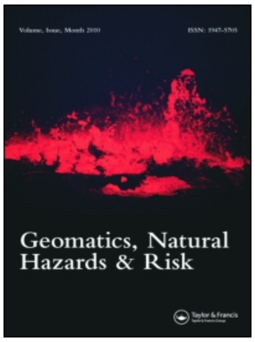

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A new approach for landslide-induced damage assessment

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ABSTRACT

The accurate evaluation of landslide-induced damage is a necessity for planning of proper and effective mitigation measures. It requires the implementation of field investigations to identify structural failures to more effectively trace landslide boundaries. Many methods have been proposed to classify landslide-induced damage of buildings. The existing methods demonstrate several advantages and drawbacks depending on the parameters considered, as lack of some important features and difficulties in applicability. A new classification approach of landslide-induced damage of facilities is proposed, which specifically focuses on assessing of damage degree and its relationship to the ground motion intensity and impact severity. The new approach is designed in two steps: a chart utilized during surveys to quantify cracks on structures and ground surface; an *a posteriori* ranking of structures performed using a cell-grid matrix. Furthermore, a damage recording scheme useful for field surveying is proposed. This approach considers several parameters derived from different existing methodologies by smoothing out drawbacks and homogenizing the considered features. The resulting approach provides a new procedure of landslide-induced damage assessment adoptable in case of private dwellings, as it does not require internal accessibility, and it is exploitable for different landslide events and for different kinds of structures and facilities.

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landslide; field survey; damage classification; building

1. Introduction

Landslides are among the most serious and damaging geohazards worldwide (Schuster 1996; Schuster and Highland 2001). In a broader sense, landslides incorporate numerous different typologies of processes featuring different involved materials and velocities of movement, thereby causing variable measures of impact and damage on man-made structures (Lue et al. 2014). For example, the intrusion of material and the destruction of walls can be detected in case of large debris flows, while relevant damage to rooftops by the falling of boulders have to be taken into consideration relatively more than the formation of small cracks during the analysis of the impact of rock falls. Damage and economic losses resulting from rapid landslides, including debris flows, earth flows and rock falls (Cruden 1991), represent the most severe of these processes and are therefore the most easily recognizable. Conversely, slow-moving landslides (Hungr et al. 2014) that impact facilities can be more difficult to detect despite their potential to induce a total or partial disruption of

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serviceability. The effects of such ground movements are generally revealed by cracks and ruptures occurring within man-made structures or on natural ground surfaces.

The investigation of landslide-induced damage can be motivated by a wide range of user functions, such as administrative (to declare restrictive rules, such as evacuations for the safety of human habitations), planning (to estimate the direct and indirect costs associated with the destruction and to assess the requisite restoration, reconstruction or relocation of affected structures), scientific (to study the phenomena with their extension and possible evolution) and engineering design (to arrange a reconstruction plan) purposes (Alexander 1986).

A comprehensive approach for the surveying and classification of landslide-induced damage plays a key role in the strategy to better delineate mass-movement boundaries by categorizing its detectable impacts on the ground, as well as to improve knowledge of the instability, to avoid repeated occurrences and to plan mitigation measures.

A considerable amount of scientific literature has been conducted with regard to a damage assessment of areas prone to and affected by slow-moving landslides (Skempton and MacDonald 1956; Burland 1977; Lee and Moore 1991; Chiocchio et al. 1997; Cooper 2008; Mansour et al. 2011). Each study presents particular benefits and constraints, i.e. the choice of the relevant parameters to use as well as a lack of concern regarding selected important features and the difficulty in applying the assessment model. Most existing damage classification methods account for different conflicting parameters, and do not consider the relevance of damage investigations on the ground surfaces. Furthermore, no single investigation takes into consideration the possibility of their assessment applicability to facilities in general in addition to buildings. These pending issues do not permit a simple and univocal application and associated set of results; therefore, a complete and easy-to-use methodology is required (Del Soldato et al. 2016).

The aim of this work is to propose a new approach with which to generate a quick assessment of slow-moving landslide-induced damage by considering, and eventually overcoming, difficulties in the process of damage surveying as well as by reducing the drawbacks revealed within previously applied methods. The approach presented herein is a well-structured and simple method for the recognition and classification of damage in order to provide a conclusive and effective categorization of the affected structures. This process is based upon an improvement of the existing methodologies (Burland 1977; Alexander 1986, slightly modified by Boscardin and Cording 1989; Chiocchio et al. 1997; Cooper 2008; Baggio et al. 2009). Furthermore, although the existing methods were only developed in order to classify the damage dealt to private or public construction structures, this methodology is also suitable for facilities, i.e. roads, pavement and infrastructure, as well as for natural ground surfaces, e.g. the external sidewalks surrounding buildings or land surfaces. This new approach allows for a detailed assessment of damage in order to investigate the interaction between the phenomena and the surrounding facilities, as well as to categorize the distinctly recognizable damage based on their intensity. This work derives from experience collected by the authors regarding slow-moving landslide- and subsidence-induced damage experienced at different sites (e.g. Herrera et al. 2010, 2012; Tomás et al. 2012, 2013b; Bru et al. 2013; Ciampalini et al. 2014; Sanabria et al. 2014; Bianchini et al. 2015a; 2015b, 2016; Del Soldato et al. 2016; Infante et al. 2016; Confuorto et al. 2017).

The outcomes demonstrated herein provide an important opportunity with which to directly enhance the classification of landslide-induced damage that affect different types of facilities in order to assess their damage level related to the intensity of ground motion and impact severity, as well as to indirectly support a more precise mapping of landslide-prone areas (Ciampalini et al. 2014). All of the additional information derived from the developed approach can be useful for a subsequent assessment of vulnerability and risk (Chiocchio et al. 1997; Papathoma-Köhle et al. 2012, 2015).

2. Existing classifications: advantages and drawbacks

In this section, some of the most relevant existing classifications of slow-moving landslide-induced damage are listed and are shown in Table 1. The first simple ranking for building damage was

Table 1. Summary of the main features of the analysed existing classification schemes for landslide-induced damages.

	Burland	Alexander	Chiocchio et al.	Cooper	DPC – Baggio et al.
Year	1977	1986	1997	2008	2009
Number of classes	6	8	8	8	4
Distinction of structure	NO	NO	YES	NO	NO
Type of process	ND	Translational or rotational movements	All types	All types	ND
Reference values	YES (mm)	NO	YES (cm)	YES (mm)	YES (mm)
Internal access needed	YES	YES	YES	NO	YES
Partition of the structure	NO	NO	NO	NO	YES
Applicability on ground surface	NO	NO	NO	YES	NO
End users	Scientific purpose	Scientific and administrative purposes	Scientific and administrative purposes	Scientific purpose	Administrative purpose

Note: ND stands for 'Not Defined'.

proposed by Skempton and MacDonald (1956), who divided the damage into three main categories according to their severity and based upon the structural elements affected by cracks absent any clearly defined threshold values: (I) architectural, damaging the appearance of the façade; (II) functional, influencing the utility of the structure; (III) structural, affecting the stability of the building. Burland (1977) presented the initial simple classification scheme originally developed for the consolidation settlement of buildings, which was subsequently slightly modified by Boscardin and Cording (1989), based upon the experience accumulated within previous research (Jennings and Kerrich 1962; MacLeod and Littlejohn 1974). The authors distinguished between different classes based on the opening of fractures (measured in millimetres), the quantity of fractures and a description of the visible damage (e.g. the distortion of doors and windows, or the sloping of floors). In 1986, Alexander published a new ranking system aimed at a mutual comparison of landslide-induced damage for several involved buildings. It is comprised of a description of the damage, including a visual description of both internal and external evidence, through a few reference values regarding the differential settlement and tilting of the floor, which are respectively expressed in centimetres and grades. In spite of a very simple categorization scheme, Alexander (1986) proposed the use of a checklist of suitable information concerning illustrations of the affected structure, the phenomenon that occurred and the specific damage.

Some drawbacks have arisen during the application of several of the aforementioned classifications (Crescenzi et al. 1994; Iovine and Parise 2002), resulting in a newly defined approach for structural assessment by Chiocchio et al. (1997) involving geologists, geomorphologists and civil engineers. A more complete classification scheme was consequently developed that considered different typologies of structure (i.e. masonry and reinforced concrete), thereby providing quantitative reference values of several parameters and suggesting particular rehabilitation measures.

Cooper (2008) conducted a study on several existing methods (e.g. Alexander 1986; Chiocchio et al. 1997) that were devised to categorize structural damage due to subsidence, earthquakes, mining and landslide phenomena, and discovered that many parameters, albeit with minor differences, were commonly utilized to evaluate and classify damage. The author presented a scheme applicable for both landslide- and subsidence-induced damage, including a description and classification of fractures and scarps detectable on the ground surface, and distinguished between either cause. For this ranking scheme, it is important to notice the omission of details regarding foundations or other subsurface amenities. Furthermore, the visibility of cracks on the exterior of the structures was considered to be a fundamental condition to eliminate the need to internal access of the edifices.

The Italian Department of Civil Protection (DPC) developed another approach to classify damage affecting structures that was conceived to assess the reliability of buildings in their capacity to safely host its inhabitants after a seismic event (Baggio et al. 2009). Their approach was composed of nine sections to gather a collection of general, building and damage information, and consisted of a detailed procedure that was devised for post-seismic event surveys and aimed at a preliminary quick classification of the magnitude of damage. The novelty of this approach was the proposed evaluation procedure for the extent of damage, which subdivided the entire structure into three parts to be assessed separately and then reassembled.

3. New approach

As discussed in Cooper (2008), a method for assessing landslide-induced damage should include the mapping of damage to both facilities and ground surface. Furthermore, it should be simple and quick to apply, and it should not require accessing the interior of the investigated edifices (e.g. often private dwellings). To achieve such a goal, the approach proposed in this work is divided into two main steps: first (Phase 1 – Table 2), the recognition and the classification of the severity of damage through means of field surveys, which is to be supported by drawings, notes and pictures; second, (Phase 2 – Table 3), an *a posteriori* categorization of the entirety of the damaged facilities. The specific goal is to propose a simple and suitable methodology with which to survey damage, which will allow an assessment of the level of criticality of each entire facility as well as the investigated area.

Considering the abovementioned benefits and constraints of the existing classifications, the newly conceived method aims at smoothing the drawbacks, homogenizing the considered features and parameters, and providing a simple procedure in order to conduct a reliable preliminary quick damage assessment. For this reason, ranking the visible damage necessarily considers numerous different parameters.

The proposed classification for recognizable damage on structures is differentiated into six levels (Table 2): *no damage* (G0), *negligible* (G1), *weak* (G2), *moderate* (G3), *severe* (G4) and *very severe* (G5). The distinction of five separate degrees of damage, in addition to a *no damage* level (G0), is derived from the classification of Burland (1977) in conjunction with the DPC (Baggio et al. 2009).

A visual description (Figure 1) of the possibly damage-affected facilities is reported in order to simplify the recognition of cracks during the field surveys.

Comparing the proposed classification of the damage level with that of existing schemes, it is possible to observe the absence of classes that refer to the conditions of collapse. This is due to the specific target of the first phase: the classification of cracks and fractures during the field surveys. Collapses can be categorized as *very severe* according to the Burland (1977) and the DPC (Baggio et al. 2009) recording schemes. The second column is concerned with the typology of the load-bearing structure (i.e. masonry or reinforced concrete frame), even if few differences regarding the crack width and the description were recorded. This distinction is maintained based upon the approaches of Alexander (1986) and Chiocchio et al (1997) in order to present as many details as possible for a description of the damage according to the analysed methodologies. The differences in the behaviours between masonry and reinforced concrete frameworks were already discussed by Nawy (1968), while the responses of steel and timber frames can be assimilated with the reactions of reinforced concrete (Grünthal 1998). The width and quantity of the cracks are important parameters with which to describe the visible fractures in facilities. The reported values are derived from the Burland (1977) and Cooper (2008) categorizations in addition to the illustrations of the Alexander (1986) and DPC (Baggio et al. 2009) approaches. The descriptions of damage are derived from the characteristics of all of the analysed classification schemes. Specific modifications are applied in order to adapt the characterizations to allow for recognition of the damage from the outside of the structures and are based upon the accumulated experience of several case studies of damage assessments. The definitions for ground damage are adopted from the Cooper (2008) classification. However, the interpretation of the severity of ground fractures contrasts with that of Cooper (2008) since

Table 2. Phase 1 classification of observable field damage affecting facilities and ground surfaces. The classification was developed based on a combination of the schemes of Burland (1977), Alexander (1986), Chiocchio et al. (1997), Cooper (2008) and DPC (Baggio et al. 2009).

Damage level	Load-bearing structures	Crack width (CW in mm)	Cracking description	Ground damage
G0 No damage	Masonry Reinforced concrete frame	–	Building is intact	Not visible
G1 Negligible	Masonry Reinforced concrete frame	≤ 1	Fine or isolated cracks, generally in internal walls or finishes not influencing the resistance of the structure; no distortion. Not visible from the outside, rarely in brickwork. Restoring with normal redecoration	Not visible
G2 Weak	Masonry Reinforced concrete frame	1 < CW ≤ 5	Settlement of foundations, distortion and inclination not involving the stability. Several slight fractures on walls and partitions inside the buildings. Doors and windows may stick slightly. Repair not urgent, some external redecoration probably required. Difficult to record from outside.	Thin cracks in hard surfaces as roads, concrete pavements. No ruptures visible in vegetated ground. No separation or distortion in vertical structures
G3 Moderate	Masonry Reinforced concrete frame	5 < CW ≤ 15 or several > 3 mm	Open cracks in walls that could influence the strength of the structure; walls disjunction and lintel deformation with sticking of doors and windows. Possible expulsion of materials and fracturing of service pipes. Visible from outside.	Change of tension in wires and fences. Open cracks, distortion, separation or relative settlement with falling of small fragment due to slight damage to road and structures. Remedial works not urgent
G4 Severe	Masonry Reinforced concrete frame	15 < CW ≤ 25 depending on number of cracks	Spread cracking and fractures in structural members conditioning the resistance of the structure. Considerable disjunction; floors inclined and walls out of perpendicular. Windows and doors too distorted to use, walls lean or bulge noticeably, service pipes disrupted. Evacuation and shoring. Noticeable from outside.	Ground surface bulged and/or depressed presenting widespread tension cracks in soil and turf. Settlement may tilt walls, fracture of structures, service pipe and cables. Remedial work necessary
G5 Very severe	Masonry	5 < CW ≤ 20 depending on number of cracks > 25 depending on number of cracks	Partial collapse of floor and open cracks on structural parts hardly damaging the stability of the structure. Out of plumb walls, structure grossly distorted, seriously cracked floors and walls, doors and windows broken. Possible major rotation or swelling of the building and collapse of part of the structure. Evacuation and cordoning; Occupant will need to be rehoused. Partial or total rebuilding requires, probably not feasible. Very obviously from outside	Extensive ground cracking with minor and major scarps, ground bulging and soil rolls. Debris, earth and mud flows, falls and slide may affect man-made facilities. Settlement causes cracks, rotation and distortion to structures and roads. Remedial works urgent.
	Reinforced concrete frame	> 20 depending on number of cracks		

Table 3. Conversion matrix from the cracks recognized within a facility to the classification of an entire structure.

	> 2/3 G5	1/3 < G5 < 2/3	< 1/3 G5	> 2/3 G4	1/3 < G4 < 2/3	< 1/3 G4	> 2/3 G3	1/3 < G3 < 2/3	< 1/3 G3	> 2/3 G2	1/3 < G2 < 2/3	< 1/3 G2	> 2/3 G1	1/3 < G1 < 2/3	< 1/3 G1	> 2/3 G0	1/3 < G0 < 2/3	< 1/3 G0
> 2/3 G5	-	-	7.00	-	-	6.533	-	-	6.07	-	-	5.60	-	-	5.13	-	-	5.00
1/3 < G5 < 2/3	-	7.00	-	-	6.300	-	-	5.60	-	-	4.90	-	-	4.20	-	-	4.00	-
< 1/3 G5	7.00	-	-	6.07	-	-	5.13	-	-	4.20	-	-	3.27	-	-	3.00	-	-
> 2/3 G4	-	-	6.07	-	-	5.60	-	-	5.13	-	-	4.67	-	-	4.20	-	-	4.07
1/3 < G4 < 2/3	-	6.30	-	-	5.60	-	-	4.90	-	-	4.20	-	-	3.50	-	-	3.30	-
< 1/3 G4	6.53	-	-	5.60	-	-	4.67	-	-	3.73	-	-	2.80	-	-	2.53	-	-
> 2/3 G3	-	-	5.13	-	-	4.67	-	-	4.20	-	-	3.73	-	-	3.27	-	-	3.13
1/3 < G3 < 2/3	-	5.60	-	-	4.90	-	-	4.20	-	-	3.50	-	-	2.80	-	-	2.60	-
< 1/3 G3	6.07	-	-	5.133	-	-	4.20	-	-	3.27	-	-	2.33	-	-	2.07	-	-
> 2/3 G2	-	-	4.200	-	-	3.73	-	-	3.27	-	-	2.80	-	-	2.33	-	-	2.20
1/3 < G2 < 2/3	-	4.90	-	-	4.20	-	-	3.50	-	-	2.80	-	-	2.10	-	-	1.90	-
< 1/3 G2	5.60	-	-	4.667	-	-	3.73	-	-	2.80	-	-	1.87	-	-	1.60	-	-
> 2/3 G1	-	-	3.27	-	-	2.80	-	-	2.33	-	-	1.87	-	-	1.40	-	-	1.27
1/3 < G1 < 2/3	-	4.20	-	-	3.50	-	-	2.80	-	-	2.10	-	-	1.40	-	-	1.20	-
< 1/3 G1	5.13	-	-	4.200	-	-	3.27	-	-	2.33	-	-	1.40	-	-	1.13	-	-
> 2/3 G0	-	-	3.00	-	-	2.53	-	-	2.07	-	-	1.60	-	-	1.13	-	-	1.00
1/3 < G0 < 2/3	-	4.00	-	-	3.30	-	-	2.60	-	-	1.90	-	-	1.20	-	-	1.00	-
< 1/3 G0	5.00	-	-	4.07	-	-	3.13	-	-	2.20	-	-	1.27	-	-	1.00	-	-

No damage	1	Negligible	1.0 ÷ 1.49	Weak	1.5 ÷ 2.49	Moderate	2.5 ÷ 3.49	Serious	3.5 ÷ 4.49	Very serious	4.5 ÷ 5.49	Potential collapse	5.5 ÷ 6.49	Unusable	6.5 ÷ 7

Safe … Uninhabitable

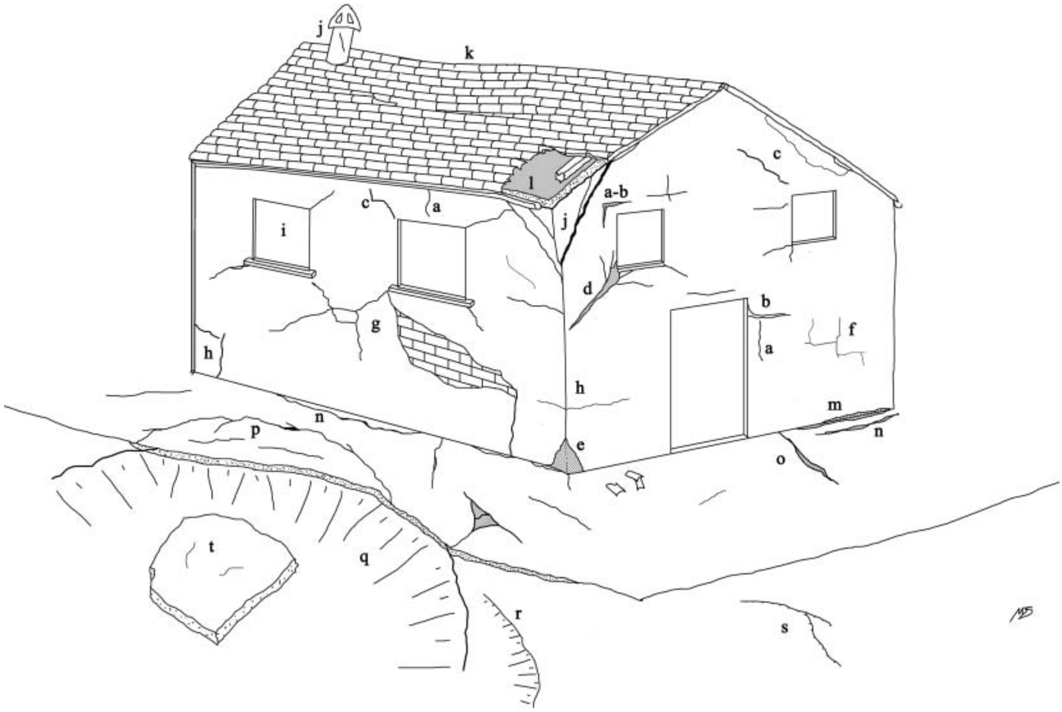

Figure 1. Reference scheme of the damage that could affect structures and the ground surface within a landslide-prone area: (a) thin and open vertical cracks; (b) thin and open horizontal fractures; (c) diagonal tension cracks; (d) severe open damage; (e) local crushing with or without a loss of material; (f) hairline fissures in plaster; (g) loss of plaster enclosed by cracks; (h) horizontal and vertical damage adjacent to the intersection of walls; (i) distortion of services such as doors, windows or chimneys; (j) unstable wedge in the intersection of walls severely affected by open cracks; (k) bent roof; (l) collapse of part of the structure (e.g. roof); (m) open and thin fractures between the external façade and the sidewalk; (n) open (sometimes filled with soil and grass) and thin parallel damages within the sidewalk; (o) open (sometime filled with soil and grass) and thin perpendicular fractures within the sidewalk; (p) damage due to the propagation of the effects of a landslide on horizontal structures; (q) extensive ground cracking with minor and major scarps; (r) a fracture retracing the scarps of the landslide with tension cracks in soil; (s) thin fissure in the ground surface; (t) piece of a horizontal structure fractured and collapsed adjacent to the scarp of the landslide.

the aim of this approach is to classify the magnitude of the cracks, and not to relate them to the conditions that can be elicited from the structures. In this way, ground surface landslide-induced damage are classified as *weak* (G2) ranging to *very severe* (G5), similar to cracks visible within facilities.

Through the means of this categorization (Table 2) in addition to visual descriptions (Figure 1), a useful scheme for recording damage is suggested (supplementary material) in order to classify cracks and ruptures within facilities and the ground surface. The suggested scheme requires several pieces of information about the surveyed structure, which are also pertinent for a possible subsequent evaluation of vulnerability or risk (Uzielli et al. 2015). It is important to note that fractures affecting foundations are not considered within this categorization because they are not visible without invasive investigation techniques.

The second phase of this work consists of a classification of the severity of the damage affecting the structures, *sensu stricto*. The aim is to estimate the strength of an entire building by partitioning it into three ideal sectors in order to consider the extent of damage with respect to the whole structure. It is fundamentally important to evaluate the extent of each damage level. There are three possibilities: (i) the damage category affects the whole structure; (ii) it affects between 2/3 and 1/3 of the whole structure; (iii) it is damaged to an extent of less than 1/3. The seriousness of damage has to be evaluated for each sector in order to better assess the real situation affecting the structure as accurately as possible. Dividing the structure into three sectors that are individually categorized increases the number of available combinations with which to classify the structure with respect to the other analysed methods. In Table 3, all of the possible combinations are shown. The value of each crossing cell was assigned by means of a simple mathematical function derived from the damage classes of the sector of the examined building. First, for the *no damage* (G0) level, a value of 1 was arbitrarily defined in order to perform the division in segments. The other values for each category of damage were assigned by dividing the number of the remaining damage classes (i.e. seven) by the starting number of the categories of cracks (i.e. five). The obtained result is adopted as a threshold with which to convert the degree of damage into quantifiable values, which are then assigned to the crossing characteristic of the entire building. In this way, values comprised of a range from 1 (*no damage*) to 7 (*unusable*) are assigned to each possible crossing. To compare these results with those of the other existing approaches, the values were grouped into eight classes (Table 3): *no damage*, *negligible*, *weak*, *moderate*, *severe*, *very severe*, *potential collapse* and *unusable*. A value of 1 was adopted solely for the *no damage* category. The other values were grouped as follows: *negligible* (1–1.49), *weak* (1.5–2.49), *moderate* (2.5–3.49), *severe* (3.5–4.49), *very severe* (4.5–5.49), *potential collapse* (5.5–6.49) and *unusable* (6.5–7). A shorter range of values was intentionally assigned to the end member classes, i.e. the *negligible* and *unusable* ranks, in order to achieve a more homogenized categorization. Structures entirely affected by the same level of damage must, however, be considered as constituted by two sectors in order to be regarded within the symmetric matrix (Table 3).

4. Applications of the developed approach

The applicability of the proposed approach for the impact of landslide-induced damage on facilities is illustrated through three case studies: (I) a structure built on the edge of a slope affected by rock falls in Finestrat (Alicante, Spain); (II) a building in San Fratello (Sicily, southern Italy); (III) an external concrete sidewalk located on the crown of the Agnone landslide (Molise, South Italy). The surveys were performed using the suggested recording scheme (supplementary material) which standardizes and facilitates the acquisition of numerous necessary data points as well as the recognition and categorization of the damage.

The first example is a three-floor masonry structure located in Finestrat, Alicante (SE Spain) built atop the crown of a natural 15 m steep slope. From a geological point of view, Finestrat is situated within the easternmost region of the Betic Cordillera, in the so-called Prebetic Zone (Colodrón et al. 1981). Three stratigraphic units can be observed along the cliff (Tomás et al 2013a, 2014). The first is represented by massive Keuper Triassic stiff gypsum located at the top. The next consists on alternating layers of clay, marl and sandstone located at the bottom. The slope is affected by an active rock spread which exhibited displacements of up to 4 cm on the façades of the buildings placed on the crown between February 2011 and August 2012, which were measured using 3D Point Clouds obtained using a Laser Scanner (Tomás et al 2013b). Currently, one-half of the building demonstrates ‘Very severe damage’ (G5) (i.e. cracks, the distortion and rotation of the structure and road), while the second half exhibits ‘Weak damage’ (G2) (i.e. tilted walls and fractured service pipes) (Figure 2). Therefore, utilizing Table 3 with $1/3 < G5 < 2/3$ and $1/3 < G2 < 2/3$, we obtain a score of 4.900, which corresponds to a ‘Very Severe’ damage level.

The second example is a private building in the village of San Fratello (in the Sicily region, southern Italy), located atop the crown of a severe landslide that occurred on 14 February 2010 involving structurally complex Cretaceous-Oligocene formations (Ciampalini et al. 2014; Bianchini et al. 2015a). The landslide, which extended up to approximately 1 km^2, was triggered by intense rainfall, thereby inducing immense damage and casualties. The damaged building is a masonry structure with visible open diagonal cracks and ruined plaster on the external façades. The building also displays a tilting and bending of constructive elements (i.e. doorways and windows), resulting in distortion and unserviceability Figure 3. According to the proposed approach, one-third of the building is affected by G3 level damage, and the remaining segments are afflicted by G5 degree damage. Due to

Figure 2. Recording scheme (a) of a building in Finestrat, Alicante (Spain) affected by cracks (arrows in b and c) and joints (arrows in d).

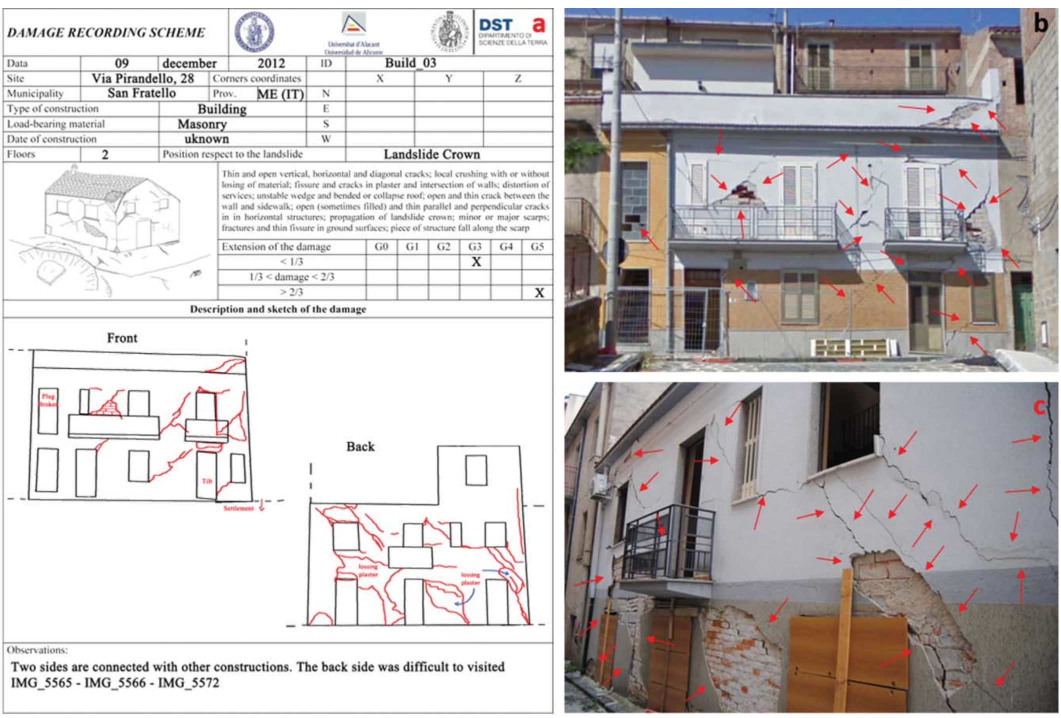

Figure 3. Recording scheme (a) of a building in the village of San Fratello (Sicily, southern Italy) affected by cracks and a loss of material (arrows in b and c).

the severity of the damage and their extent, the entire structure is categorized as '*Potential collapse*' using Table 3, reaching a score of 6.067 (i.e. >2/3 G5 and <1/3 G3). Despite the severity of tilting and level of cracking that affected the building, the collapse had not occurred due to the lateral structural constraints of other close edifices; however, in January 2013, the structure was demolished (Bianchini et al. 2015a).

The third example focuses on a facility situated atop the crown of a large and deep-seated landslide that occurred in the Colle Lapponi-Piano Ovetta area, in the municipality of Agnone (Molise region, southern Italy), which is widely affected by landslide-induced displacements (Calcaterra et al. 2008; Del Soldato et al. 2016). The investigated landslide is a relevant reactivation of an old deep-seated landslide that occurred in January 2003 due to a heavy rainfall event (Calcaterra et al 2008). It has demonstrated a structurally complex formation since the beginning of the 19th century (Almagià 1910). The analysed concrete road presents several forms of damage that were induced by downslope displacements, including fractures and open cracks (arrows in Figure 4(b, c)). These fractures are occasionally filled by soil and grass (respectively represented in grey and green in the scheme of Figure 4(a)). The ground movements resulted in the distortion and tilting of the lateral masonic supporting wall, which exhibits two large cracks (arrows in Figure 4(c)), as well as the rotation of a mast immediately adjacent (arrow in Figure 4(a)). According to the proposed approach, this facility is classified as '*Very severe*' as a consequence of the major damage identifiable in class G5 (i.e. cracks, the distortion and rotation of a structure and road) as well as some damage from class G3 (i.e. cracks, distortion, separation or relative settlement with the falling of small fragments) as described in Table 2.

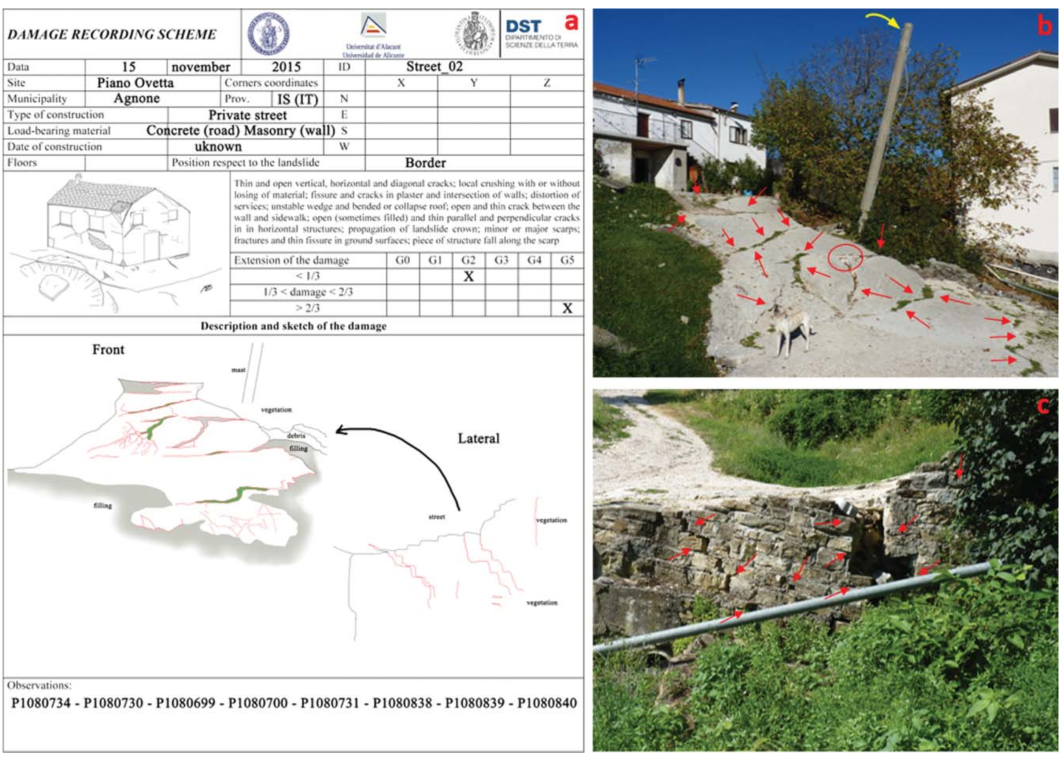

Figure 4. Recording scheme (a) of a private concrete road atop the Colle Lapponi – Piano Ovetta landslide in the Agnone municipality (Molise region, southern Italy) that is affected by significant cracks (arrows in b and c) and by evidence of movement along the pillar (arrow in b).

5. Discussion and conclusions

The aim of this study was to discover and develop a simple new classification approach for a quick but reliable assessment of slow-moving landslide-induced damage by exploiting the different features of existing methodologies. With this ambition, the advantages and drawbacks of existing methods (Burland 1977; Alexander 1986; Chiocchio et al. 1997; Cooper 2008; Baggio et al. 2009) were critically examined based upon the experience of the authors of this study. The analysis conducted heretofore highlighted the means through which all of the previous classification approaches are characterized by similar descriptions of damage, but still involve various parameters that determine the differences in the categorization of the buildings.

The proposed approach is a well-structured method with which to classify buildings located in areas affected by and prone to landslides. It was developed in two consecutive phases: (i) an investigation and classification of cracks affecting buildings and facilities; (ii) an assessment of the degree of damage of the buildings and facilities. As a consequence of the suggested recording scheme involving a detailed graphical description of the possible damage, the first phase is susceptible to the subjectivity of the operator. A new description of cracks and fractures, constructed by merging and improving those already existing in the literature, as well as a scheme for recording damage for surveying purposes were subsequently proposed. Several pieces of information regarding the investigated structure are required in order to conduct a more precise investigation, e.g. the age of the structure and the load-bearing characteristics of the structure. The approach is also suitable for fractures that affect natural and man-made ground surfaces. Descriptions of cracks include details concerning natural and ground surface fractures and are based on a simple subjective observation without spacing involving reference values. Admittedly, these descriptions are used primarily as additional information to better classify the damage of the structures. The second phase is an *a posteriori* analysis of all of the recorded damage that affects the structures and is based upon the severity and extent of the damage. Because a cell-grid numerical matrix is employed to categorize the entire structure, the second phase is detailed and is completely objective. Furthermore, the ability to recognize the damage from the exterior of buildings is highlighted, since the operator often does not have access to private, dangerous or fenced areas and structures. It is important to note that, in contrast to the other classifications of landslide-induced damage, this approach only dedicates a single class (the eighth, which is '*unusable*') to categorize buildings affected by collapses where it is unsafe to live. In this way, additional differentiations with which to classify structures and facilities affected by damage are available. These improvements, which are derived from the DPC approach, have proven very useful in consideration of that, in several cases, the damaged buildings or structures were not homogeneous, whereupon the possibility to consider the extent of each class of damage allows for a better assessment of the real situations. Ground fractures, roads and pavement cannot be considered during the second phase of the methodology, as it only involves structures and facilities in order to assess the damage throughout the entire edifice. It is worth highlighting that the applicability of the presented classification approach has been tested only for slow-moving landslides. It would be interesting to apply the same ranking scheme to different typologies of mass-movements and eventually improve the damage features, e.g. the descriptions and dimensions of cracks, in order to enlarge the application field. Moreover, it could be interesting to investigate the applicability of the scheme to different phenomena that induce significant damage to structures and infrastructure, i.e. subsidence and earthquakes.

The results obtained by applying the proposed method suggest the approach demonstrates a high efficiency for the classification of damage as well as the categorization of buildings, structures and facilities affected by different typologies of landslides, e.g. a rock spread in Finestrat (Alicante, Spain), rotational-translational sliding and flowing in San Fratello (Sicily region, southern Italy) and deep-seated slow-movement in Agnone (Molise region, southern Italy). The applicability of the newly proposed approach to buildings and facilities (e.g. the illustrated example in Agnone, southern Italy) increases the capacity to study landslide-induced damage and their consequences in order to improve the usefulness of planning for administrative purposes. The information provided by the application of this method can support an assessment of the vulnerability and risk within a risk analysis, as well as the management of possible dangerous events. Nevertheless, the deployment of these data requires the expertise of involved technicians in order to avoid alarming people needlessly.

It would be interesting to investigate the possibility to observe three different degrees of damage within the same building, but the difficulty inherent in creating a scheme with three axes must be considered. Further research should be conducted in order to investigate the possibility of evaluating the extent of damage within buildings and structures in three segments. In conclusion, the resulting approach provides a new procedure for the assessment of landslide-induced damage, which can also be employed in the case of private dwellings, as it does not require internal accessibility. The first phase is rapid and easy-to-use in the field, and the second phase is objective, being based on a numerical cell-grid matrix. Furthermore, the sample applications illustrated herein indicates that it is exploitable for different typology of landslide events and for different kinds of structures and facilities.

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