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Numerical analysis of the nonlinear behaviour of a masonry building undergoing slow-moving landslide-induced displacements

Analyse numérique du comportement non linéaire des bâtiments en maçonnerie soumis à des déplacements induits par des glissements de terrain lents

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ABSTRACT: The paper shows the preliminary results of a numerical analysis aimed at investigating the response – in terms of onset and development of damage – of a masonry building with shallow foundations undergoing slow-moving landslide-induced displacements. The analysis is performed by applying the Equivalent Frame method to a representative damaged masonry building located in the historic centre of Lungro town (Calabria region, southern Italy) interacting with a slow-moving landslide in complex-structured and weathered soils. A three-dimensional settlement pattern is imposed at the foundation level by way of a displacement-controlled analysis that makes use of both vertical and horizontal displacement information gathered from conventional (ground-based) and innovative (remote-sensing) monitoring techniques. The obtained outcomes, owing to the good matching of the modeled building response with damage data collected by multi-temporal in-situ surveys, can help in defining representative building-landslide models to be used for predicting and preventing the damage in slow-moving landslide-affected urban areas.

RÉSUMÉ: Cet article montre les résultats d'une analyse numérique visant à étudier la réponse – en termes d'apparition et de développement des dommages – d'un bâtiment en maçonnerie avec des fondations peu profondes subissant des déplacements induits par des glissements de terrain lents. L'analyse est effectuée en appliquant la méthode de l'Equivalent Frame à un bâtiment en maçonnerie endommagé représentatif situé dans le centre historique de la ville de Lungro (région de Calabre, sud de l'Italie) en interaction avec un glissement de terrain lent dans des sols à structure complexe et altérés. Un modèle de tassement tridimensionnel est imposé au niveau de la fondation grâce à une analyse contrôlée par déplacement utilisant à la fois des informations de déplacement vertical et horizontal grâce à des techniques de surveillance conventionnelles (au sol) et innovantes (à distance). Les résultats obtenus, en raison de la bonne correspondance de la réponse du bâtiment modélisée avec les données de dommages collectées par des enquêtes in situ multi-temporelles, peuvent aider à définir des modèles représentatifs bâtiments-glissements de terrains à utiliser pour prédire et prévenir les dommages dans zones urbaines touchées par les glissements de terrain lents.

KEYWORDS: Settlement-induced damage; Masonry buildings; Slow-moving landslide; Monitoring.

1 INTRODUCTION

Slow-moving landslides affecting built-up areas are often responsible for the onset and development of damages on the exposed facilities (e.g., buildings) whose functionality or even stability might be seriously compromised with relevant social and economic consequences (Corominas et al., 2014; Mansour et al., 2011; Peduto et al., 2018). In this regard, the availability of reliable damage forecasting tools – e.g., empirically-based (Peduto et al., 2017) according to information gathered from in-situ surveys (Ferlisi et al., 2015; Palmisano et al., 2018) – can turn out to be useful in decision-making processes at large (municipal) scale and, if required, in selecting the most suitable risk mitigation measures either structural or non-structural (Ferlisi et al., 2019). On the other hand, numerical analyses carried out at detailed scale on single buildings undergoing settlements induced by slow-moving landslides (Nicodemo et al., 2020; Sangirardi et al., 2020) are required if the role played by several factors (e.g., geometry, load distribution and mechanical properties) concurring to the attainment of a certain damage severity level has to be recognized for displacement-based design purposes (Ferlisi et al., 2019).

According to such an evidence, this paper shows the preliminary results of a numerical analysis aimed at estimating the effects – in terms of onset and development of the damage to the superstructure of a given masonry building – of slow-moving landslide-induced displacements acting at the foundation level. The numerical analysis involves applying the Equivalent Frame (EF) method (Lagomarsino et al. 2013) to a well-known case study in Lungro, a municipality of the Calabria region (southern Italy) whose urban area is widely affected by slow-moving landslides (Antronico et al., 2015; Gulla et al., 2017; Peduto et al., 2017).

2 CASE STUDY AND AVAILABLE MONITORING DATA

In the historic centre of Lungro municipality, several low-rise masonry buildings (mainly made of pebbles, or erratic/irregular stones) rest – with their shallow foundations – within or on the boundary of slow-moving landslides that extend down to the Tiro river (Figs. 1a and 1c). For each of these buildings, multi-temporal in-situ damage surveys carried out using ad-hoc predisposed fact-sheets (Ferlisi et al. 2015; Peduto et al. 2018) allowed collecting useful information in terms of state of maintenance and damage severity levels (Burland et al., 1977) associated with the crack patterns exhibited by the bearing walls (Fig. 1a).

Among the surveyed buildings, one exhibiting a very severe (D5) damage during the last damage survey carried out in July 2020 (Figure 1a, b) was selected for numerical analysis purposes. The "modeled building" rests on complex-structured and weathered soils constituting the displaced mass of a slow-moving landslide recently characterized based on geological and geomorphological criteria, monitoring data and detailed multi-temporal field surveys (Peduto et al., 2021). Accordingly, it corresponds to an active slide (Fig. 1a) with two sliding surfaces reaching maximum depths of about 15 m and 25 m from the ground surface, respectively, as highlighted by the inclinometer installed in a borehole (S_20) nearby the main façade of the selected building (Figs. 1a and 1c).

Along the same S_20, the involved geomaterials were grouped in two main classes having similar grain size distributions (Fig. 1c) including colluvial soil (COV), up to 15.5 m from the ground surface, and degraded phyllites (CHAOT), whose depths range from 15.5 m to 66 m. To retrieve the main COV mechanical parameters, consolidated-drained triaxial tests were carried out on specimens obtained from undisturbed samples. The average values of the elastic moduli are summarized in Table 1 along with the value of the average equivalent Young's modulus (E_{eq}) used in the numerical analysis.

Furthermore, data collected by way of both conventional and innovative monitoring techniques are available (Fig. 2). As for the former, inclinometer (S_20) data gathered from April 2006 to July 2019 revealed that superficial displacements (Fig. 2b) are mainly north-east oriented (Peduto et al. 2021). On the other hand, the latter were derived from the processing of COSMO-SkyMed Synthetic Aperture Radar (SAR) images acquired on ascending orbit (from October 2012 to April 2014) via a SAR Tomography interferometric (DInSAR) technique (Fornaro et al. 2014); they consist of velocity values – along the Line of Sight (LOS) sensor-target direction – associated with coherent pixels whose spatial distribution is shown in Fig. 2a. Importantly, both monitoring systems highlighted movement rates that are typical of extremely slow to very slow landslides (Cruden and Varnes, 1996).

Table 1. Average values of the parameters (ε_{50} and E_{50}) and equivalent Young's modulus (E_{eq}) value derived from consolidated-drained triaxial tests on the investigated colluvial (COV) soil (Fig. 1).

Sample [n°]	Z [m]	h_i [m]	ε_{50} [%]	E_{50} [MPa]	E_{eq} [MPa]
1	3.25	0.95	0.82	6.19	14.70
2	4.65	0.95	0.98	11.10	
3	5.15	0.58	1.07	13.60	
4	5.80	1.26	1.50	7.10	
5	7.68	1.25	1.15	24.53	
6	8.30	1.91	1.57	16.32	
7	11.50	5.60	0.49	25.11	

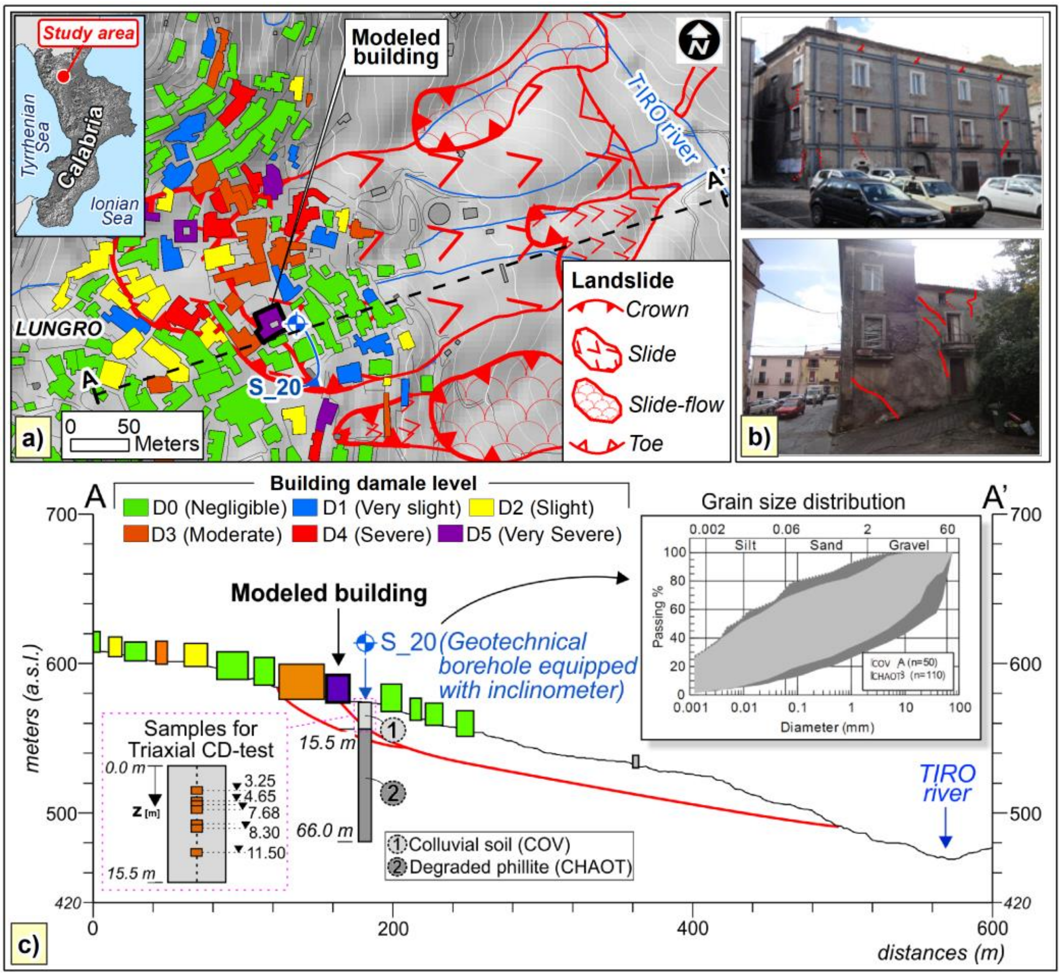


Figure 1. Case study: a) an excerpt of the landslide inventory map in Lungro historic centre (from Peduto et al., 2021) with buildings distinguished according to the damage severity level (from Nicodemo et al., 2020) and localization of the geotechnical borehole equipped with inclinometer installed in front of the modeled masonry building shown in b); c) longitudinal cross-section along the A–A' profile sketched in (a) with grain size distribution of the involved colluvial (COV) and degraded phyllites (CHAOT) soils along the geotechnical log (S_20) and depths of the soil samples collected in (COV) for the laboratory tests.

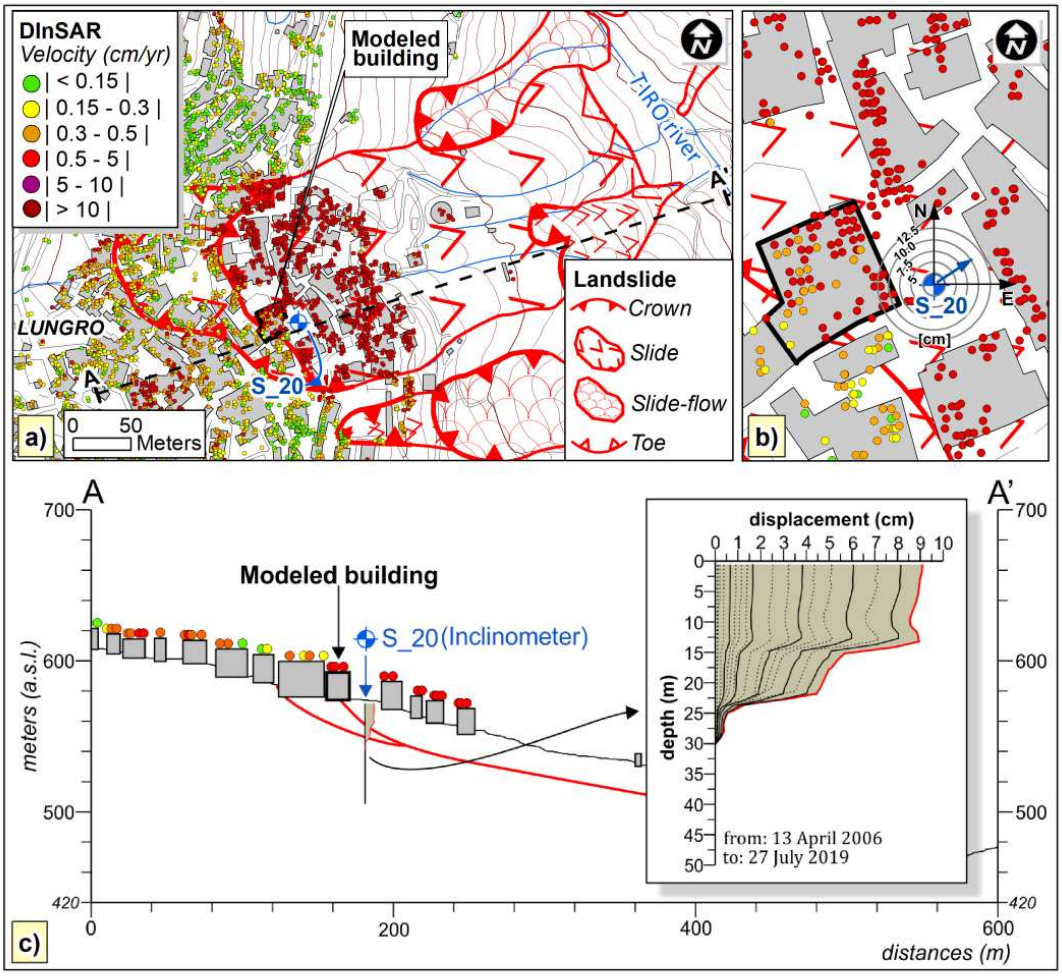


Figure 2. Monitoring dataset: a) surface (DInSAR) monitoring benchmarks referring to Cosmo-SkyMed data (from Peduto et al., 2017) on ascending orbit (period October 2012 – April 2014) overlaid to the landslide inventory map and deep (inclinometer – S_20) measurements (from Gullà et al., 2017) with azimuthal direction show in b); and c) the A–A' longitudinal cross-section with indication of the detected sliding surfaces along with the recorded displacements (period April 2006–July 2019).

3 MODEL

The selected masonry building (Fig. 1b) was modeled using the academic version of the TREMURI software that allows simulating the global non-linear behaviour of masonry walls with certain physical/mechanical properties based on the EF method. The modeled building has a jointed structural geometry (Fig. 3a) resulting in asymmetric loads with a maximum height equal to 10.4 m. It includes three stories (total height of 8.6 m) and a raising floor with height of 1.8 m located on the lateral western portion of the main façade (W1). The exterior and interior masonry walls have thicknesses varying from 50 cm to 100 cm directly connected with the building footprint whose dimensions in plan are equal to 25.70 m × 15.70 m along x and y directions, respectively (Fig. 3b).

The floors were modelled as membranes (5 cm thick) having a linear-elastic orthotropic behaviour, with tie-rods placed at every floor level simulating the presence of the steel elements (Fig. 1b) adopted for the building reinforcement (after 2005). The masonry walls were schematized in the EF method as idealized frames whose deformable elements (i.e., piers and spandrels – Fig. 4a), connected to each other by rigid nodes, may experience either a flexural or a shear failure mode. Average values of the physical and mechanical parameters for existing buildings made of disorganized stones, as provided by the commentary of the Italian Technical Code (N.T.C. 2008), were adopted for the numerical simulations along with the values provided for similar parameters concerning floors and steel tie-rods (Table 2).

Table 2. Average vales of the parameters assigned to the masonry walls, floors and steel tie-rods of the modeled building.

Element	Parameter	Value
Masonry wall	E (Young's modulus) [MPa]	870
	G (shear modulus) [MPa]	290
	ρ (density) [kg/m^3]	1900
	f_m (compressive strength) [MPa]	1.4
	τ_0 (shear strength) [MPa]	0.026
Floor	E_1 (Young's modulus) [MPa]	4000
	E_2 (Young's modulus) [MPa]	0.4
	G_{12} (shear modulus) [MPa]	300
	$\upsilon_{12} = \upsilon_{21}$ (Poisson ratio)	0.0
Tie-rod	E (Young's modulus) [MPa]	206000
	G (shear modulus) [MPa]	78400
	ρ (density) [kg/m^3]	7850
	f_y (tensile strength) [MPa]	235

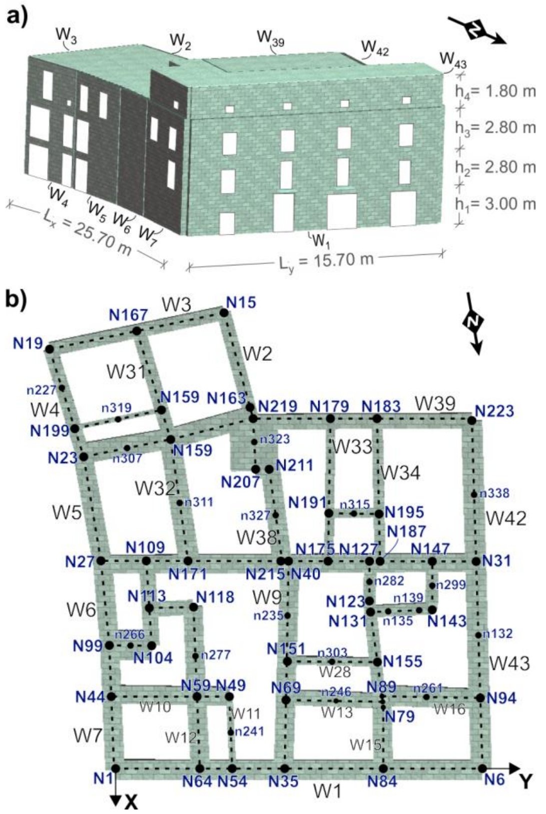


Figure 3. a) 3D view of the modeled masonry building shown in Fig. 1 undergoing slow-moving landslide-induced displacements with (b) layout of foundation plan with indication of the computational nodes.

As for the soil-foundation interaction model, linear springs were placed at the nodes at the base of the equivalent frame model, as generated by the TREMURI software (Fig. 3b). The corresponding vertical (K_z) and horizontal (K_x, K_y) stiffness were estimated according to the formulations proposed by Gazetas (1991) based on the shape/size of the foundation base (Fig. 4b) and the elastic parameters of interacting soil (Table 1).

4 NUMERICAL SIMULATION AND RESULTS

The numerical analysis first involved applying in 10 steps the building self-weight. Accordingly, the nodal forces acting at the foundation computational nodes were estimated based on the distribution of masses pertaining to the masonry walls and the static stiffness values assigned to the springs; related settlements were reset to zero (Ferlisi et al., 2020). Then, a three-dimensional settlement pattern was imposed in correspondence of the foundation nodes where the springs have been placed (Fig. 3b) according to the deformation mode really experienced by the modeled building due to its interaction with the slow-moving landslide. The above pattern was derived based on the monitoring data gathered from both conventional (inclinometer) and innovative (DInSAR) techniques.

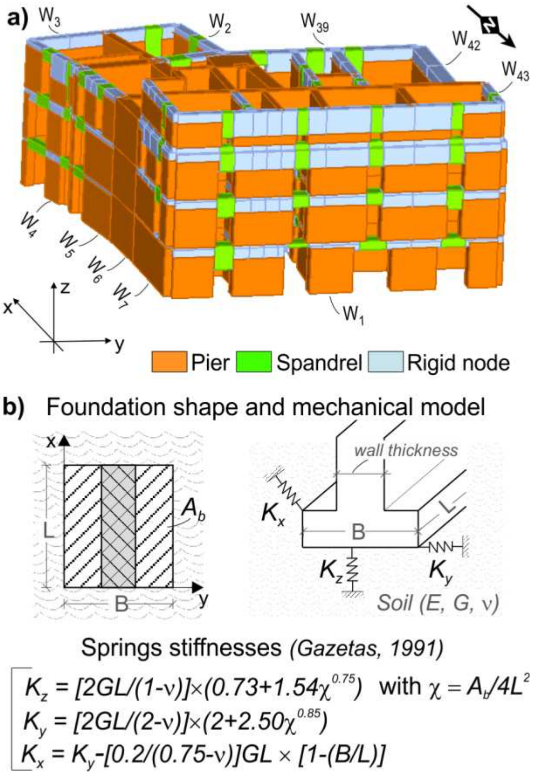
In particular, considering a time period equal to one year, the DInSAR-retrived velocity values along the vertical direction (Vz, Fig. 5a) for each coherent pixel within the building footprint was used to compute the corresponding settlements (δz) (Nicodemo et al. 2018; Noviello et al., 2020) which, in turn, were interpolated using a cell size of 2 m × 2 m (Fig. 5b) according to the resolution of the COSMO-SkyMed data used to retrieve the settlements imposed to each foundation node (Fig. 5c).

On the other hand, the inclinometer data were used to derive the direction of the horizontal displacements and the velocity rates along the building (x and y) orientations (Fig. 5b). The combination of both displacements measurements allowed deriving the inclinometer-DInSAR settlement pattern (Fig. 5d) which represented the key input data for the numerical simulation.

Indeed, the numerical simulations were carried out on the building model (Fig. 3a) by imposing settlement troughs that increased omothetically in value according to the derived pattern (Fig. 5d).

The onset and development of damage in each masonry element were simulated by increasing settlements until the attainment of a given plastic behavior/failure mode in piers and spandrels composing the building walls (Fig. 6). Then, the achieved results were compared with the crack distributions recorded on the building façades during the multi-temporal damage surveys. In particular, four damage scenarios – corresponding to four in-situ damage surveys carried out in a time interval between 2005 to 2020 – were considered. For each scenario a displacement-controlled analysis was performed until reaching a given (imposed) differential settlement (Δ).

The numerical results show that the damage scenarios (Fig. 6) concerning the main façade (W1) and the lateral façade (W43) well-match with the recorded visual damage; indeed, a good correspondence can be observed between the failure mode of piers and spandrels composing the façades of the modeled building and the "real" crack distributions.



$$K_z = [2GL/(1-\nu)]\times(0.73+1.54\chi^{0.75}) \quad \text{with } \chi = A_b/4L^2$$
$$K_y = [2GL/(2-\nu)]\times(2+2.50\chi^{0.85})$$
$$K_x = K_y-[0.2/(0.75-\nu)]GL \times [1-(B/L)]$$

Figure 4. a) Sketch of the exterior walls of the modeled building using the TREMURI software with structural elements (piers and spandrel) connected by rigid nodes according to the Equivalent Frame (EF) method, and b) the adopted soil-foundation interaction model with springs located at the base of the equivalent frame model whose translational (vertical K_z and horizontal K_x, K_y) stiffness is estimated using the formulations proposed by Gazetas (1991).

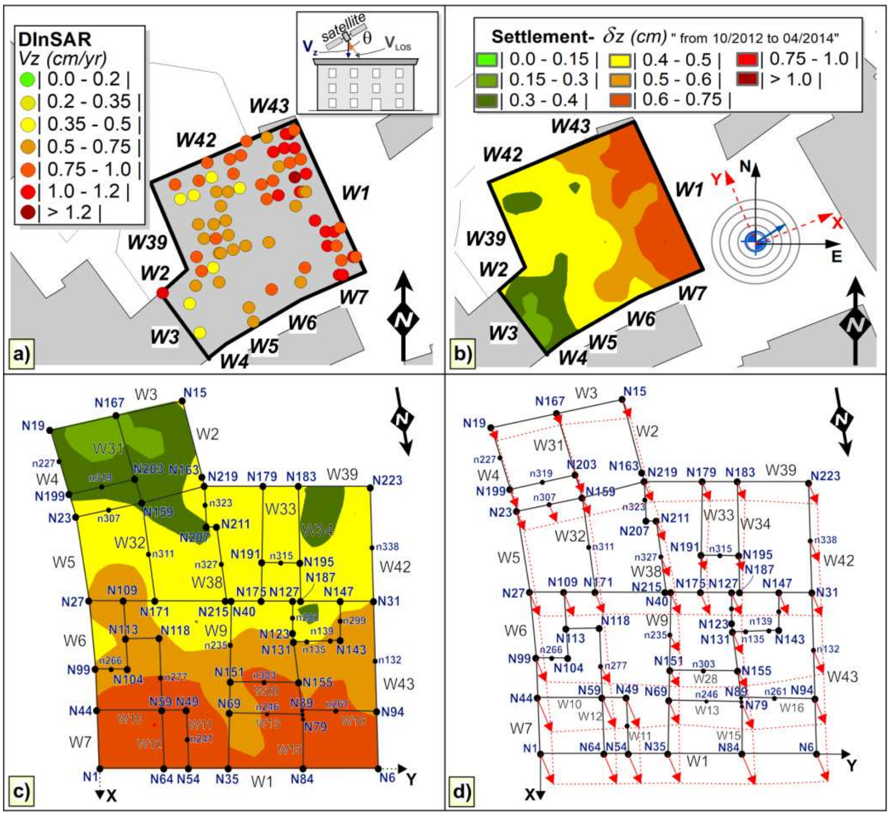


Figure 5. a) Average vertical velocity (Vz) and (b) settlement pattern (δz) computed within the masonry building footprint using the Cosmo-Skymed (DInSAR) data along with the horizontal (δx and δy) displacement components derived by S_20 inclinometer; (c) DInSAR-derived settlement pattern (δz) overlapped to the building model's foundation nodes and d) exemplificative scheme of the combined (vertical and horizontal) imposed settlements.

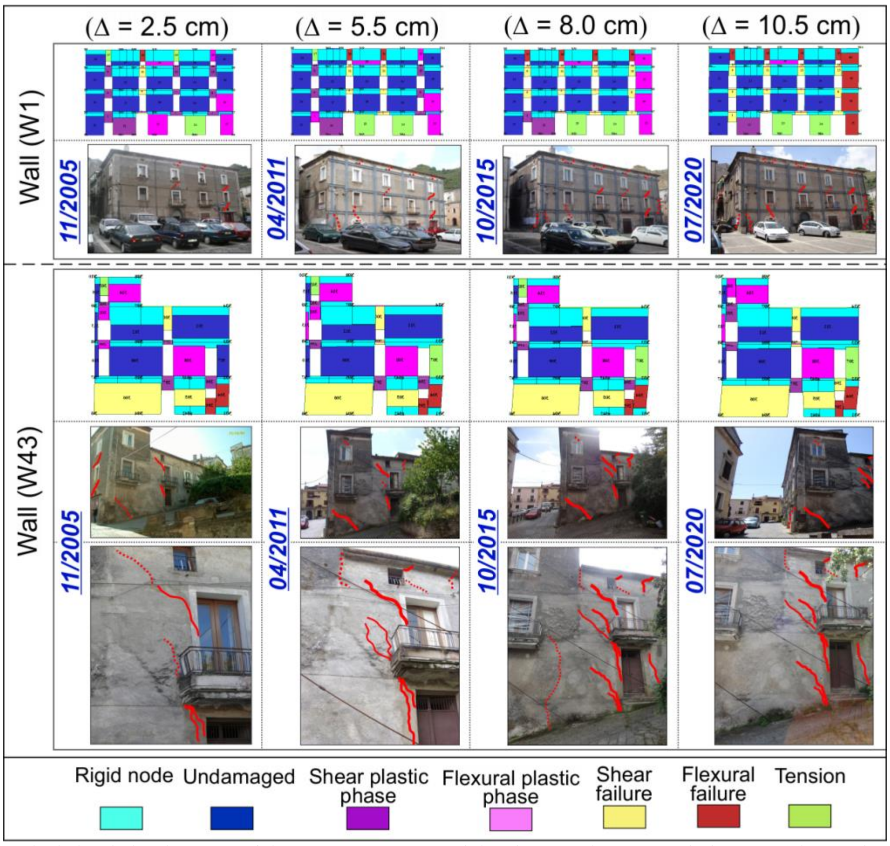


Figure 6. Results of numerical simulation in terms of damage occurrence and development in structural elements (piers and spandrel) of frontal (W1) and lateral (W43) walls of the modeled masonry building undergoing slow-moving landslide-induced displacements, omotetically increased according to the vertical (DInSAR-derived) and horizontal (inclinometer-derived) settlement pattern, and their comparison with the building crack pattern evolution collected during multi-temporal in-situ damage surveys.

5 CONCLUSIONS

This paper showed the results of a numerical analysis aimed at investigating the response of a masonry building undergoing slow-moving landslide-induced displacements. To this aim, based on the geometrical and mechanical characteristics of a "modeled building" selected in the urban area of Lungro (Calabria region, southern Italy), the EF method was applied thanks to the availability of monitoring data collected by way of conventional and innovative techniques that allowed us reconstructing the settlement pattern used as input in the numerical analysis. The results obtained for the modeled building were compared with the information on the damage really exhibited by the same building in terms of crack distribution on its façades, being the latter collected during multi-temporal damage surveys.

The capability of the used model is testified by the results of numerical simulations – in terms of damage occurrence associated with increasing imposed settlements in the four considered time intervals – because they well-match with the visual damage recorded during the multi-temporal damage surveys on the considered façades.

However, the proper interpretation of damage onset and its development over the time would require more sophisticated numerical analyses which involve the use of codes capable to follow the progressive increase of cracks' width and spreading – and the associated damage severity level – in the structural elements (piers and spandrels) composing the masonry walls as well as in the application of settlement patterns validated by means of numerical approaches aimed at simulating the time-evolution of the slow-moving landslide-induced displacements.

Nevertheless, considering the encouraging results, applying the presented procedure to several real cases could lead to define representative building-landslide typified models to be considered in predicting the damage and in preventing it by way of well-designed structural interventions, if required.

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