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Probabilistic analysis of vulnerability of buildings to slow-moving landslides: a study in two municipalities in southern Italy

Analyse probabiliste de la vulnérabilité des bâtiments exposés à des glissements de terrain lents: une étude dans deux municipalités du sud de l'Italie

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ABSTRACT: The paper presents a probabilistic analysis of the vulnerability of buildings interacting with slow-moving landslides. With reference to two municipalities of the Calabria region (southern Italy) severely affected by this type of slope instabilities, the combination of data collected by way of expeditious damage surveys with building settlements retrieved from the use of Differential Interferometry Synthetic Aperture Radar (DInSAR) techniques allows generating separate couples of empirical fragility and vulnerability curves for the two investigated urban areas. The comparison of the obtained results highlights that the use of such tools for damage forecasting purposes in other landslide-affected areas requires selecting – from a statistical point of view – building samples belonging to the same data population (i.e. referring to homogeneous land-urban systems).

RÉSUMÉ: Le document présente une analyse probabiliste de la vulnérabilité des bâtiments exposés à des glissements de terrain lents. En ce qui concerne deux municipalités de la région de Calabre (sud de l'Italie) gravement touchées par ce type d'instabilités des pentes, la combinaison de données collectées au moyen d'enquêtes rapides sur les dommages et des tassements extraites de l'utilisation des techniques du radar à ouverture synthétique à interférométrie différentielle (DInSAR) permet de générer des couples distincts de courbes de fragilité et de vulnérabilité empiriques pour les deux zones urbaines étudiées. La comparaison des résultats obtenus montre que l'utilisation de tels outils à des fins de prévision des dommages dans d'autres zones touchées par des glissements de terrain nécessite la sélection - d'un point de vue statistique - d'échantillons de bâtiments appartenant aux mêmes données de population (c'est-à-dire se référant à des systèmes homogènes urbain-territoriaux).

Keywords: slow-moving landslides; settlements; damage; masonry buildings; fragility/vulnerability curves

1 INTRODUCTION

The interaction of slow-moving landslides with the built environment is often associated with consequences to the exposed facilities (e.g. buildings, infrastructure). Therefore, the prediction of these consequences has become a relevant issue under both the scientific and technical perspectives in order to identify the most suitable strategies for land-use planning and urban management. For geotechnical engineers involved in setting-up reliable forecasting models at site-specific scale, rich datasets are necessary. These should encompass a thorough knowledge on *i)* soil properties, *ii)* landslide mechanisms and their intensity (e.g., displacement rates, absolute/differential displacements), *iii)* exposed building characteristics (e.g., structural and foundation typology, state of maintenance). When addressing analyses at municipal scale less data-demanding approaches such as empirical ones can turn out to be useful (Mansour et al., 2011; Peduto et al., 2017a).

In this regard, this paper presents a probabilistic approach for the analysis and prediction of the damage to buildings in areas affected by slow-moving landslides by means of empirical fragility and vulnerability curves. As a recent breakthrough in geotechnical engineering (Peduto et al., 2017a, 2017b), these probabilistic analyses combine the results of expeditious visual building damage surveys with measurements of building settlements derived from the differential interferometric processing of satellite synthetic aperture radar images (DInSAR). The latter represents a well-established remote sensing technique that, in the last decades, thanks to its accuracy/precision (Nicodemo et al., 2016; Peduto et al., 2017a, 2018), successfully proved to complement with conventional techniques for slow-moving landslide detection and monitoring (Gullà et al., 2017) as well as to analyse the behaviour of buildings interacting with landslide-affected areas (Ferlisi et al., 2018; Peduto et al., 2017a, 2018).

Hereafter, both fragility and vulnerability curves are first generated for two well-documented case studies in Calabria region (southern Italy) where several slow-moving landslides affect the urban areas; then, the obtained results are compared in order to discuss their exportability to other municipalities exhibiting similar landslides and features of the built environment.

2 CASE STUDIES AND AVAILABLE DATA

The selected case studies correspond to the well-documented urban areas of Lungro and Verbicaro municipalities in the northern sector of the Calabria region (southern Italy) (Ferlisi et al., 2018; Gullà et al., 2017; Nicodemo et al. 2017; Peduto et al. 2016, 2017a, 2018).

The urban area of Lungro (Fig. 1a), located in a geological context where the Lungro-Verbicaro Unit dating back to the Middle Trias and made up of metapelites and metacarbonates prevails (Gullà et al. 2017), is widely affected by slow-moving landslides of different types (Fig. 1a). The latter interact with masonry buildings – mainly located in the historic centre – and reinforced concrete buildings located in the south-east area of the old centre.

Independently of the structural building typology, this interaction led to damages (Fig. 1a) whose severity levels were recorded by way of in-situ surveys (Ferlisi et al., 2015; Nicodemo et al., 2017) and categorized by adapting the classification system proposed by Burland et al. (1977) on the basis of the visual interpretation of crack patterns (D0 = negligible; D1 = very slight; D2 = slight; D3 = moderate; D4 = severe; D5 = very severe).

Quite similar geological setting and landslide types as well as urban fabric features can be found in the Verbicaro municipality (Fig. 1b). The whole urban area lays on the Frido Unit that is constituted by low-grade metamorphic rocks, usually marked by extensional brittle–ductile shear zones, and includes metapelites, phyllites, shales and metalime-stones, tectonically overlaid to the Lungro–Verbicaro Unit (Borrelli et al., 2018). Verbicaro is composed by a historic centre – mainly characterized by masonry buildings on shallow foundations – and newly developed areas with reinforced concrete buildings built since the early 1960s. In these areas, slow-moving landslide-affected buildings (Fig. 1b) recorded damages of different severity even compromising their stability.

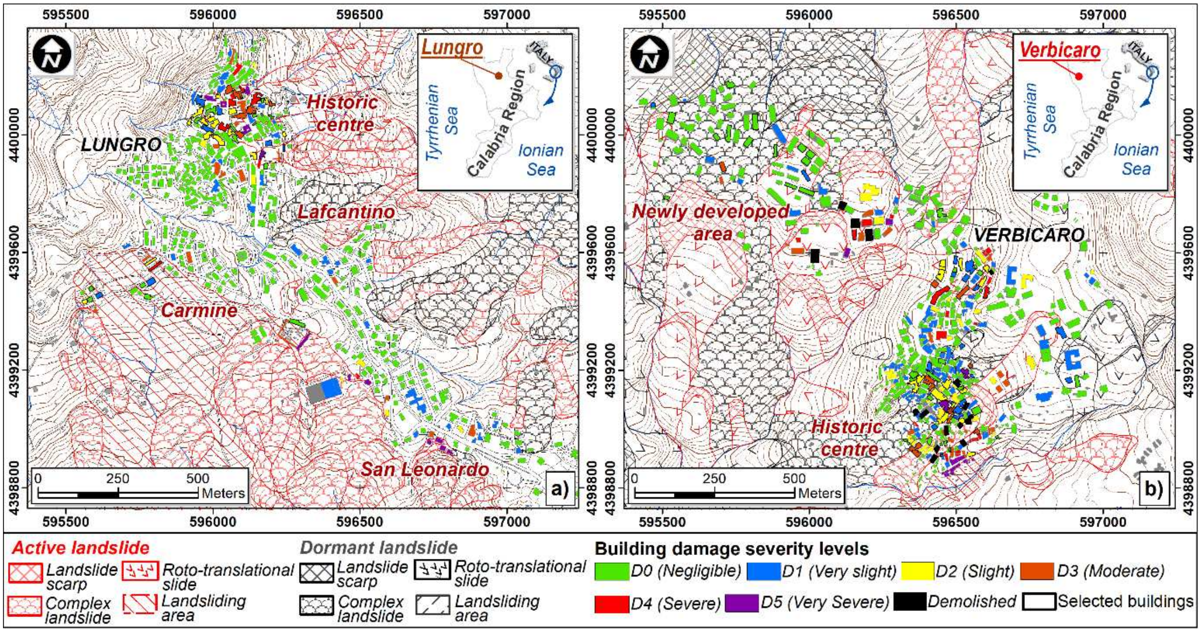


Figure 1. The study areas of a) Lungro and b) Verbicaro: inventory maps of the slow-moving landslides classified based on their state of activity and surveyed buildings distinguished according to the recorded damage severity levels.

In both study areas, damage affects both reinforced concrete and masonry buildings (Fig. 1). In particular, in Lungro urban area the collected data highlight that out of 291 reinforced concrete and 183 surveyed masonry buildings, 44% and 60%, respectively, recorded damage (i.e. whose severity is higher than D0); whereas in the Verbicaro urban area, the percentages equal 34% and 50%, respectively, for a total of 253 reinforced concrete and 239 masonry surveyed buildings.

For both municipalities, measurements of building settlements derived from the interferometric processing of satellite synthetic aperture radar images (DInSAR) via the tomographic analysis (Fornaro et al. 2009, 2014), which is a recent processing framework particularly effective for very high-resolution single building monitoring (Nicodemo et al., 2018; Peduto et al. 2019). In particular, the SAR dataset consists of 35 ENVISAT images acquired on ascending orbit in the period August 2003 to January 2010 as well as 39 COSMO-SkyMed images acquired on ascending orbit from October 2012 to April 2014. The distribution of DInSAR velocities is shown respectively for ENVISAT and COSMO-SkyMed radar sensors in Fig. 2a and Fig. 2b over Lungro area and in Fig. 2 c and Fig. 2d over Verbicaro area.

3 METHODOLOGY

The methodology used for the generation of both empirical fragility and vulnerability curves is the one proposed by Peduto et al. (2017a).

Three input data are considered, namely: building typology; damage scale; intensity parameter. First, the exposed buildings are identified by intersecting – in a GIS environment – the information gathered from the map of built-up area with the landslide inventory map also distinguishing reinforced concrete and masonry building. As for the damage scale, as previously said, the classes proposed by Burland et al. (1977)

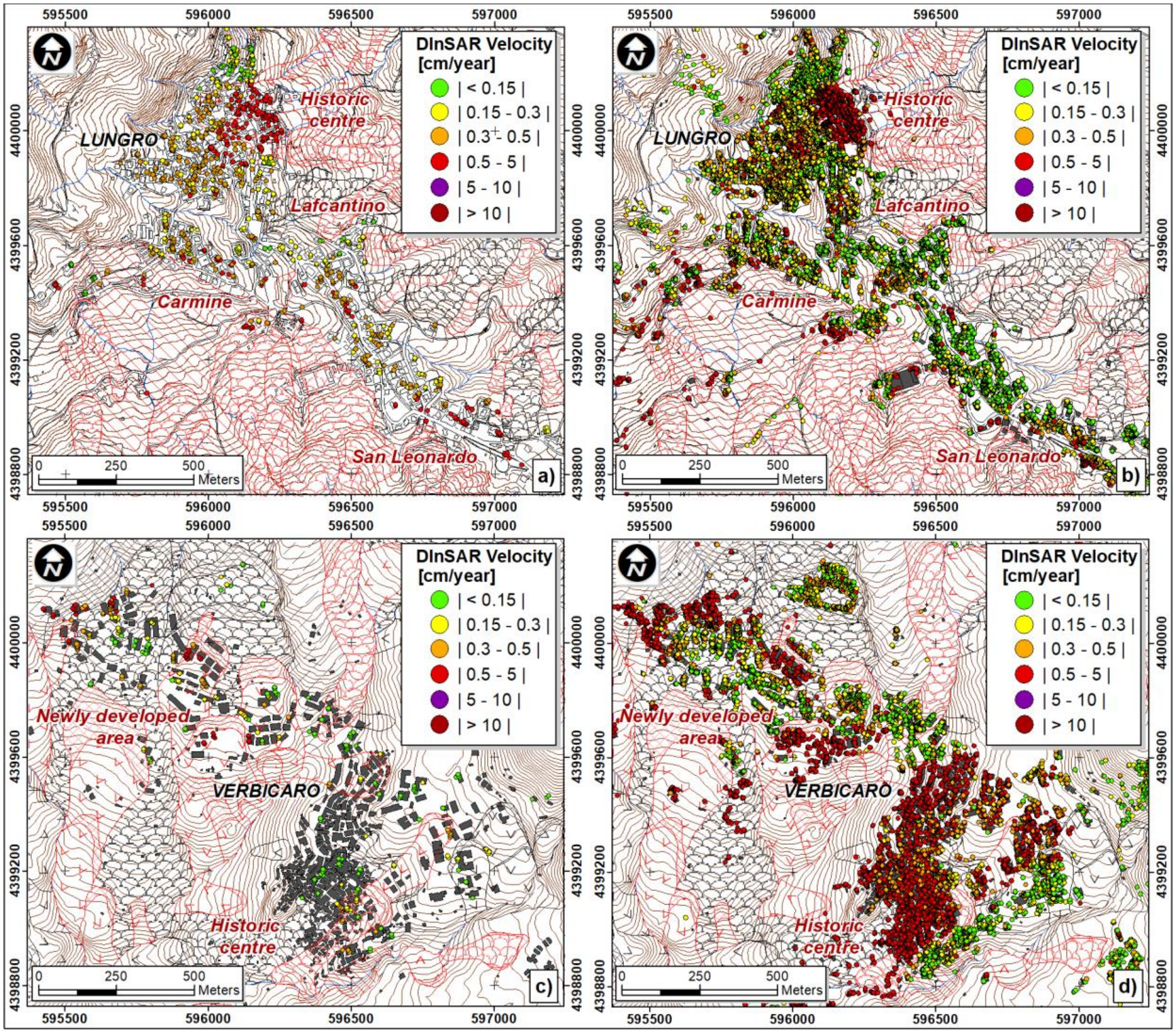


Figure 2. DInSAR velocity distribution derived from SAR images acquired on ascending orbit by ENVISAT (period 2003–2010) radar sensor over the Lungro (a) and Verbicaro study areas (c) and acquired on ascending orbit by COSMO-SkyMed (period 2012–2014) radar sensor over the Lungro (b) and Verbicaro study areas (d).

are assigned during in-situ visual inspections using ad-hoc predisposed fact-sheets (Ferlisi et al. 2015; Nicodemo et al. 2017).

The selected intensity parameter is the differential settlement (Δ), which is computed as the maximum difference of the cumulative settlements (derived by multiplying the DInSAR velocity along the vertical direction for the observation period of the available SAR dataset) recorded by the DInSAR benchmarks within the building perimeter (Nicodemo et al. 2016, 2017 2018; Peduto et al., 2016a, 2017a, 2017b).

Starting from these input data, empirical fragility curves, which provide the conditional probability P(•) for a randomly selected building at risk to be in, or exceed, a certain damage severity level (Di) when the intensity parameter (Δ) equals a given value, are generated using the Eq. 1 (Peduto et al., 2017a, 2017b; Nicodemo et al., 2017; Ferlisi et al., 2018):

$$\mathrm{P}(\mathrm{Damage} \geq \mathrm{D_i}) = \phi\left[\frac{1}{\beta_i} ln\left(\frac{\Delta}{\overline{\Delta}_i}\right)\right] \tag{1}$$

To this aim, a log-normal distribution function ϕ[] is used as probabilistic model where the fragility parameters (median $\overline{\Delta}_i$ and standard deviation β_i) are computed using the maximum likelihood method according to Shinozuka et al. (2000).
Then, the empirical vulnerability curve, which relates the expected mean level of damage severity (μ_D) to a given building and the value of the landslide intensity parameter (Δ), is derived. For this purpose, first the $\mu_D(\Delta)$ data are obtained by adapting the Eq. 2 (Pitilakis and Fotopoulou, 2015), wherein the discrete probability P_i associated with each damage severity level Di (extracted from the generated fragility curves) is multiplied for a numerical index d_i (taken for this application as 1, 2, 3, 4, and 5 for D1, D2, D3, D4, and D5, respectively).

$$\mu_D(\Delta) = \sum_{i=1}^{5} \mathrm{P_i} * \mathrm{d_i} \tag{2}$$

Finally, $\mu_D(\Delta)$ data are fitted using as regression model the tangent hyperbolic function (Lagomarsino and Giovinazzi 2006):

$$\mu_D = \mathrm{a}[\mathrm{b} + \tanh(\mathrm{c} * \Delta + \mathrm{d})] \tag{3}$$

where a, b, c, and d are the four fitting coefficients that must be determined based on the analyzed dataset.

4 RESULTS

Following the procedure described above, for both municipalities fragility curves were derived using the Eq. 1 (Figs. 3a and 3b) adopting the estimated fragility parameters ($\overline{\Delta}_i$ and β_i) summarized in Table 1.
The selected intensity parameter (i.e., the differential settlement, Δ) was computed as the cumulative value recorded by two coherent pixels for

Table 1. Median ($\overline{\Delta}_i$) and standard deviation (β_i) parameters of the log-normal distribution function used for each damage severity level derived by adopting the maximum likelihood estimation method according to Shinozuka et al. (2000).

Damage severity levels	**Lungro**		**Verbicaro**	
	$\overline{\Delta}_i$	β_i	$\overline{\Delta}_i$	β_i
D1 (Very Slight)	1.25	0.59	0.94	0.60
D2 (Slight)	1.86	0.35	1.57	0.36
D3 (Moderate)	2.70	0.25	2.09	0.29
D4 (Severe)	3.61	0.25	2.45	0.21
D5 (Very Severe)	4.66	0.16	3.26	0.15

each building covered by both ENVISAT and COSMO-SkyMed radar sensor images within the period spanning from August 2003 to October 2012. 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. Accordingly, as for Lungro case study, 29 masonry buildings (globally exhibiting all of the five levels of damage severity) were analyzed; whereas for Verbicaro case study, the analyses dealt with 30 masonry buildings.
In order to investigate the homogeneity of the sample of buildings with respect to the recorded damage severity level, a comparison of the results obtained for the two municipalities was carried out. To this aim, the two-sample nonparametric Kolmogorov-Smirnov (K-S) test (Fig. 4) was used. In particular, the K-S statistics check the hypothesis whether both samples belong (or not) to the same data population by quantifying the distance between the empirical distribution functions of the two considered samples. The result of the K-S test for the analyzed masonry buildings in Lungro and Verbicaro areas (Fig. 4) highlights that differences between the two samples are observed. Indeed, the values of the maximum distances D_{max} (Fig. 4) between the couples of empirical distribution functions – defined according to the K-S test –

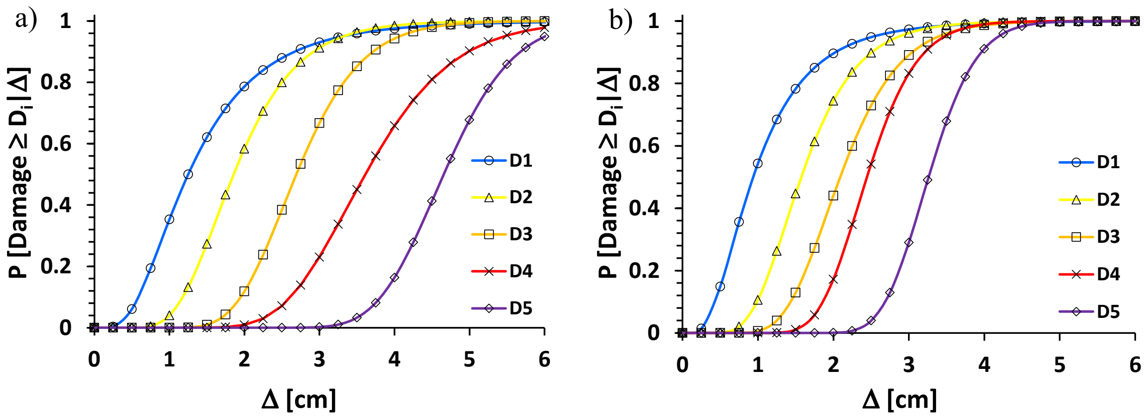
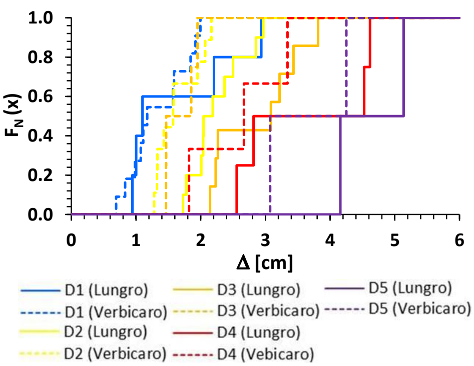


Figure 3. Empirical fragility curves for masonry buildings in a) Lungro and b) Verbicaro study areas.



DL	D_{max}	D_{crit} α=1%	D_{crit} α=5%	D_{crit} α=10%	D_{crit} α=15%	D_{crit} α=20%	Test $D_{max} < D_{crit}$
D1	0.40	0.73	0.62	0.56	0.58	0.50	**Yes**
D2	0.67	0.67	0.45	0.51	0.42	0.45	**No**
D3	1.00	0.83	0.71	0.64	0.60	0.57	**No**
D4	0.50	093	0.84	0.78	0.73	0.68	**Yes**
D5	0.50	0.99	0.98	0.95	0.93	0.90	**Yes**

Figure 4. Results of two-sample K-S goodness-of-fit test used to compare, for each considered damage severity level (D1,...,D5) the two samples of masonry building surveyed in Lungro and Verbicaro study areas.

are lower than the critical values D_{crit} provided by Kolmogorov-Smirnov for all significance levels (α) only for the sub-samples of buildings exhibiting D1, D4 and D5 damage levels; whereas the validity of the hypothesis is rejected for those buildings with D2 and D3 damage levels.

Table 2. Fitting coefficients of the tangent hyperbolic functions used to generate the vulnerability curves for masonry buildings in Lungro and Verbicaro study areas.

Study area	**Fitting coefficient**			
	a	b	c	d
Lungro	2.70	0.85	0.47	-1.26
Verbicaro	2.62	0.91	0.74	-1.53

Therefore, vulnerability curves (Fig. 5) were derived separately for the two municipalities using the Eqs. 2 and 3. The values of the used fitting coefficients (a, b, c, d) are reported in Table 2.

5 DISCUSSION AND CONCLUSIONS

The paper presented a probabilistic analysis of the vulnerability of buildings interacting with slow-moving landslides by means of empirical fragility and vulnerability curves. The results obtained in two well-documented case studies in Calabria region highlighted the potential of combining the results of building damage surveys with measurements of building settlements derived from DInSAR data.

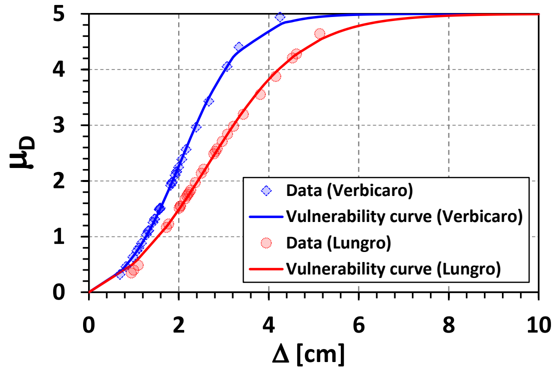


Figure 5. Empirical vulnerability curves for masonry buildings in Lungro and Verbicaro areas.

In order to check the exportability of the tools to other municipalities, a K-S test was carried out on the sample of buildings analyzed with respect to the their response (in terms of recorded damage) to increasing values of the intensity parameter (Δ). The results highlighted that the two samples do not belong to the same data population; accordingly, two different vulnerability curves were derived showing that overall the μ_D is higher in Verbicaro than in Lungro with reference to fixed values of Δ. This may be related to the several factors presiding over the building response to interacting slow-moving landslide mechanisms, such as the type of landslides and the hydro-mechanical properties of the involved soils as well as the position of the building within the unstable area, the foundation typology and main features of the superstructure (i.e. structural typology, number of floors, state of maintenance). Therefore, *exportable* tools require taking into account all the above mentioned factors by generating, for instance, fragility/vulnerability curves referring to homogeneous land-urban systems and typified features.

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