the period taken into account (2005–2011), the buildings show a significant worsening of their structural conditions, as indicated by an increase in their tilt angles, as well as by new cracks on previously undamaged buildings (Fig. 7). For the neighourhood of San Leonardo, it is important to clarify that it already underwent stabilization measures; despite this, the results of this work indicate that such measures have not reduced the landslide activity. Moreover, as Gullà et al. (2006) reported, the presence of galleries of a salt mine located at the slope foot and disused since the 1980s seems not to have produced any effect on building degradation.

Using the data taken in 2005 and 2011, the damage index applying Eq. (1) has been estimated (Fig. 8; Table 4). Table 4 shows the evolution of the ADI over time for the San Leonardo, Cemetery, and Carmine areas. In particular, the areas of San Leonardo and Cemetery are

Fig. 4 Photo survey clearly indicating the increase in lesions, across the 2005–2011 period, affecting a building located in the historical centre
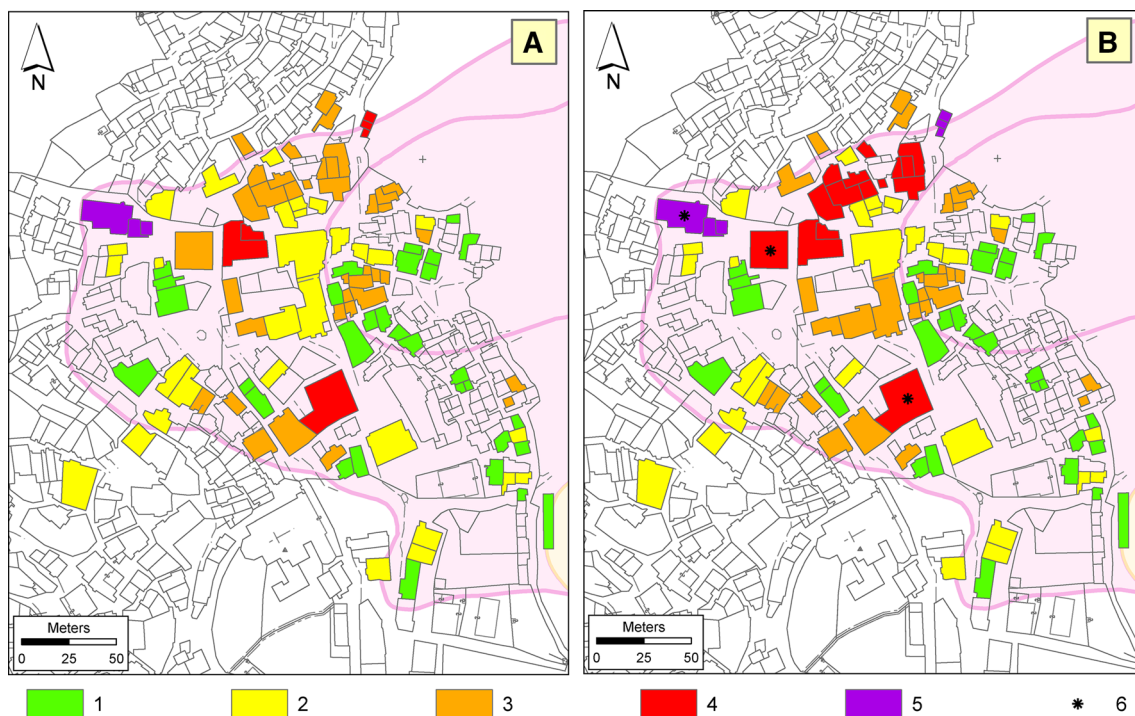

May 2005

April 2011

| | 1 | | 2 | | 3 | | 4 | | 5 | * | 6 |

Fig. 5 Historical centre of Lungro. Landslide damage to building in 2005 (**a**) and 2011 (**b**). *1* Negligible, *2* slight, *3* moderate, *4* serious, *5* severe, *6* buildings undergoing safety measures

affected by phenomena classified as complex landslides falling within the B landslide category, while the Carmine area is affected by a landslide zone falling within the C landslide category. A remarkable increase in the ADI can be observed for the buildings located along or near the

main scarp of the landslides falling into the B category (San Leonardo and Cemetery area); vice versa, a moderate increase is observed for the buildings located along or near the main scarp of the landslide zone falling into the C category (Carmine).

Table 4 Number of buildings belonging to the various damage classes and assessment of the damage index (ADI), for 2005 and 2011, in the four areas under investigation

Site and landslide category	Number of damaged buildings in each class						Aggregated Damage Index (ADI)
	None	Negligible	Slight	Moderate	Serious	Severe	
San Leonardo (B)							
2005	1	3	1	1	2	2	0.52
2011	1	1	1	2	1	4	0.66
							+27 %
Cemetery area (B)							
2005	10	3	2	2	2	0	0.22
2011	10	0	5	1	1	2	0.28
							+27 %
Carmine (C)							
2005	20	5	3	3	0	0	0.13
2011	20	5	2	1	3	0	0.15
							+15 %
Historical Centre (D)							
2005	182	31	31	36	6	1	0.16
2011	182	31	27	28	15	4	0.17
							+6 %

Fig. 6 Photo comparison showing an increase during the analysis period in the crack pattern of a building located in the Cemetery area

Discussion

The application of the macrodamage index ADI for two different years (2005 and 2011) showed that the damage evolution does not vary for the same landslide category: the areas of San Leonardo and Cemetery, falling within the landslide category B (complex landslides in degraded and chaotic phyllites with a 10–20 m depth) despite the differences in terms of macrodamage diffusion and entity, show the same ADI percentage increase (about 27 %). Moreover, data obtained through the comparison of pictures has highlighted the retrogressive character of landsliding phenomena.

The lowest ADI values (between 0.13 and 0.17) were recorded in the areas of Carmine and the historical centre (C and D categories respectively) characterized by the same depth range (20–30 m), which is higher compared to the areas of San Leonardo and Cemetery, which—instead—show higher ADI values. With reference to the factors used for the definition of the landslide categories under investigation and for the damage index, it is possible to hypothesise that depth is inversely correlated to the macrodamage index. Moreover, it seems that depth, in the time interval observed, causes a greater damage to the "slight" and "moderate" classes, as compared to the "serious" and "severe" classes. In fact, for the areas of Carmine and the historical centre, which have been affected by landslides of different categories (C and D respectively) but are located at the same depth (20–30 m), a higher number of buildings falling within the "slight" and

Fig. 7 Photo comparison showing an increase during the analysis period of tilt angles of buildings located on the edge of the landslide slope in the area of San Leonardo

"moderate" damage categories (between 20 and 26 % of the global amount of buildings) has been recorded as compared to the "serious" and "severe" classes (0–10 %).

On the other hand, a positive correlation seems to exist between landslide medium velocity and the macrodamage index. In fact, for the area of San Leonardo, showing higher displacement velocities (from 10 to 18 cm/year), an ADI with the highest values (up to 0.66) of the area under investigation has been observed. For the area of Cemetery, affected by the same landslide category but with slower displacement velocities, (6.66 cm/year on average), lower ADI values have been recorded (up to 0.28). This is also explained in Fig. 9, which shows the damage index, averaged over the investigation period, relative to the Cemetery area, San Leonardo and historical centre, related to the average displacement velocity of mass movements. The increasing trend of the interpolation curve, despite its inference from a few experimental data, clearly shows that for velocity values higher than 7 cm/year, average damage indexes significantly increase. This critical value (7 cm/year) can be considered, relative to the study case, as a threshold of the average displacement velocity of mass movements, above which it could be necessary to increase the frequency of the monitoring activity and to adopt preventive measures for ensuring public safety.

The assessment carried out shows that urban planning in this area has not taken into account the geological fragility of the slopes, mainly affected by active slow-moving landslides. Critical analysis of some historical documents highlights that the landslide problem had already been detected at the beginning of the twentieth century, and that

the most critical area was the one of the historical centre (Gullà et al. 2006). Thus, despite the awareness of slope movement, the newly developed urban area was built on landslide-prone areas.

Moreover, it is clear that—even if reinforced concrete buildings and the implementation of ad-hoc structural reinforcement measures are the most suitable elements to limit landslide damages and slow down their evolution—the same is not a solution to the problem per se. In fact, the building of reinforced concrete structures does not guarantee lower landslide damage, if slope stabilisation measures are not implemented. Vice-versa—as shown by damage assessment in the historical centre—masonry buildings can guarantee a less relevant and widespread damage, despite the fact that they are located in a landslide area with specific features; in fact, the ADI values in the area are the lowest that were recorded in the whole area under investigation. On the contrary, if the damage evolution as assessed in the area of San Leonardo remains the same, in a time span of 20 years, starting from 2006, the area would be completely affected by severe damages.

Conclusion

This work proposes to analyse the relationship between some characteristics of landslides and the building damage evolution through a macrodamage index in an area (southern Italy) affected by slow movements, which, over time, have caused relevant effects on the urban centre.

Fig. 8 Newly developed urban area of Lungro. Landslide damage to building in 2005 (**a**) and 2011 (**b**). *1* Negligible, *2* slight, *3* moderate, *4* serious, *5* severe
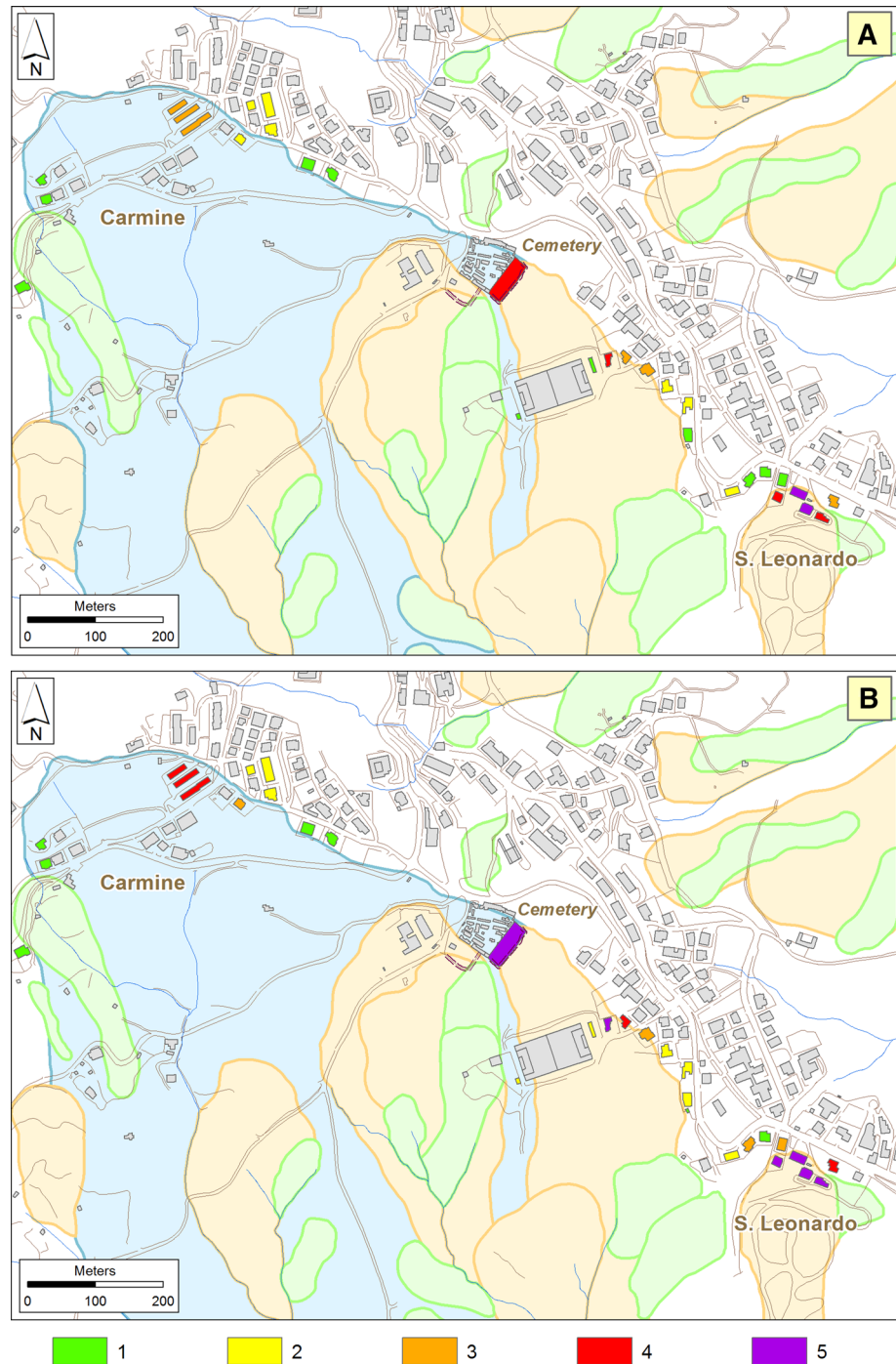
A series of geological and geomorphological studies and field surveys, supported by monitoring via conventional geotechnical techniques, allowed us to classify four categories of landslides based on the following criteria: landslide movement, type of material and estimated depth. Moreover, for two of these categories, the geotechnical surveys of deep seated displacements assessed velocities. The time evolution of the macrodamage index was analysed and correlated to the features of the movements.

The results showed an inverse correlation between the macrodamage index and the depth of the mass movement. Vice-versa, a positive correlation seems to exist between average displacement velocity of landslides and the macrodamage index.

The obtained results have also highlighted that the reinforced concrete structures do not always guarantee a lower landslide damage, if they are not accompanied by slope stabilization measures. On the contrary, masonry
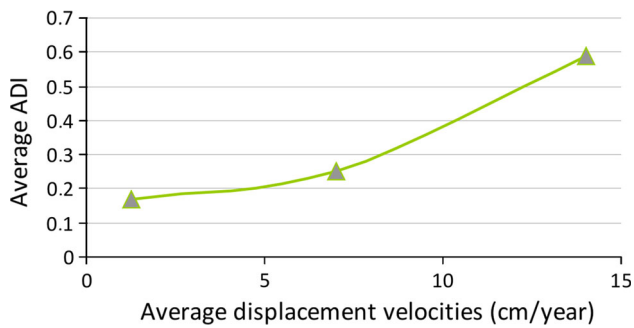
Fig. 9 Average damage index over the whole period of observation versus average displacement velocities of mass movements

buildings, even if located in a landslide area with specific features, can suffer a not relevant and widespread damage.

The indications provided can be employed to reorganize the integrated monitoring network, and to systematically check damage evolution for a better territorial management. The results can surely provide a useful tool to plan and design risk mitigation measures for the town of Lungro, as well as to suggest the necessary reclaiming works.

The simple approach introduced and used in this work, as well as the ADI macrodamage index, can be applied to other case studies with the aim to plan an ad-hoc monitoring campaign of structures affected by damages caused by slow-moving landslides, and develop maintenance measures. In fact, as pointed out in this study, the detection of a threshold value of the landside velocity above which the macrodamage index rapidly rises, may suggest the need to increase the monitoring of structures in time and space, and thus to plan repair measures.

Finally, by improving the macro-damage index introduced in this work, another index that permits collection of indicative values of the repairing costs for zones of urban areas affected by slow-moving landslides can be assessed.

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