

# A procedure for the analysis of building vulnerability to slow-moving landslides

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**Abstract** – Slow-moving landslides yearly induce huge economic loss worldwide in terms of damage to structures/infrastructures and interruption of human activities as well. Within the landslide risk management framework, the vulnerability analysis is a key step entailing procedures mostly based on the identification of the exposed elements, the damage classification and the definition of an intensity criterion.

The present paper introduces a two-scale procedure for the analysis of building vulnerability to slow-moving landslides. The intensity parameter (i.e. absolute or differential settlement) derives from the information provided by Differential Interferometric Synthetic Aperture Radar (DInSAR) satellite data, which in the last decade proved to be capable of providing cost-effective long-term displacement archives of structures/infrastructures.

The obtained results over two slow-moving landslide-affected areas allowed the generation of empirical fragility curves for masonry buildings that, once further validated, can be valuably used for damage analysis and forecasting.

## I. INTRODUCTION

Amongst natural hazards, landslides have one of the highest impact worldwide in terms of loss of life and injury to people as well as loss of and damage to public and private buildings, infrastructure, lifelines, agricultural lands and economic activities.

As for slow-moving landslides, even if they usually have a low probability of generating “catastrophic” events (i.e. a significant loss of human life) they can have considerable social and economic consequences [1, 2]. For this reason, studies pursuing slow-moving landslide risk analysis for properties [3] are of great interest to both the scientific and technical community in order to identify the most appropriate strategies for urban planning and risk mitigation by means of structural and/or non-structural works. In this regard, fundamental

steps in the landslide risk analysis [3] are represented by analyses of hazard and consequences to the exposed elements.

As for consequences (given by the product of vulnerability of buildings for their value), they have been slightly addressed in the scientific literature, in particular at large scale [3], as they require a deep knowledge on characteristics of both landslides (e.g. volume, velocity, displacements, etc.) and exposed elements (stiffness/strength, state of maintenance, value, etc.). Indeed, their estimation is complicated by overlaying factors [4] such as: the strongly site-specific nature of landslides; the spatial distribution of the landslide intensity and its variability; the quantitative heterogeneity of vulnerability of different elements at risk for qualitatively similar landslide mechanisms; the lack of extensive data inventories of structural damages and the variability of vulnerability over the time.

The availability of a damage inventory is essential in the estimation of the consequences on properties interacting with slow-moving phenomena (e.g. large landslides on fine-grained soils). In particular, a back-analysis of induced damages to built-up areas allows detecting the spatial distribution of damages depending on landslide types and intensity [5] and, accordingly, defining a procedure for consequence analysis.

Focusing on landslide intensity, and particularly referring to the displacement rates of both the unstable masses and structures/infrastructures with them interacting, in addition to conventional monitoring techniques (i.e. inclinometers, GPS, topographic leveling) useful information may be derived via Synthetic Aperture Radar satellite data processed via Differential Interferometric (DInSAR) techniques. These latter, in the previous decade, have proven effective for extensively monitoring structures/infrastructures on unstable slopes [6, 7, 8] also being able to complement superficial and deep displacement monitoring [8]. Several SAR archives are currently available spanning a long time interval of about 20 years, at different scale of spatial resolution,

from the high resolution (i.e. the former generation ERS1-2, ENVISAT, RADARSAT1-2 and the current Sentinel-1 missions, all operating at C-band) to the very high resolution SAR sensors (i.e. Cosmo-SkyMed, TerraSAR-X missions, both currently operating at X-band). The former group of sensors is more suitable for large scale analyses and the latter, thanks to the meter-scale resolution, is capable of following the behavior even of single detected structures/infrastructures [9].

This paper presents the results of the application of an original procedure for the analysis of vulnerability to slow-moving landslides at two different scales for both building aggregates (at large scale) and single buildings (at detailed scale). In particular, the intensity parameter derives from DInSAR data at either high- or very high-resolution and the damage assessment results from in-situ damage surveys.

## II. VULNERABILITY ANALYSES

Within landslide risk analysis, the analysis of consequences to buildings includes identifying the elements at risk and assessing their vulnerability [3].

The former activity involves detecting and classifying the exposed buildings [10, 11] on the basis of reliable information – to be collected via image processing and field surveys – dealing with some relevant building characteristics (including the age of construction, structural and foundation typologies, occupancy type, number of floors, etc.).

In analyses at large scale, in order to overcome the difficulties associated with time consuming data collection [10], the use of aggregated levels (e.g. homogeneous groups of buildings) is recommended. The scientific literature counts few contributions regarding this subject, and even less concerning the geometrical individuation of such homogenous aggregations [6, 12].

According to [13], the vulnerability of buildings expresses the degree of loss of a given building or set of buildings at risk when they mechanically interact with a given landslide of given intensity. It can be assessed in terms of structural damage or in terms of operation failure. In particular, it depends on both the landslide type mechanism and related intensity (i.e. differential displacements and/or their velocity whose spatial attributes result, for instance, from the location of the exposed element in the area affected by a slow-moving landslide) and the above-mentioned building characteristics.

The outcomes of vulnerability analysis can be achieved via different methods: the direct approach and the event tree approach for a qualitative assessment based on empirical data [14] and expert judgment [15]; the consequence model [5] involving a rational framework based on key factors affecting the consequence of failure [16].

Among consequence models, “fragility curves” –

developed in the field of the earthquake engineering for quantifying the expected damage of single facilities at detailed scale – can be mentioned. These curves provide the conditional probability for every element at risk to be in, or exceed, a certain damage state under a landslide event of given intensity. Based on the scale of the study area, the availability and quality of input data as well as the local construction technology [17, 18] four main categories of fragility curves can be distinguished: empirical, engineering judgmental, analytical and hybrid.

Three main types of input data are necessary: damage scale; building typology; intensity criterion/parameter.

Up to now few examples of slow-moving landslide fragility/vulnerability functions were proposed [17, 18].

## III. THE PROPOSED PROCEDURE

The proposed two-scale procedure for the analysis of building vulnerability to slow-moving landslides includes (Fig.1): a first phase (Phase I) in which elements at risk are identified; a second phase (Phase II) including damage classification as well as the selection of an intensity parameter; a final phase (Phase III) leading to the construction of fragility curves.

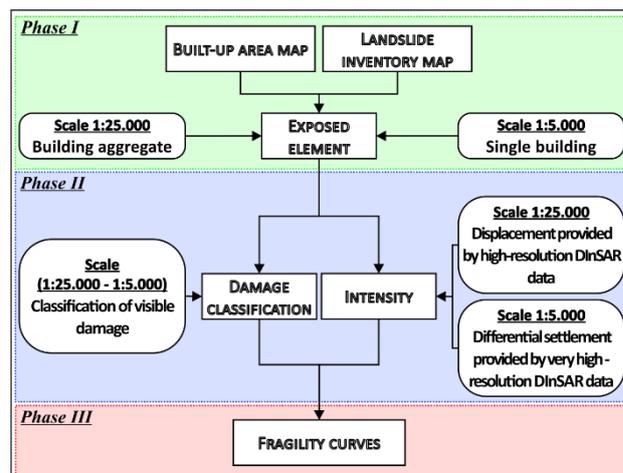


Fig. 1. Flowchart of the proposed procedure for the vulnerability analysis.

As for the exposed elements (Phase I), depending on the scale of analysis, they coincide with either building aggregates (1:25,000 scale) or single buildings (1:5,000 scale). In the present study, building aggregates located on landslide-affected areas (i.e. “vulnerable areas” [6, 13]) were identified based on topographic maps, landslides inventory maps (at 1:25,000 scale) and urban plans following the procedure described in [6] and, then, homogenized according to the structural typology. Similarly, single buildings at 1:5,000 scale were identified using topographic and landslide inventory maps (1:5,000 scale).

In Phase II, damage is classified according to the scale of analysis and the specific exposed elements. In particular,

at 1:25,000 scale “vulnerable areas” were first identified and, then, the analysis of surveyed damage was carried out based on data collected via fact sheets. The latter concern: the occupancy type; the geometric description of the element at risk; the date of damage occurrence; the description of the damage, specifying whether it concentrates either on structural or non-structural elements; the state of maintenance and so on.

The availability of fact sheets allowed the qualitative classification of damage in four severity classes (D0 = no damage; D1 = slight; D2 = moderate; D3-D4 = from severe to very severe) (modified from [5, 12]). Subsequently, according to [13] the equivalent damage of one vulnerable area coincides with the weighted average of the individual damage suffered by buildings included in the vulnerable area.

At 1:5,000 scale ad-hoc predisposed fact-sheets (modified from [7]) were filled in for surveyed buildings, thus providing an overview of the built-up area characteristics, state of maintenance and damage severity. This latter was, in turn, differentiated in six classes (D0 = no damage; D1 = very slight; D2 = slight; D3 = moderate; D4 = severe; D5 = very severe) adapted from a more detailed classification of damage to buildings provided by [19].

The intensity parameter at 1:25,000 scale corresponds to the cumulative displacement recorded by the vulnerable area. This parameter derived from high-resolution ERS1-2 and ENVISAT DInSAR data analysis. In particular, each building was first associated with a DInSAR-derived cumulative displacement by multiplying the estimated average displacement velocity for the period of observation. Then, the average of building cumulative displacements within the vulnerable area weighted on the number of DInSAR benchmarks covering each building was computed (modified from [6]).

At 1:5,000 scale, the intensity parameter is associated with the differential settlements derived from the analysis of very high-resolution Cosmo-SkyMed DInSAR cumulative settlements for each building.

In Phase III (Fig. 1), by specializing the procedure proposed by [17, 18, 20], fragility curves can be derived for either building aggregates (1:25,000 scale) or single buildings (1:5,000 scale) merging the information gathered on damage severity and magnitude of the intensity parameter (i.e. cumulative displacement at 1:25,000 scale or differential settlements at 1:5,000 scale).

#### IV. ANALYSIS AT LARGE SCALE

The test area (557 km<sup>2</sup>) includes 21 Municipalities within the territory of the National Basin Authority of “Liri-Garigliano and Volturno” rivers (Benevento Province, southern Italy). Its territory counts several slow-moving landslides (covering around 25% of the extension of the test area) which caused losses to structures/infrastructures

[6]. Base (i.e. topographic) maps at 1:5,000 scale and thematic (i.e. geological, geomorphological, landslide inventory) maps at 1:25,000 scale, developed for the PsAI-Rf (Hydrogeological Setting Plans – Landslide Risk excerpt) project (Italian Law 365/2000) are available. The geological map of the area highlights the existence of Mesozoic-Tertiary lithological units mainly consisting of clayey-sandy-arenaceous and clayey-calcareous-siliceous strata covered by marly-calcareous, arenaceous and arenaceous-conglomeratic units [6 and citations therein]. These latter units together with the geo-structural setting mainly control the geomorphological features of the area. As for the available landslide inventory (Fig.2) a total of 2,180 slow-moving landslides are mapped: 766 rotational slides; 267 rotational slide–earth flows; 1,117 earth-flows; 30 deep seated gravitational slope deformations (DSGSD); moreover, 158 creep phenomena, 65 earth flow-creeps and 2 rotational-creeps were also inventoried [6].

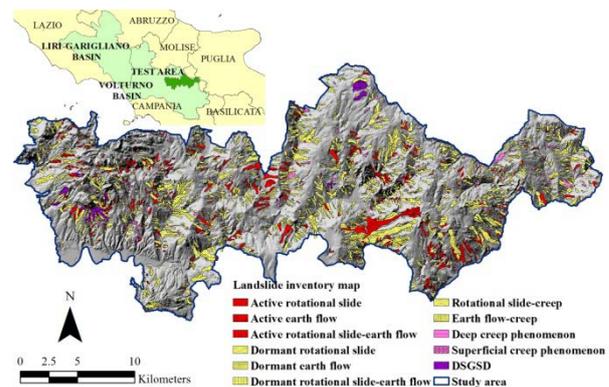


Fig. 2. The landslide inventory map (1:25,000 scale) for study area [6].

DInSAR displacement data (Fig. 3) used for the present study were collected within the Italian *Piano Straordinario di Telerilevamento* (2010). They include 208 ERS images on ascending orbit (period September 1992 – September 2000) and 134 on descending orbit (period November 1992 – December 2000).

The dataset of landslide-induced building damage consists of damage fact-sheets compiled during an extensive survey carried out in 2001.

The data analysis revealed the presence of 95 damaged buildings (all of masonry typology) whose severity ranges from D1 to D3-D4.

Then, over a total number of 27 vulnerable areas, for which both DInSAR data and the results of the damage survey were available, the average cumulative displacement and the corresponding equivalent damage were computed.

By merging the above information, the relationship in Figure 4 was derived.

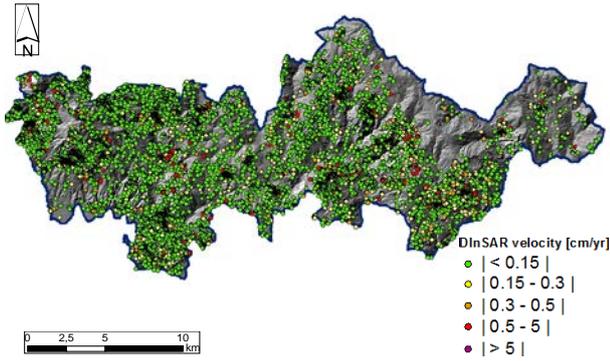


Fig. 3. ERS DInSAR data distribution.

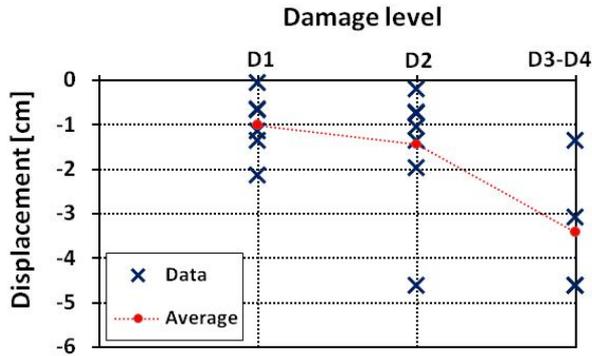


Fig. 4. Cumulative displacement vs. damage severity for masonry building aggregates over the study area.

Finally, by adopting a log-normal distribution [18], empirical fragility curves were derived for masonry building aggregates in the study area (Fig. 5) with reference to slight, moderate and severe to very severe damage level.

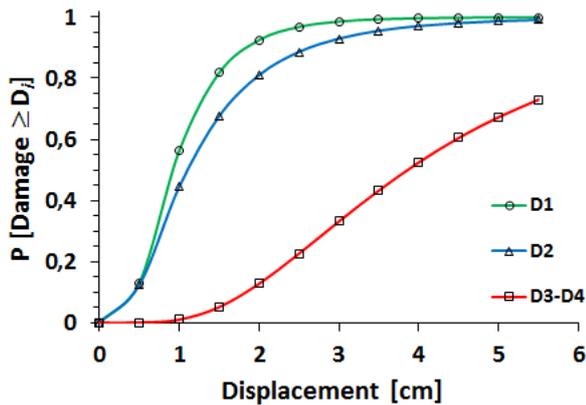


Fig. 5. Empirical fragility curves for masonry building aggregates over the study area.

## V. ANALYSIS AT DETAILED SCALE

The analysis at detailed scale refers to Lungro urban area (Fig. 6) (Calabria region, southern Italy) that from a geological point of view shows the presence of the Lungro-Verbicaro Unit, dating back to the Middle Trias, made up of metapelites and metacarbonates [8]. The inventory map of typified landslides (Fig. 6),

prepared following the procedure proposed by [8], shows that several landslides affect the area. These phenomena were distinguished in six typified categories (Tab. 1) that from a kinematic point of view present the following characteristics: (i) T\_A1 landslides with ordinary velocity from 2 to 4 cm/year and critical velocity higher than 200 cm/year; (ii) T\_A2 landslides with ordinary velocity from 5 to 7 cm/year and critical velocity higher than 20 cm/year; (iii) T\_B1 landslides with ordinary velocity from 0.5 to 5 cm/year and critical velocity higher than 80 cm/year; (iv) T\_B2 landslides with ordinary velocity from 4 to 20 cm/year and critical velocity higher than 100 cm/year; (v) T\_C landslides with ordinary velocity from 0.5 to 5 cm/year and critical velocity higher than 40 cm/year; (vi) T\_D landslides with ordinary velocity from 0.2 to 0.5 cm/year and critical velocity from 2 to 5 cm/year.

Table 1. Characteristics of typified landslides [8].

LT	Width (W) [m]	Length (L) [m]	L/W	Depth [m]	Velocity [cm/year]		Geomaterial	kinematic_ TYPE
					ordinary	critical		
T_A1	25-100	$\leq 180$	$\leq 2.5$	about 6	2-4	$> 200$	detritic-colluvial covers	complex landslide
T_A2	15-100	$\geq 80$	$> 2.5$	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	$> 300$	$\geq 2.5$	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

The SAR image dataset used in the present study was processed according to the SAR tomographic analysis [23], which is particularly effective for single building monitoring with very high-resolution data. It consists of 64 ENVISAT images acquired on both ascending (no. 35, August 2003 to January 2010) and descending (no. 29, May 2003 to February 2010) orbits as well as 39 COSMO-SkyMed images acquired on ascending orbit from October 2012 to April 2014. It is worth noting that the Cosmo-SkyMed mission, composed by a constellation of four satellites, is currently the most advanced operational SAR system particularly effective for monitoring purposes of the built environment thanks to the very high spatial resolution of the acquired images as well as to the very fast acquisition scheduling of the multi-sensor mission. Figures 6a-b show the distribution of DInSAR coherent pixel derived from ENVISAT and Cosmo-SkyMed data, highlighting the significant coverage increase achieved by the latter higher quality dataset and the highest velocity values recorded in the central-eastern portion of the historic centre mainly affected by T\_D landslides.

The analysis of available damage datasets (1812 – 2011) indicates that frequently Lungro historic centre was severely affected by slow-moving landslides [8, 24]. Furthermore, a damage survey, carried out in October 2015 over the entire urban area, revealed that 111 buildings are in landslide-affected areas (Fig. 7a). For the purpose of the present study, the analysis then

focused on 49 buildings (37 reinforced concrete and 12 masonry ones) located on landslides and covered by at least two coherent pixels in both ENVISAT and Cosmo-SkyMed datasets. In Figure 7b and 7c the distribution of different levels of recorded damage is shown referring, respectively, to building typology and typified landslides.

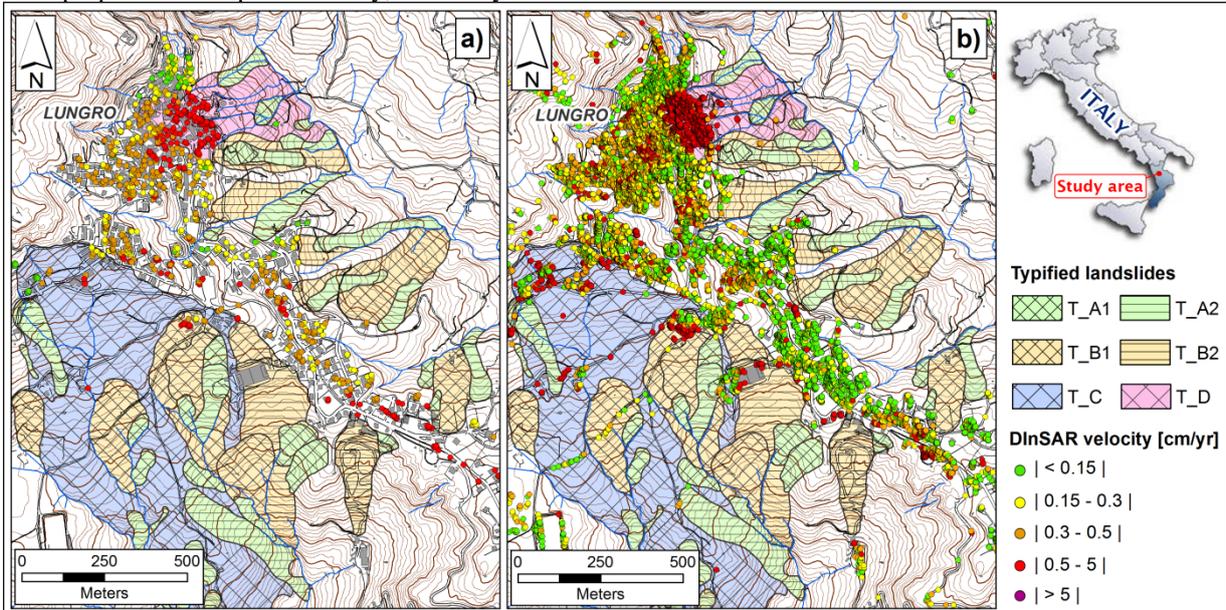


Fig. 6. The study area and the landslide inventory map overlaid by a) ENVISAT and b) Cosmo-SkyMed DInSAR data.

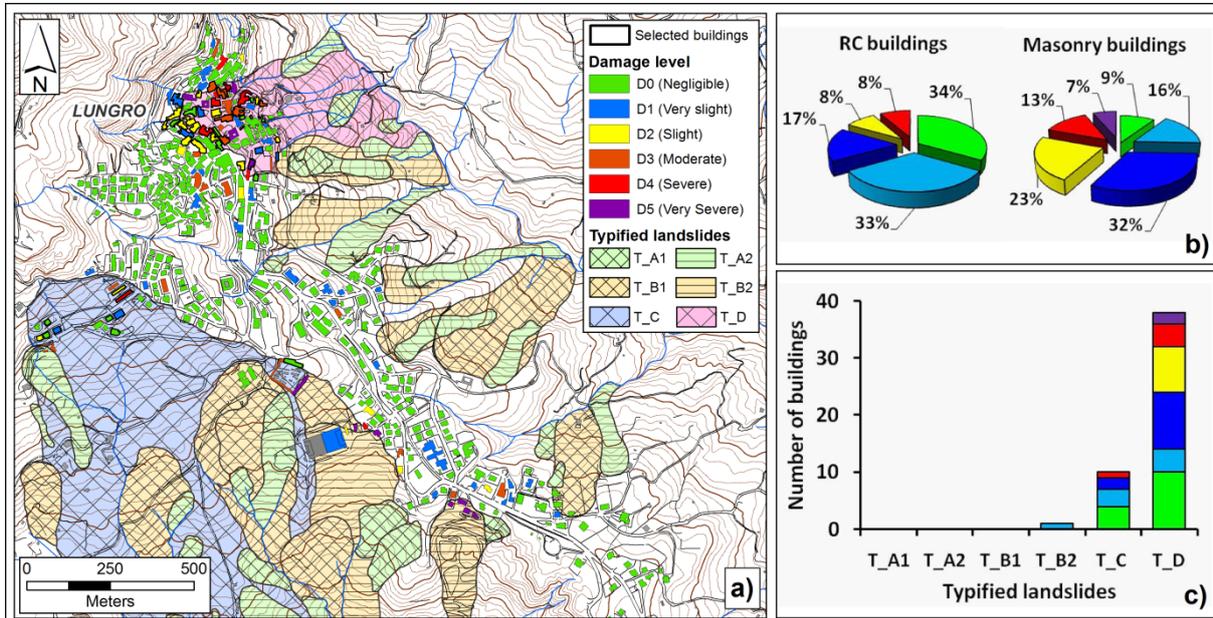


Fig. 7. a) Results of 2015 damage survey; distribution of damage level according to building typology (b) and typified landslides (c).

Then, differential settlements were computed for each building as the maximum difference of the cumulative settlements recorded by the coherent pixels within its perimeter. In particular, 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 available dataset. Moreover, for the period February

2010 - October 2012, when DInSAR data were lacking, a constant velocity value equal to the one associated to the longest available dataset (i.e. ENVISAT) was assumed. The merge of the above information with the results of the damage survey allowed retrieving the relationship between differential settlements and the level of damage for both reinforced concrete (Fig. 8a) and masonry (Fig. 8b) buildings located on different typified landslides within Lungro area.

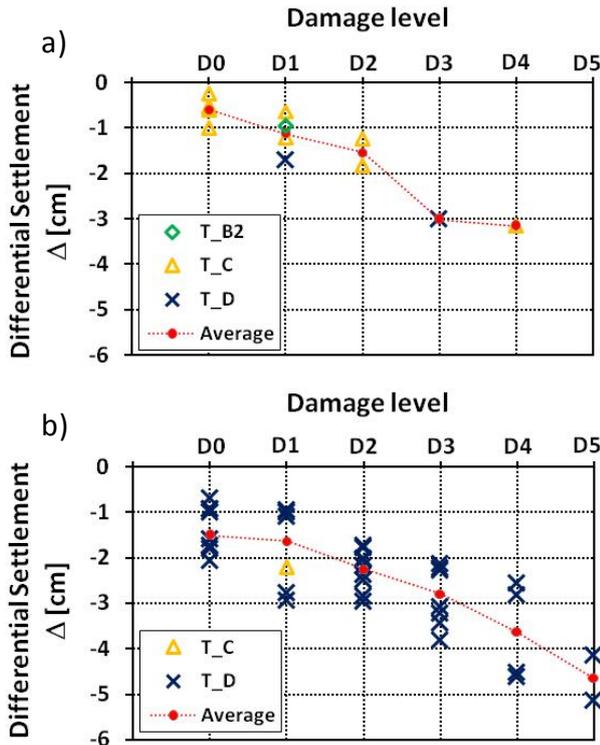


Fig. 8. Damage level vs. differential settlements for a) reinforced concrete and b) masonry buildings.

Finally referring to masonry buildings, whose sample included structures suffering from damage level spanning from D1 to D5, empirical fragility curves were derived by adopting a log-normal distribution [18], Fig. 9.

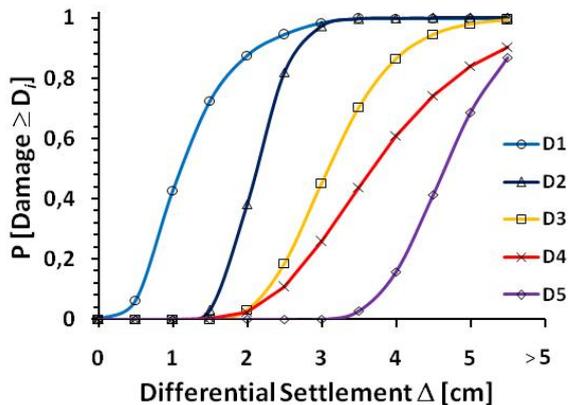


Fig. 9. Empirical fragility curves for masonry buildings in Lungro area.

## VI. DISCUSSION AND CONCLUSION

The proposed procedure for the analysis of building vulnerability to slow-moving landslides allowed the retrieval of preliminary relationships between the damage severity and the selected DInSAR-derived intensity parameters (i.e. cumulative displacement and differential settlements) at two different scales of analysis and for two different structural typologies (i.e. reinforced concrete and masonry buildings). The results highlight a general increasing trend of damage severity with intensity, independently from both the scale of analysis and the structural typology. The advantage of using such a widespread information as DInSAR data also brought to the preliminary generation of empirical fragility curves that, once further validated, may open new perspectives for helping authorities in charge of land use planning to select most suitable zones to be urbanized also addressing restoration and adaptation policies.

## ACKNOWLEDGEMENTS

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