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ASSESSMENT OF LANDSLIDE DAMAGE TO BUILDINGS AT THE URBAN SCALE

Fabrizio PALMISANO, Ph.D. A.M.ASCE[1]; **Claudia VITONE**, Ph.D.[2]; **Federica COTECCHIA**, Ph.D.[3]

[1] Adjunct Professor, DICAR, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy (corresponding author). E-mail: fabrizio.palmisano@poliba.it

[2] Associate Professor, DICATECh, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy

[3] Full Professor, DICATECh, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy

ABSTRACT

This article aims to deepen the knowledge in the field of landslide risk assessment by introducing a new multi-level approach to the vulnerability assessment. It focuses on an original methodology for damage assessment of either masonry or reinforced concrete ordinary buildings at the urban scale. This methodology is an essential part of *Level 1* of the abovementioned multi-level approach. It starts from filling in on-purpose designed forms that are completed when a damage grade is assigned to each building within the region under study, according to a new damage classification. The end-product of the application of the methodology is the so-called the landslide damage geotechnical chart. The chart includes not only the damage grade of the buildings within the urban center investigated, but also the geomorphological and geotechnical maps of the town/area under study, and information concerning the direction of the settlements reconstructed to have caused the damage. The application of the methodology to the historical town of Bovino, in the south of Italy, is also reported.

AUTHOR KEYWORDS

Damage, vulnerability; masonry; reinforced concrete; buildings; landslide.

INTRODUCTION

The assessment of landslide risk is a research topic of spreading interest across the scientific community involved with either geotechnical or structural engineering. This interest stems from the awareness of the still dramatic impact of landsliding on the socio-economic development of vast areas and of the concurrent boosting request for urbanization across landslide prone areas (Ciampalini et al. 2014; Cotecchia et al. 2014, 2015, 2016; Petley 2012). Following the definition given by the United Nations (UNDRO 1979), *Vulnerability* is related to the (potential) results of event occurrence determined through qualitative, semi quantitative or quantitative methods in terms of loss, disadvantage or gain, damage, injury or loss of life.

In this scenario, this article intends to contribute to the advancement of landslide vulnerability assessment, through the provision of a method for both survey and analysis of damage intended to define whether it is caused by landsliding, in particular (although not exclusively) for structures interacting with slow to very slow landslides (Cruden and Varnes 1996; Hungr et al. 2014). The original methodology of damage diagnosis being proposed applies to ordinary buildings, made of either masonry or reinforced concrete, and it has been devised for vulnerability assessment at the urban scale (i.e., a scale classified as medium to large according to Cascini 2008). It has been developed through studies that have been carried out within a four-year research project (PS_119 2007-2010), financed by the Apulia Region (southern Italy) and aimed at the definition of a landslide risk assessment methodology. Such research project has resulted in the Multiscalar Method for Landslide Mitigation (MMLM) validated in the Daunia Apennines as pilot region (Cotecchia et al. 2014, 2015, 2016).

In the following, the damage assessment methodology is first introduced as part of a new methodology for the vulnerability assessment at the urban scale (Palmisano 2011) and, successively, it is explained in detail, with the provision of on-purpose designed survey damage forms to be used for the assessment.

MULTI-LEVEL APPROACH TO URBAN SCALE VULNERABILITY ASSESSMENT

At the urban scale, it is both technically impossible and economically inconvenient to perform detailed investigations of the buildings. The complexity of the investigations, the large number and the variety of the vulnerable elements, make it necessary the adoption of a multi-level approach (Palmisano 2016a), from the urban scale to the scale of the single building. The aim is to sort out the vulnerability level of buildings to budget the different intervention options and support the definition of both mid-term and long-term mitigation strategies.

The multi-level approach for landslide vulnerability assessment at the urban scale includes the following two levels of analysis (Palmisano 2011):

- *Level 1.* The vulnerability assessment at this level can be developed through the work steps reported in Fig. 1 and it covers all the buildings across the area under study. Given the scale of analysis, it should be based on information of easy acquisition, such as general building data (e.g., construction year, structural typology, use), and on the results of visual inspections of the building conditions. The accomplishment of *Level 1* assessment results in: i) the assignment of both a damage grade and a first instance vulnerability grade to each building; ii) the sorting out of the buildings at 'highest vulnerability'.
- *Level 2.* This level involves only the buildings recognized as at 'high vulnerability' or at 'high damage' in *Level 1*. A complete structural vulnerability assessment should be carried out, making use of detailed inspections of the buildings, standard and non-standard tests, numerical analyses, strategies for remedial actions. This advanced assessment will also corroborate the interpretation of the landslide damage grades

assigned to buildings in the *Level 1* studies and configures the knowledge for a check of the vulnerability grades proposed.

This article focuses on Step 2 of the *Level 1* approach (Fig. 1) through the outline of an original methodology for landslide damage assessment of ordinary (masonry and reinforced concrete) buildings that can be applied at the urban scale. In the framework in Fig. 1, this Step is preceded by Step 1 that frames the application of ‘simple models’ (Palmisano 2014; Roca et al. 2011) to interpret the response of buildings subjected to foundation settlements. The simple models are used to back-analyze observed crack patterns and derive the foundation settlement geometry that may have, eventually, caused them. They should be based on fundamental principles of structural mechanics, such as the limit theorems of plasticity, that are valuable at this level, since they afford the description of the essential phenomena controlling the structural capacity (Roca et al. 2011), despite being of relatively simple use. Among this category of models, the Strut-and-Tie Model (Ritter 1899) and the Load Path Method (LPM hereafter; Schlaich et al. 1987) have been successfully used for long time to analyze reinforced and pre-stressed structures. By using the LPM, it has been possible to define the most recurrent typologies of crack patterns that affect ordinary buildings subjected to foundation settlements (Palmisano 2016b; Palmisano and Elia 2013, 2015). In Fig. 2 some examples of simple crack patterns and damages to masonry and R.C. buildings due to foundation settlements are shown. For more complex cases of LPM applications see also Palmisano (2016b).

The *Level 1* methodology (Fig. 1) makes use of the characterization of the crack patterns such as those in Fig. 2 to discern if the damage is due to foundation settlements. Moreover, it should be noted that the back analysis of the crack patterns through LPM makes it possible to derive also the settlement direction (Fig. 2). This information, when collected for several buildings in the urban area, can be of use to recognize the morphology of a landslide body, even when landslide features are hidden by urbanization or are unclear.

The damage assessment at the urban scale (Step 2, *Level 1* in Fig. 1), that is the main object of the present article, aims to provide rapid and objective data that, together with the geomorphological and the geotechnical ones, are fundamental for both the diagnosis of the landslide damage distribution across the territory and the vulnerability assessment (i.e., Step 3). This Step may be very useful in urban areas also to acquire indirect evidence of landslide activity, otherwise of difficult detection solely on geomorphological basis.

The third part of the proposed methodology (Step 3 in Fig. 1) benefits from the results of the previous steps and aims to assess the *Level 1* structural landslide vulnerability at the urban scale. In particular, the geometry and the structural and historical data about the buildings, acquired in Step 2, are used as input data for the evaluation of structural vulnerability, whereas the damage data are useful at this step to further support the characterization of landslide-structure interaction. This part of the methodology will be covered in a forthcoming article.

It is worth noting that the vulnerability assessment methodology here proposed is significantly different from other approaches present in the literature, which, most often, account for purely qualitative damage analyses (e.g., Liu et al. 2002; Cardinali et al. 2002; Leone et al. 1996), often for specific landslide events. Indeed, the studies of landslide vulnerability of structures are few, probably because they require multidisciplinary research work, in both structural and geotechnical engineering. Only recently structural vulnerability assessment has been included in natural hazard and risk analyses, although seldom for landslide risk. For landslides, vulnerability has been assessed mostly through the use of empirical fragility curves, derived from the qualitative survey of structural damage (e.g., Uzielli et al 2015; Peduto et al. 2017a, b). The qualitative analyses, though, result in curves that account only for the grade of structural damage, irrespective of the type of damage and of its correlation with the direction of the foundation settlement causing that damage. Hence, it is evident the need for a new procedure that, starting from the mechanical analysis of the structural behavior of a building, evaluates the potential damage that it may undergo when subjected to foundation settlements due to landsliding.

To this aim, the proposed methodology is fully deterministic and based on the strong coupling between the geomorphological and the geomechanical knowledge of the landslide mechanism and the structural behavior of the interacting building. Its starting point (Step 1) is the interpretation of the structural behavior of a building subjected to foundation settlements (e.g., Palmisano 2016). The main aim is to strictly correlate the damage with the structural response and, hence, with the relevant foundation settlement. As shown in the following, such deeper investigation of the structural behavior is thought to be extremely useful to support geotechnical and geological studies for stability analyses in urbanized areas.

In the following, after a brief review of the classifications of structural damage reported in the literature, a new landslide damage classification of buildings is proposed (Phase 2.1 of Step 2, Fig. 1) and the survey methodology to acquire the data of use in the assessment is outlined in detail (Phase 2.2 of Step 2, Fig. 1). Thereafter, the application of Steps 1 and 2 of the methodology (Fig. 1) is presented for the town of Bovino in the Daunia Apennines (southern Italy).

LANDSLIDE DAMAGE ASSESSMENT AT THE URBAN SCALE

Key features of the methodology

As shown in the framework in Fig. 1, the proposed methodology starts with the definition of a new classification of reference for the damage assessment (Phase 2.1). This draws inspiration from the most relevant classifications of structural damage due to foundation settlements reported in the literature, which, though, have never been related to landslide effects.

On-purpose in-situ surveys should result in the filling in of original damage forms that, as discussed in the following, have been designed both to gather sufficient data to recognize if damages stem from foundation settlements and to assign, to each building, a damage grade within the new damage classification. Such recognition can be pursued by using the 'simple models' selected in Step 1 in Fig. 1, e.g., the Load Path Method. Through these models the damaged buildings most likely damaged by foundation settlements (Palmisano 2016b) will be selected. The third phase of Step 2 entails the mapping of damage with the indication of the foundation settlement direction that has been reconstructed to be the cause of the damage (except for the buildings whose damage is not related to foundation settlements). The damage map (see Phase 2.3 in Fig. 1) will also contain the damage grades assigned to the buildings and the geo-morphological features of the landslide processes and indications about their kinematics, as resulting from geo-morphological and geotechnical studies. Through such multi-theme mapping, it is derived what here defined as the 'landslide damage geotechnical chart' of the urban area. This represents the ground of comparison between the settlements diagnosed as cause of the building damages and the landslide induced ground settlements. From such comparison, the features and grade of damage that landsliding is causing to the buildings, given their structural features, is diagnosed. Such evidence is the starting point for the physically based modelling of the landslide effects at the urban scale and, hence, for the *Level 1* vulnerability assessment, to be developed in Step 3 (Fig. 1). Hence, this article aims to fill the gap in the literature by introducing a tight link between landslide geomechanics and structural damage mechanics. This is why the proposed methodolgy can be considered as systematically applicable to survey structural damage due to landslides.

The methodology has been prompted by the study of landsliding in urban centers where landsliding is peculiarly slow, so it benefited by this particular circumstance, although it is applicable also to other landslide conditions/activity.

Building damage classification

According to Burland (1997), the assessment of thw degree of building damage can be a highly subjective. It may be influenced by a number of factors such as experience, the attitude of insurers, the cautious approach of a professional engineer or surveyor who might be concerned about litigation, market value and 'saleability' of the property. This is why the availability of a classification of damage is a key issue for a correct development of assessment of the causes of building damages.

Burland et al. (1977), starting from previous studies, proposed a classification of damage for foundation settlements based on the features of the damage affecting walls and making reference to the ease of its repair (i.e., plaster, brickwork and masonry). In this classification, six categories of damage of increasing severity have been identified.

After Burland et al. (1977), Alexander (1986) proposed an intensity scale for structural damage caused by subsidence, compression, or extension of the ground during landslides. The classification was developed based upon field surveys of the 1982 Ancona landslide (Italy). He characterized the building conditions by adapting post-earthquake building inspection forms, used in Italy at that time, to inspect the landslide effects.

Later, the classification of building damage by Leone et al. (1996) distributed the damage grade between 0 and l, to represent the degree of loss of the element. With sufficiently detailed diagnostic analyses, the progression of damage from 0 to 1 could result in the calculation of the loss rate.

Benefiting from these published experiences in damage surveying and classification, as well as from the most developed experience in damage surveying provided in earthquake engineering by using the European Macroseismic Scale 1998 (EMS-98 hereafter; Grüntal

1998), a new building damage classification has been developed, with the specific aim to address it to landslide damage assessment at the urban scale.

The original classification proposed in the following has mainly taken inspiration from the EMS-98 because it represents the most widespread and tested damage classification in the field of structural engineering. However, since the proposed classification cannot be solely limited to damages induced by seismic actions, many modifications at the original EMS-98 were needed. Moreover, given the objectives of the *Level 1* assessment (Step 3; Fig. 1) at the urban scale, the new damage classification reports elements useful to characterize the landslide structural vulnerability (Step 3 in Fig. 1) and, to this aim, it merges some issues from Burland et al. (1977) and Boscardin and Cording (1989) classifications with the classification from EMS-98 (Fig. 3). The classification here proposed (Fig. 4), hence, derives from the original combination of both structural experience in the seismic field (EMS-98) and geotechnical experience in tunneling excavation (Burland et al. 1977), significantly revised and completed by the experience in the landsliding field. This is why the proposed classification can be considered as new. Moreover, the strict correlation between this classification and other ones present in the literature (mainly EMS-98 and Burland et al. 1977; see Fig. 3) makes it also possible the comparison between new data (resulted from the application of the proposed methodology) and those coming from old databases and that ordinarily exist only in a scattered form.

The proposed classification is reported in Figs. 3 and 4; it defines six grades of damage, from 0 to 3c, as the severity of the damage increases. Grades 0 and 1 relate to serviceability limit state, grade 2 to serviceability/ultimate limit state, grade 3a, 3b and 3c refer to ultimate limit state, ultimate limit state/collapse and collapse, respectively. As it can be noticed from Fig. 4, each grade of damage depends not only on its level, but also on its extension.

Differently from the classification by Burland et al. (1977) and from others that deal with foundation settlements (e.g., Cooper 2008), the proposed classification introduces quantitative descriptions of both the level and the extension of the damage (Fig. 4) to have an evaluation of the damage grade as objective as possible trying to reduce at the minimum the subjective interpretation of the surveyor.

The choice of the damage grade should always be on the safe side (i.e., focusing on the worst condition). For example, for a building with both 'damage level 2 in few elements' and 'damage level 3 in few elements', since the latter corresponds to the higher damage grade 2, this grade should be assigned.

1st level damage survey forms and diagnosis of the damage patterns

The issue of using standardized damage forms to characterize the conditions of building interacting with landslides mainly follows the examples from Alexander (1986) and the procedure adopted by the Italian National Department of Civil Protection (DPC 2009) for the immediate assessment of aftermath damage caused to buildings by seismic events.

The surveyors can fill in the damage forms after direct and rapid site surveys (i.e., only visual inspections). The aim is to obtain the most possible objective description of the features and the damages of the building, devoid of any subjective interpretation of the surveyor.

The forms are designed to detect typological features and damage characteristics of either ordinary masonry or reinforced concrete buildings. Therefore, these forms are not applicable to 'non-ordinary' buildings, such as theatres, churches, sports facilities, industrial buildings. It is worth highlighting that, although the methodology being proposed has been defined with reference to slow-moving landslides, these forms can also be used in the immediate aftermath of rapid landslides.

The damage survey forms for ordinary buildings are reported in the Supplemental Data of the online release of this article. They are composed by the following sections:

- Section 1: building identification.
- Section 2: building description.
- Section 3: structural typology.
- Section 4: damage to structural elements and partition walls, existing emergency measures.
- Section 5: damage to non-structural elements (partition walls excluded) and existing emergency measures.
- Section 6: external danger and existing emergency measures.
- Section 7: further notes.
- Section 8: damage grade.

Sections 1, 2, 5-8 are identical for both masonry and R.C. buildings.

It is worth noting that even if the forms here proposed have been inspired by those by DPC (2009), they can be considered as completely different from them mainly for the following reasons:

- The aim of DPC (2009) forms is to give a quick and temporary judgement about the usability of a damaged building in the aftermath of an earthquake; hence, they include very few data about the building and its damages. The aim of the proposed form, instead, is to detect typological features of the building as well as to give detailed information about damages in order to detect and monitor landsliding in urban area.
- The DPC (2009) forms, in the damage section, include only crack patterns due to seismic actions while the proposed forms provide data about any damage feature, not only associated to foundation settlements.
- To fill in the damage section of DPC (2009) forms, the judgement of the surveyors is needed in order to evaluate if the observed damage is caused by the earthquake. On the other side, to fill in the damage section of the proposed form no judgement is needed to

evaluate the cause of the damage since the aim of this section is to detect all kind of damages.

- Section 8 of the proposed form is completely new and it is the result of the Step 1 (Fig. 1) of the proposed methodology.

Moreover, it is worth noting that the proposed forms can be also considered as new since, in the literature, nothing similar appears to be proposed, especially, with reference to the damage section and to the correlation between damages and foundation settlement by using a structural mechanics approach.

Before starting the survey, general information about the building should be acquired, e.g., from the Technical Office of the Municipality, the owner, people involved in the construction and/or in the maintenance and building management. This information should concern the year of construction, the used materials, the possible modifications, enlargements and damages over the years, etc. In the forms, circle boxes are used for a single choice, while square boxes for multiple choices.

In Section 1 the grey area concerns information that may be partly given by the Technical Office of the Municipality, while the white areas indicate fields that must be completed by the surveyor. The grey area of Section 1 is consistent with the current Italian Codes; obviously, if the form is used in another Country, the grey area should be updated accordingly. The 'building location' refers to its position inside a block of buildings, while the 'use code' is relevant to public services and it is the same as that given by DPC (2009).

In Section 2, the most important data about the building should be collected: dimensions, age, current usability, type of use and ownership, etc. It is worth noting that data to be collected in the forms should be easily found out by visual inspections. In this respect, the age of the building is a non-robust piece of information, as it can be obtained only by means of interviews, either of the owners or of the tenants of the building. The 'construction age' periods indicated in the forms are relevant to the most important changes in the Italian technical standards. If the form is used in another Country, the 'construction age' periods should be updated accordingly.

The structural typology should be defined in Section 3, through an array where the rows contain the typologies of horizontal structures (roof excluded) and columns those of vertical structures. It is also possible the multiple-choice option, that is useful to describe buildings including different typologies of both horizontal and vertical structures.

Buildings are considered made of reinforced concrete if the entire elevation bearing structure is in reinforced concrete. If in the same building there are both masonry and reinforced concrete vertical bearing structures, the column *M* in Section 3 of the masonry building form should be filled in. In particular: box *M1* should be marked if the vertical R.C. structure is limited to the upper floor, while all the other floors have masonry vertical structures; box *M2* should be marked if the vertical R.C. structure is limited to the lower floor, while all the other floors have masonry vertical structures; box *M3* should be marked if on the same floor there are both vertical R.C. and masonry structures, or if there are some floors with vertical R.C. structures and others with vertical masonry structure (cases *M1* and *M2* excluded).

In the masonry building form (Section 3), the possible presence of isolated columns (R.C., masonry, steel, wood) should be indicated in column *L*, whereas for 'strengthened' masonry, column *N* should be optioned. In particular, the following boxes should be marked: *N1* if the masonry has been strengthened by reinforced or unreinforced injections or by reinforced plaster; *N2* for masonry that has undergone other strengthening systems.

Regarding masonry composed by artificial units (columns *E*, *F*, *G* in Section 3 of the masonry building form), solid units are those having hole percentage not higher than 15%, perforated units from 15% to 45% and hollow units higher than 45%. Without in-situ tests, it is quite impossible to understand the unit typology. Hence, in this case, the surveyor team should select the type of worst performance (i.e., hollow units), provided that this choice is declared in Section 7. Section 3 of the forms is completed by a matrix concerning the roof structure typology.

Sections 4 and 5 concern the damage of structural and non-structural elements and the existing emergency measures. These sections are the most innovative, since they strongly differ from those of the forms by DPC (2009). While the latter include only crack patterns due to seismic actions, the proposed forms can provide data about any damage feature, not only associated to foundation settlements. This is because the aim of this section is to minimize the subjective judgment of the surveyors about the cause of the observed damage.

The damages of the structural elements and of the partition walls are in the same group, that is different from that of damages to other non-structural elements. This is of particular importance for R.C. structures, for which architectural components often hide moderate damages and, hence, the assessment of damages of non-structural elements is the only way to evaluate the damage grade of the building by using only visual inspections.

The assessment of the damage extension must be carried out separately for each row with reference to the entire building (if the inspection is partial, the damage extension is referred to the part of the building that has been inspected).

In the Supplemental Data of the online release of this article, the most significant typologies of cracks indicated in Section 4 of the forms are shown in order to support the surveyor team to correctly fill in this section of the forms.

At the end of Sections 4 and 5, the presence of existing emergency measures should be indicated. If, according to the surveyor team, further emergency measures should be adopted, they could be indicated in 'further notes' in Section 7.

Section 6 deals with external danger and existing emergency measures. External danger may arise from the instability of neighboring buildings (danger of collapse or falling objects) or even from the unsafety of distribution networks.

In the first part of Section 7, information about the accuracy of the survey has to be given. The second part of this section is dedicated to free notes, sketches and/or further comments about the degree of reliability of the gathered information.

In Section 8 the surveyor should indicate the damage grade of the building, by selecting it from the damage classification proposed in Fig. 4. Since the damage description is prescribed to be very detailed in the forms, this last step can be solely based on a careful analysis of all the data introduced in the dedicated sections. In emergency conditions, the classification of the specific building damage grade derived in Section 8 will allow to establish which buildings are either usable, or usable only after emergency measures, or not usable.

As mentioned in the previous paragraphs, the proposed classification introduces quantitative descriptions of both the level and the extension of the damages (Fig. 4) to have an evaluation of the damage grade as objective as possible trying to reduce at the minimum the subjective interpretation of the surveyor. It is worth highlighting that while this is an appropriate aim, it realistically cannot be fully achieved. Human subjectivity will always be a factor (Terwel and Jansen 2015; Terwel 2017), and must be considered by the recipients of the final document (i.e., landslide damage geotechnical chart) of this methodology. Subjectivity can have both negative and positive effects. In order to reduce negative effects such as emotional bias and surveyor fatigue, it is auspicial that an experienced structural engineer help the surveyor team to fill in Section 8 of the forms.

The second part of Section 8 deals with the possible causes of the damage. To this aim, according to the approach proposed (Step 1 in Fig. 1), the surveyor team becomes able to assess whether the damage is caused by foundation settlements. If this is the case, the corresponding box should be marked and a sketch of the building plan also providing indication of the direction of the settlement causing the damage is to be provided. This sketch should be done only when it is possible to associate, in an objective way, the observed damage with the direction settlement. In the Supplemental Data of the online release of this article the graphic lexicon to indicate, on the building plan, the pattern of differential building settlements is shown. This lexicon applies to buildings whose cracks are evident along the boundary walls. When the damaged portion is inside, the arrows indicative of the settlement direction should be drawn inside the perimeter of the building plan. In Section 8, the box 'undecided' can be used either if the surveyor team is not sure if the damage is due to foundation settlements or if it can be ascribed not only to foundation settlements.

At this stage of the analysis, it cannot be assessed yet if the foundation settlement has been caused by either landslide movements, or intrinsic structural defects of the building (e.g., under-dimensioning of the foundations). To this aim, the structural survey will have to be put in a more general survey context, also implementing the results of the geomorphological and geotechnical studies of the slopes interacting with the buildings.

The landslide damage geotechnical chart

The experience gathered in urban areas has shown that within these areas the detection of landslide activity cannot rely solely on multiple-year analysis of topographic maps and aerial photos and in-situ geomorphological surveys. Rather, the use of topographic monitoring, either through on-site equipment, or through satellite monitoring (e.g., GPS, DInSAR, PS-INSAR), of equipment to monitor underground displacements (e.g., inclinometers), is crucial (Cotecchia et al. 2014, 2015; Ciampalini et al. 2014; Peduto et al. 2017). Furthermore, very recent experience is showing how the combination of these data with the results of building damage surveys is guaranteeing more successful assessments of landslide activity.

The integration of topographic, geological, geomorphological and geotechnical survey data, along with the results of geotechnical modelling of the equilibrium of the landslide bodies (e.g., through limit equilibrium) and of the slope stress-strain conditions (e.g., through numerical modelling), represent, on the whole, the database characterizing the ground movement conditions. Their comparison with the ground movements inferred to cause building damages, as result of the Step 2 analyses discussed above, may result in: as first, the assessment of the causes of the building damage (of whether it is caused by landsliding); consequently, also in an improvement of the characterization of the landslide activity. Hence, the last phase of the damage assessment (Phase 2.3 of Step 2 in Fig. 1), entails the implementation of the building damage maps and of the arrows indicative of the settlement geometries within a map reporting the topographic features of the area and the database quoted above as providing the characterization of the landsliding. The result of such implementation will be defined as the 'landslide damage geotechnical chart', i.e, the end-product of both Steps 1 and 2 of the *Level 1* assessment (Fig. 1).

This chart should include the geomorphological map of the urban area under study, indications about the kinematics of the landsliding, the damage grade of all the buildings for which damage appears to depend on foundation settlements, as well as the direction of the settlements causing the damage (according to Section 8 of the damage forms).

It is worth noting that the information about the settlement direction that has caused the observed damage can be considered as an innovative aspect of the methodology since similar charts present in the literature (even if based on different approaches and classifications) contains only information about the damage grade.

To assess whether the damages of the buildings are connected to landsliding, it is then required a careful comparison of the building foundation settlements, the settlements that the landslide mechanism is expected to generate and any other settlement expected to occur due to other causes. To this aim, the representation of the settlement direction in the proposed chart appears to be useful to support the identification of both the contours of the landslide body and the direction of the landslide movement.

APPLICATION OF THE METHODOLOGY TO THE TEST SITE

Geomorphological and geotechnical setting

One of the pilot test sites of application of the building damage assessment procedure presented has been the town of Bovino (647 m a.s.l.), in the Daunia Apennines, where also the Multiscalar Method for Landslide Mitigation, MMLM, has been validated (Cotecchia et al. 2016; Cafaro et al. 2017).

As for most of the urban centers in the Daunia Apennines, it lies on a promontory whose slopes are location of several ancient slow-moving landslides that have, ever since, affected the economic development of the town. As discussed in some detail by Cotecchia et al. (2014, 2015) and Cafaro et al. (2017) most of the landslides are roto-translational, from medium depth to deep and from very slow to slow. The geo-morphological map of the southern portion of the town is shown in Fig. 5. The toes of the larger landslides emerge along the river Biletra located at the bottom of the valley. The landslide activity is often made evident by cracks visible on structures and infrastructures located upslope, about the landslide rear scarps, whereas bulging is frequently noticed during spring, within the lower-middle portion of the unstable slopes.

The Apennine sector where Bovino is located is mostly made up of Meso-Cenozoic tectonic units (Sannio, Fortore and Daunia Units), that include turbiditic formations, in which limestones and sandstones are found interbedded with clayey strata. In particular, at Bovino the Faeto Flysch outcrops across the whole promontory, from North to South (Fig. 5). Only the old part of the town is founded on the Synthem of Bovino, a sequence of conglomerates interlayered with medium-coarse arenaceous strata. In general, the tectonic events have modified the original sedimentary set-up of the geological formations and often even the soil micro- to meso-structures (Nardelli et al. 2016; Silvestri et al. 2007; Vitone and Cotecchia 2011; Vitone et al. 2013a,b; Cotecchia et al. 2014). Consequently, at Bovino the clays may be locally found to be fissured and, in general, the rock strata are fractured and float as disarranged rock masses within the fine soils (Cotecchia et al. 2015).

The Pianello suburb, in the south-western part of the town, is location of the highest concentration of landslides and of the most relevant damages to structures. The largest one, i.e., body A in Fig. 5, extends from the top of the Pianello slope, where its main scarp almost overlaps the slope crest, to the toe of the slope, at the Biletra river. The geotechnical model has been derived on the basis of laboratory tests (physical characterizations and mechanical tests, i.e., oedometers, consolidated undrained triaxial tests, Bromhead ring shear tests) carried out in the laboratory on undisturbed samples taken down three boreholes during the in-situ campaign of the four year research Project PS_119 (Cotecchia et al., 2016). The experimental investigation allowed for the characterization of the weakest portion of the Faeto Flysch (FAE in the following), i.e., mainly clays of both medium to high plasticity (PI ≅ 35-55%) and activity (A ≅ 0.8-1.1) of rather poor strength (peak parameters: $c'_{min-max}$ = 0-25 kPa, $\phi'_{p\ min-max}$ = 13°-26°; residual strength, Bromhead ring-shear: ϕ'_r = 8.5°).

Only in its north-eastern portion, about the eastern side of the rear scarp, body A (Figs. 5 and 6) involves the FAE unit richer in calcareous strata. Although interbedded with the clayey strata, the strength of these strata allows for a local higher steepness of the slope. Body A has been recognized to be a deep slow compound roto-translational slide, according to inclinometer monitoring (e.g., I2 readings in Fig. 5b), which has provided evidence to a currently active slip surface at 47 m depth. This body was already present in late 1800 and it is currently active in late winter –mid spring, with rates of about 2cm/year. Both bodies B-D

(Fig. 6) are medium-deep clay-slides; body B has been assessed to be of 25 m maximum depth, based upon inclinometer monitoring and limit equilibrium back analyses.

As often observed in the Daunia Apennine, also in the town of Bovino the weakness of the clays in the slopes is connected to their high plasticity and to fissuring (Cotecchia et al. 2014) and it is one of the main factors predisposing the slopes to landsliding. At Pianello, the trigger of landslide A was most probably a deforestation taking place in mid 1800. At present, this body is moving very slowly along a deep shear band, where the operational friction angle is about 15°. Another internal factor that predisposes body A to sliding is the piezometric regime, that is characterized by very high piezometric heads down to large depths. The trigger of current reactivation of sliding for body A has been found to be the seasonal variation of the pore water pressures within the slope (Cotecchia et al. 2014), that has been monitored by means of piezometers installed from small to large depths (e.g., piezometers down P1, P2 and P3 in Fig. 5). It seems that these variations make body A be mainly quiescent in summer and active from mid-winter to mid-spring. Body B is in interaction with Body A, since it overlaps body A at its top-east portion, i.e., the steeper portion of the hillslope due to the intensifying of rock interbedding strata. It is among the most active landslides in Bovino and occurs in one of the portions of the town where building damage is most frequent, as discussed in the following.

Landslide damage assessment

As recurrently observed in the urban centers of the Daunia Apennines, the Bovino historical centre benefits from being founded on the most stable outcropping, here represented by the Synthem, a formation of cemented conglomerates (Cotecchia et al. 2014). The most recent urbanization, instead, has usually compelled the founding of buildings on the clay outcroppings and, in the case of Bovino, the new town is founded not only on high plasticity clay outcroppings of FAE, but also on soils either part of the landslide bodies shown in the map (Fig. 5), or in interaction with the landslide bodies (e.g., back of the rear scarps). As in Bovino, other common feature among the urban centers within the Daunia Apennines is the major concentration of the building damages in the depletion zones of the landslides. This seems to occur despite the different structural typologies of the buildings that, in Bovino, are mainly represented by:

- Masonry buildings: 2-3 floors; masonry vertical structures; vaults and/or composite beams (R.C. or steel) - blocks or wooden floors as horizontal structures.
- R.C buildings: 3-8 floors; R.C., composite beams (R.C.) - blocks as horizontal structures; isolated footings or strap footings or beams as foundations.

The results of the *Level 1* analyses of both Steps 1 and 2 for Bovino are mapped in the landslide damage geotechnical chart shown in Fig. 6. As result of the application of the methodology, this chart reports not only the damage grade of the buildings, but also the information concerning the direction of the settlements (arrows in the chart) reconstructed to have caused the damage through the diagnosis of the crack patterns carried out by means of the Load Path Method. The chart in Fig. 6 includes the damage grade only for those building that, according to Section 8 of the forms, resulted to be damaged by foundation settlements. In Fig. 7 some typical damage observed in Bovino are shown (the building numbers refer to those indicated in Fig. 6).

It is worth mentioning that landslide contours indicated in Fig. 6 are updated to 2010 (taking account also of the preliminary results, at that time, of the damage assessments) so that they are slightly different from those, less recent, in Fig. 5. Conversely, the damage grades and the settlement directions, as above-mentioned, are updated to the surveys performed in 2013.

The surveys were performed by teams composed of three people (i.e., a structural engineer, as leader, and two students of Master of Engineering Courses); they were carried out between

2008 and 2013 and included all the buildings located in Bovino. The surveys cannot be considered fully exhaustive because the surveyors could not enter many buildings and because buildings were restored/repainted during the damage monitoring and crack patterns were hidden for long. For the last reason, some surveys had to be repeated 2-3 times. Among the buildings reported as damaged in Fig. 6, the surveyors could enter only those marked with the asterisk '*' in the figure. No documentation was given by the municipality and, hence, general data of the buildings were acquired by interviewing the inhabitants. If the survey was limited to the external part of the buildings, it was possible to fill in about 20-25 forms per day. For complete surveys, instead, the time spent to fill in the forms depended on the dimension of the building (never more than one hour per building).

Among the damaged buildings in Fig. 6, those numbered as 10-13, 15-18, 23-24, 27 have R.C. structure while the others have masonry structure. Moreover, buildings 10-12, 15-17, 23 are public while the others are residential buildings. At the time of the surveys, buildings 16-17, 20, 26 were declared unusable by the municipality while in building 12 some retrofitting works were in progress.

According to recent information obtained by the Technical Office of the municipality, after 2013 some of the most damaged buildings in Fig. 6 were retrofitted (buildings 11 and 17), declared unusable by the municipality (buildings 8 and 15) or demolished (20 and 26). It should be specified that the retrofitting carried out on buildings 11 and 17 regarded only seismic actions and not differential settlements induced by landsliding.

Moreover, some further information about buildings 24-26 should be added. They were originally built with masonry structure in the 1960s as part of a lot of seven identical buildings. In the 1990s, because of damages due to foundation settlements, two of them (the building 24 and that between this one and building 26 in Fig. 6) were demolished and rebuilt with R.C. structure. This is noteworthy since building 24, even if recently rebuilt with a different structural typology, is again exhibiting crack patterns relevant to foundation settlements.

The landslide damage geotechnical chart (Fig. 6) shows that most the damaged buildings is located either at the back or within the crown area, or on the lateral borders of the landslides. It follows that buildings located within the landslide body are likely to be mainly subjected to ‘rigid-body’ displacements, so that they do not exhibit any damage.

The chart shows that, except for one case (i.e., the building 13 in Fig. 6), all the buildings have shown crack patterns typical of lateral settlements. Even if this aspect requires further investigation, a preliminary interpretation is proposed in the following. As mentioned above, most of the damaged buildings are located either in the crown area or on the lateral borders of the landslides. This means, firstly, that differential settlements within the landslide body are not so large to produce structural damages. The main reason of this could be that building dimensions are negligible with respect to the landslide settlement shape and, hence, differential settlements are negligible. This consideration does not apply to the borders of landslides where, in general, high values of differential settlement have been observed. Moreover, on the borders a 'hogging' landslide settlement shape is activated, which could justify why only crack patterns due to lateral settlements have been observed in Bovino (i.e., typologies a-d and l of Fig. 2). The central settlement damages observed in the internal part of building 13 (Fig. 6) can be, hence, suspected to be due to intrinsic structural defects of the building (e.g., under-dimensioning of the foundations of the internal columns).

In some cases, the landslide damage geotechnical chart (Fig. 6) shows a strict correlation between the settlement direction and the main landslide movement (for instance see buildings 6, 11-12, 20, 23, 28 in Fig. 6). Moreover, when buildings are located on the lateral borders of the landslides some torsional movement is testified by the crack patterns (e.g., buildings 16-18, 26 in Fig. 6).

As said before, landslide damage assessment at the urban scale may be very useful as indirect evidence of landslide activity in urban areas, since the assessment of landsliding in such urbanized contexts may result to be not easy if based solely on geomorphological studies.

At Bovino, the landslide contours in the chart in Fig. 6 result from geomorphological studies carried out up to 2010, whereas the structural damages are updated to 2013. This discrepancy in time clearly emerges from some discrepant results reported in the landslide damage geotechnical chart (Fig. 6). In particular:

- settlement directions of buildings 24-25 seem to suggest that these buildings should be included in the crown of the landslide body L;
- settlement direction of the building 23 shows that the crown contour of landslide C1 should be moved further south-east;
- according to settlement directions of the buildings 21-22 the crown contour of landslide body L should be moved further south-east and, hence, landslide C4 should be eliminated or its contour should be modified (e.g., moved further south-east);
- the eastern contour of landslide B should be moved further east and, maybe, the northern contour of landslide A should be moved further north to take account of settlement direction of the buildings 6 and 15;
- the western contour of landslide G should be moved further west to take account of settlement direction of the building 10.

Some further considerations are necessary about the area where the buildings 1-9 and 13 are located. The fact that in this area damages due to foundation settlements are evident in buildings built in different periods with different structural conception can be due either to the presence of a landslide not indicated in the chart or to a significantly different contour of the landslide body B.

CONCLUSIONS

This article introduces a new multi-level approach to landslide vulnerability assessment and, in this framework, it focuses on the *Steps* involving the landslide damage assessment, to both R.C. and masonry structures, at the urban scale. Although tested for slow landslides, the new methodology here presented is also applicable to other landslide conditions/activities.

Differently from what commonly found in the literature, the methodology, although dealing with the urban scale, is fully deterministic and comes out from the multidisciplinary coupling between the knowledge of structural damage mechanics and landslide geomechanics. The landslide damage geotechnical chart, that is the end-product of the application of the methodology, does not only show the level of damage to buildings but, for each building, it can include: (i) the damage grade, (ii) the identification of the possible causes of damage and (iii) the settlement direction (both reconstructed through the diagnosis of the crack patterns carried out by means of the Load Path Method), (iv) the profile of the landslide body as the outcome of both geomorphological and geotechnical studies.

The validation of the methodology within a pilot site in the south of Italy has shown that the landslide damage geotechnical chart can represent a powerful tool to detect and monitor landsliding at the urban scale even in areas where, due to urbanization, geomorphological studies are not sufficient for tracing the contours of the landslide bodies.

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FIGURE CAPTIONS

Figure 1. Approach proposed by Palmisano (2011) for the *Level 1* landslide vulnerability assessment of structures.

Figure 2. Typical damages to buildings subjected to foundation settlements. (a)-(h): masonry buildings. (i) masonry and R.C. buildings. (l), (m): R.C. buildings. $\Delta i,j$: differential settlement between nodes *i* and *j* at the origin of the crack pattern.

Figure 3. Comparison of the proposed classification with those by Burland et al. (1977) and Grüntal (1998).

Figure 4. Proposed damage classification.

Figure 5. Geological and geomorphological map of Bovino. 1) Debris, 2) Sinthem of Bovino, 3) Toppo Capuana marls, 4) Faeto Flysch (a: clayey strata), 5) geological contact (a: stratigraphic, b: tectonic), 6) landslide (a: crown, b: body), 7) continuously cored boreholes (PS_119; a: inclinometers, b: piezometers); b) inclinometer readings along borehole I2.

Figure 6. Landslide damage geotechnical chart of Bovino.

Figure 7. Some typical damages due to foundation settlements observed in Bovino (for the building numbers refer to Fig. 6).

Figure 1

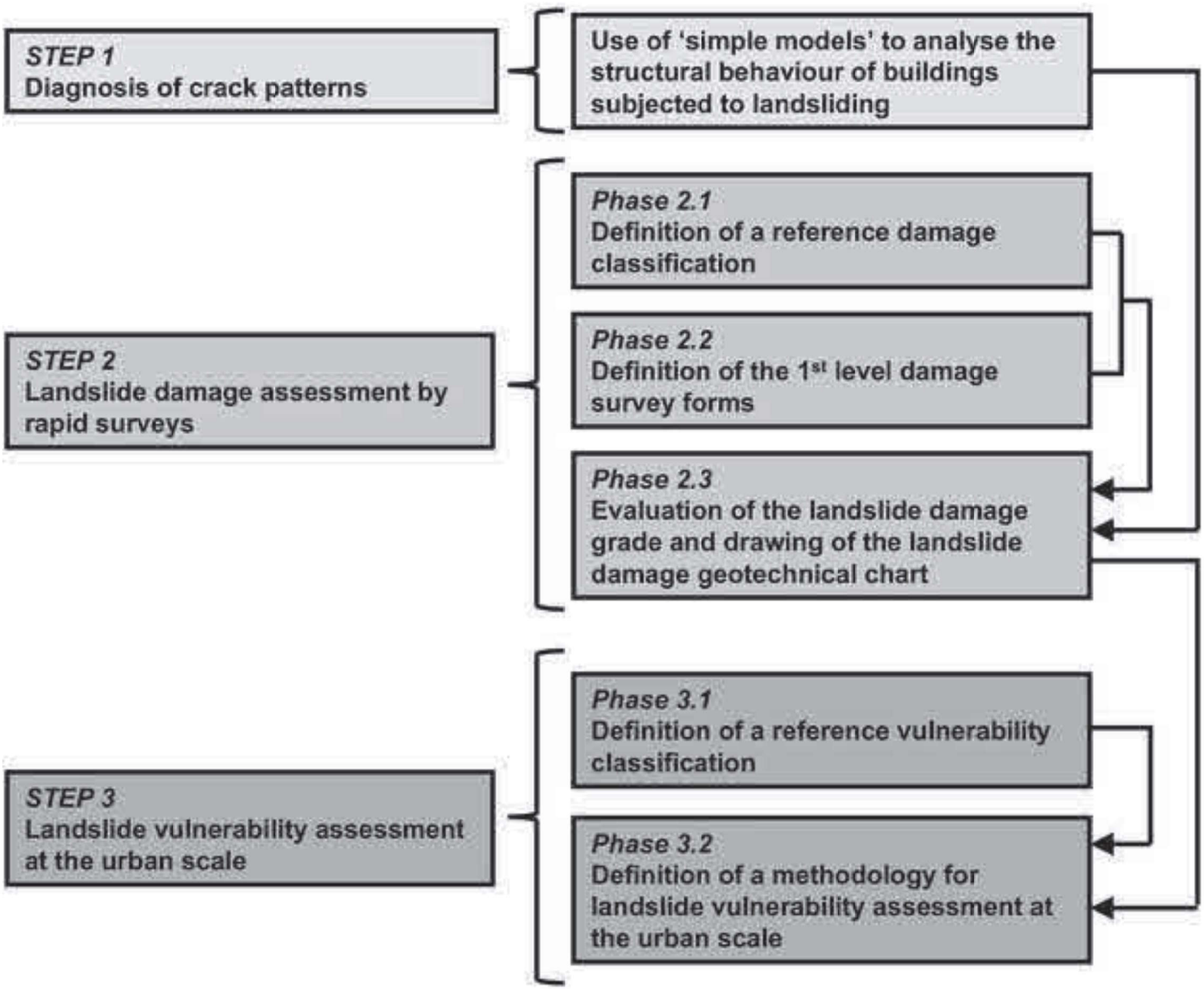

STEP 1
Diagnosis of crack patterns
Use of 'simple models' to analyse the structural behaviour of buildings subjected to landsliding
STEP 2
Landslide damage assessment by rapid surveys
Phase 2.1
Definition of a reference damage classification
Phase 2.2
Definition of the 1st level damage survey forms
Phase 2.3
Evaluation of the landslide damage grade and drawing of the landslide damage geotechnical chart
STEP 3
Landslide vulnerability assessment at the urban scale
Phase 3.1
Definition of a reference vulnerability classification
Phase 3.2
Definition of a methodology for landslide vulnerability assessment at the urban scale

Figure 2

Click here to download Figure Fig.2 rel.02.tif

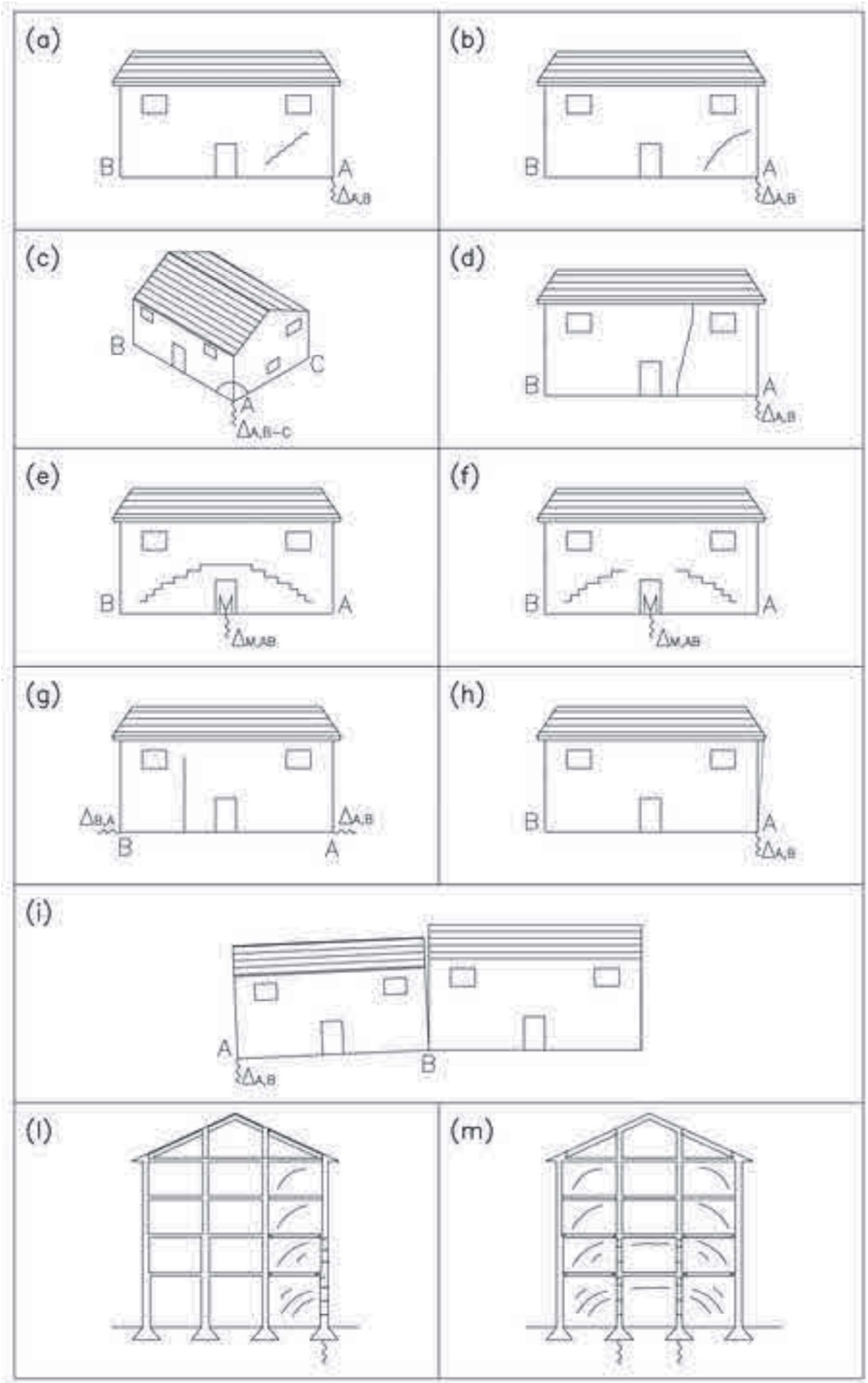
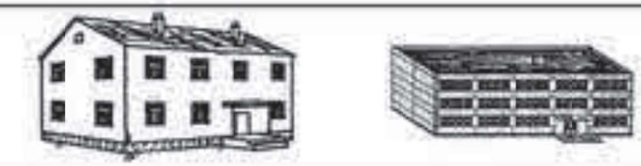
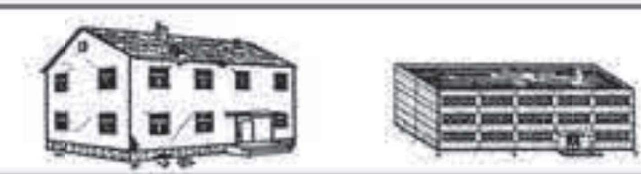
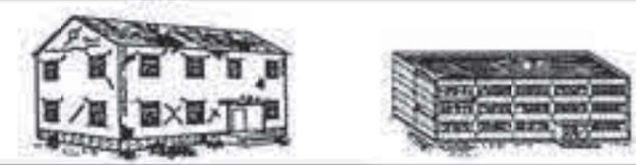
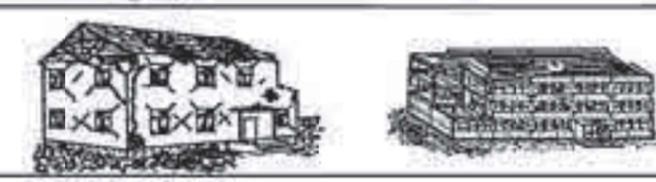


Figure 3

Burland et al. (1977) Classification		EMS 98 Classification (Grüntal 1998)		Proposed Classification	
0	Negligible			0	Negligible damage
1	Very slight	1		1	Negligible to slight damage
2 3	Slight Moderate	2		2	Moderate damage
4	Severe	3		3a	Substantial to heavy damage
		4		3b	Very heavy damage
5	Very severe	5		3c	Destruction

LEVEL OF DAMAGE

Level of damage	Description
0	No damage; crack width in masonry elements ≤ 0.1 mm; crack width in R.C. beams and floors ≤ 0.3 mm; crack width in R.C. columns, walls, nodes ≤ 0.3 mm; out of plumb of vertical elements ≤ 0.1%; reduction of steel bar diameter due to oxidation ≤ 5% of the nominal diameter.
1	Crack width in masonry elements > 0.1 mm and ≤ 1 mm; crack width in R.C. beams and floors > 0.3 mm and ≤ 1 mm; crack width in R.C. columns, walls, nodes > 0.3 mm and ≤ 0.5 mm; out of plumb of vertical elements > 0.1% and ≤ 0.2%; reduction of steel bar diameter due to oxidation > 5% and ≤ 10% of the nominal diameter.
2	Crack width in masonry elements > 1 mm ≤ 5 mm; crack width in R.C. beams and floors > 1 mm and ≤ 4 mm; crack width in R.C. columns, walls, nodes > 0.5 mm and ≤ 2 mm; out of plumb of vertical elements > 0.2% and ≤ 1%; reduction of steel bar diameter due to oxidation > 10% and ≤ 20% of the nominal diameter.
3	Crack width in masonry elements > 5 mm; crack width in R.C. beams and floors > 4 mm; crack width in R.C. columns, walls, nodes > 2 mm; out of plumb of vertical elements > 1%; reduction of steel bar diameter due to oxidation > 20% of the nominal diameter.

+

EXTENSION OF DAMAGE

Extension of damage	Description
few	Not more than 1/3 of the elements are damaged.
many	More than 1/3 and not more than 2/3 of the elements are damaged.
most	More than 2/3 of the elements are damaged.

DAMAGE GRADES

Grade of damage	Description of grade of damage for masonry buildings	Description of grade of damage for R.C. buildings
0	*Negligible damage* Damage of level 0 or damage of level 1 in few elements.	*Negligible damage* Damage of level 0 or damage of level 1 in few elements.
1	*Slight damage* Damage of level 1 in many elements or damage of level 2 in few elements or fall of small pieces of plaster only or fall of loose stones from upper parts of buildings in few cases.	*Slight damage* Damage of level 1 in many elements or damage of level 2 in few elements.
2	*Moderate damage* Damage of level 1 in most elements or damage of level 2 in many elements or damage of level 3 in few elements or fall of fairly large pieces of plaster.	*Moderate damage* Damage of level 1 in most elements or damage of level 2 in many elements or damage of level 3 in few elements or fall of brittle cladding and plaster or falling mortar from the joints of wall panels.
3a	*Heavy damage* Damage of level 2 in most elements or damage of level 3 in many elements or failure of individual non-structural elements (partition walls).	*Heavy damage* Damage of level 2 in most elements or damage of level 3 in many elements or spalling of concrete cover due to buckling of reinforced bars.
3b	*Very heavy damage* Damage of level 3 in most elements or serious failure of walls or partial structural failure of roofs and floors.	*Very heavy damage* Damage of level 3 in most elements or cracks in R.C. elements with compression failure of concrete or fracture of bars or bond failure of beam reinforced bars or tilting of columns or collapse of a few columns or collapse of a single upper floor.
3c	*Destruction* Total or near total collapse.	*Destruction* Collapse of ground floor or parts (e.g. wings, floors) of buildings.

Figure 5

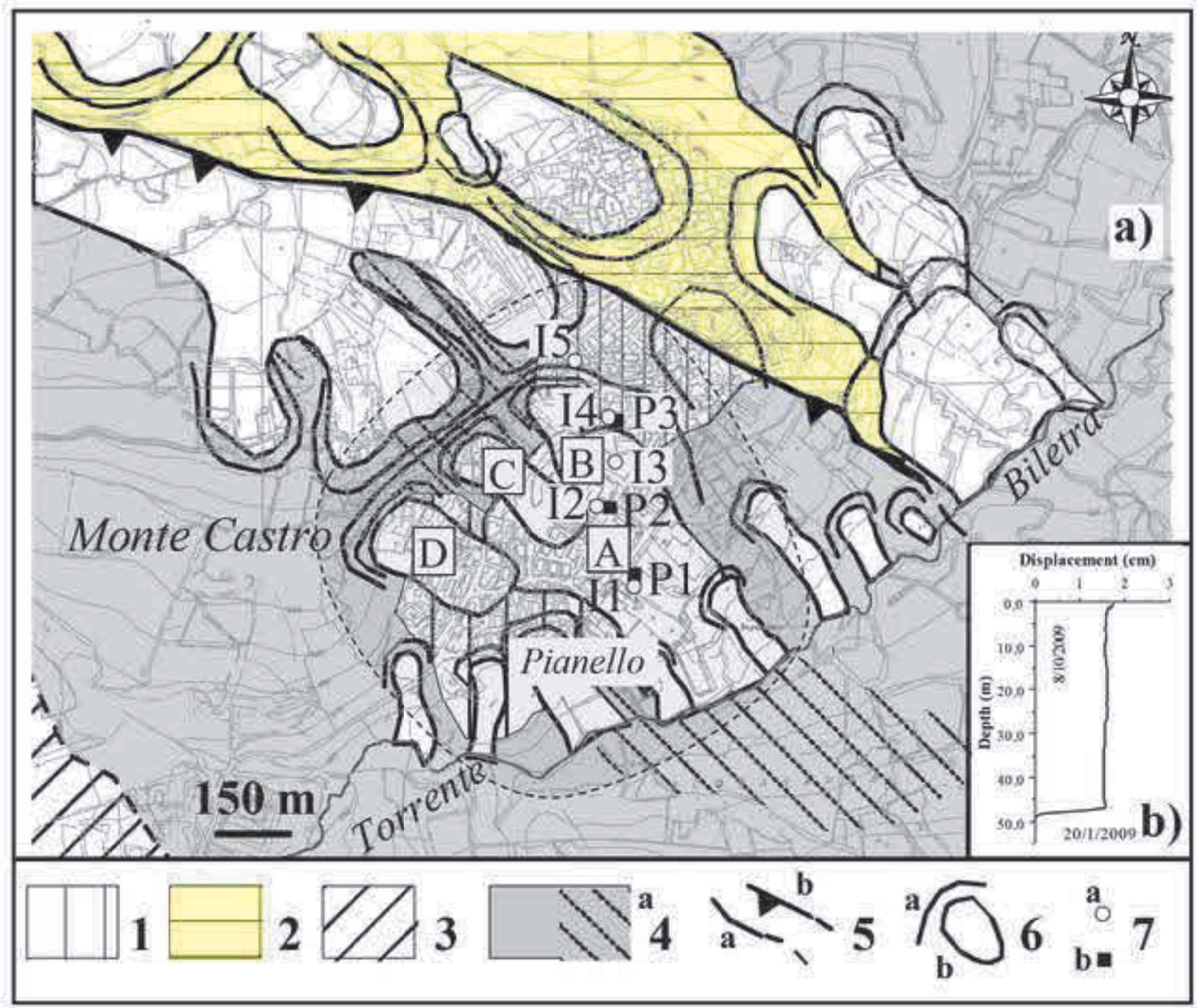
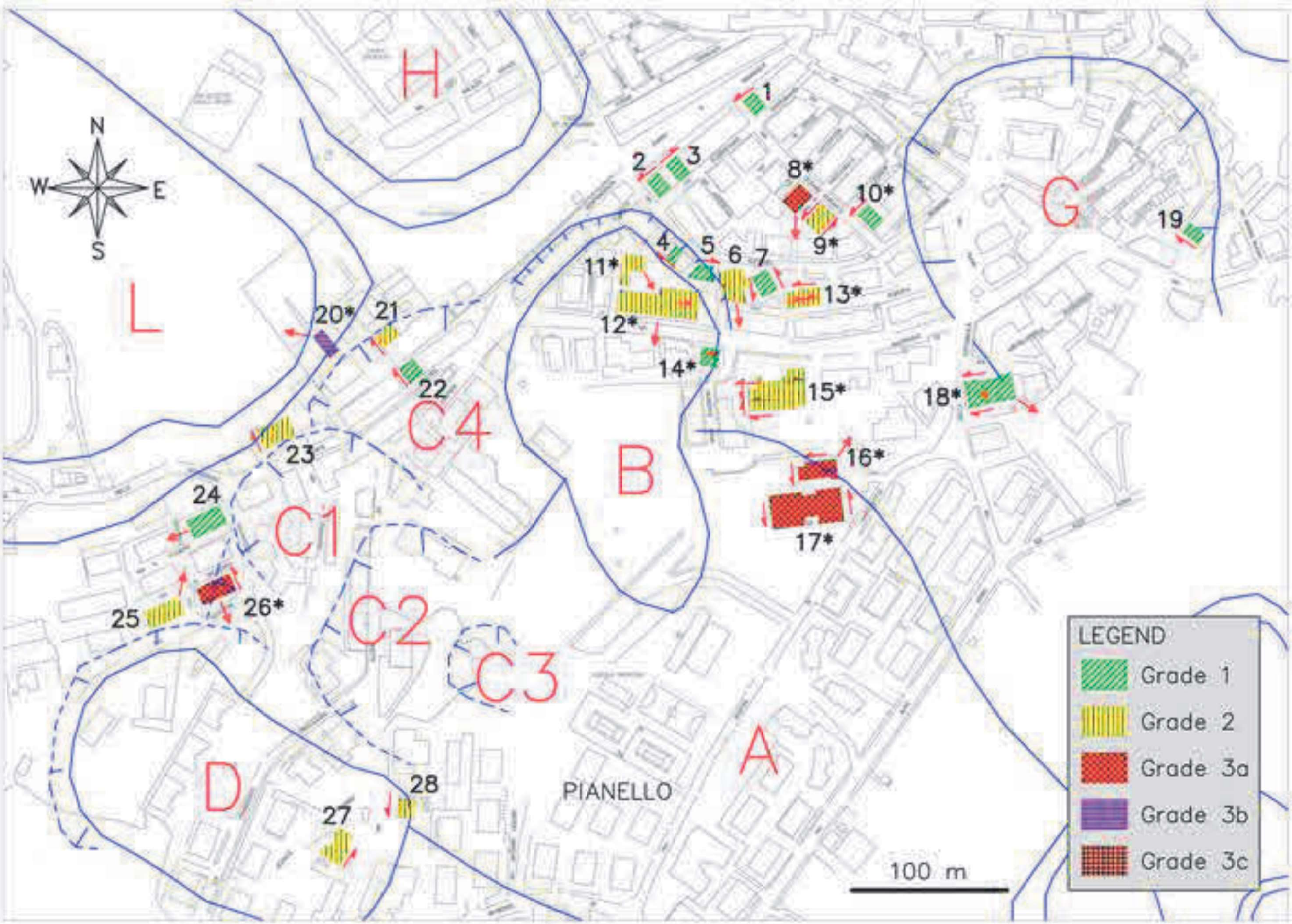

a)
Monte Castro
Pianello
Biletra
Torrente
150 m
I1
I2
I3
I4
I5
P1
P2
P3
A
B
C
D
b)
Displacement (cm)
Depth (m)
8/10/2009
20/1/2009
1
2
3
4
5
6
7
a
b

Figure 6



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building (6): masonry structure

building (8): masonry structure

building (11): R.C. structure

building (13): R.C. structure

building (17): R.C. structure

building (26): masonry structure

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Supplemental Data File 3 (to be included in the electronic version of the article)

Supplemental Data File 4 (to be included in the electronic version of the article)

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SD4. Settlement typologies rel.02.pdf

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Fabrizio Palmisano, DICAR, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy, fabrizio.palmisano@poliba.it

Claudia Vitone, DICATECh, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy, claudia.vitone@poliba.it

Federica Cotecchia, DICATECh, Politecnico di Bari, Via Orabona 4, 70125, Bari, Italy, federica.cotecchia@poliba.it

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