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1 **ASSESSMENT OF LANDSLIDE DAMAGE TO BUILDINGS AT THE URBAN**  
2 **SCALE**

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9

10 **ABSTRACT**

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

24

25 **AUTHOR KEYWORDS**

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

27

## 28 **INTRODUCTION**

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

37 In this scenario, this article intends to contribute to the advancement of landslide vulnerability  
38 assessment, through the provision of a method for both survey and analysis of damage  
39 intended to define whether it is caused by landsliding, in particular (although not exclusively)  
40 for structures interacting with slow to very slow landslides (Cruden and Varnes 1996; Hungr  
41 et al. 2014). The original methodology of damage diagnosis being proposed applies to  
42 ordinary buildings, made of either masonry or reinforced concrete, and it has been devised for  
43 vulnerability assessment at the urban scale (i.e., a scale classified as medium to large  
44 according to Cascini 2008). It has been developed through studies that have been carried out  
45 within a four-year research project (PS\_119 2007-2010), financed by the Apulia Region  
46 (southern Italy) and aimed at the definition of a landslide risk assessment methodology. Such  
47 research project has resulted in the Multiscalar Method for Landslide Mitigation (MMLM)  
48 validated in the Daunia Apennines as pilot region (Cotecchia et al. 2014, 2015, 2016).

49 In the following, the damage assessment methodology is first introduced as part of a new  
50 methodology for the vulnerability assessment at the urban scale (Palmisano 2011) and,

51 successively, it is explained in detail, with the provision of on-purpose designed survey  
52 damage forms to be used for the assessment.

53

#### 54 **MULTI-LEVEL APPROACH TO URBAN SCALE VULNERABILITY ASSESSMENT**

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

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

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

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

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

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

101 even when landslide features are hidden by urbanization or are unclear.

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

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

115 It is worth noting that the vulnerability assessment methodology here proposed is significantly  
116 different from other approaches present in the literature, which, most often, account for purely  
117 qualitative damage analyses (e.g., Liu et al. 2002; Cardinali et al. 2002; Leone et al. 1996),  
118 often for specific landslide events. Indeed, the studies of landslide vulnerability of structures  
119 are few, probably because they require multidisciplinary research work, in both structural and  
120 geotechnical engineering. Only recently structural vulnerability assessment has been included  
121 in natural hazard and risk analyses, although seldom for landslide risk. For landslides,  
122 vulnerability has been assessed mostly through the use of empirical fragility curves, derived  
123 from the qualitative survey of structural damage (e.g., Uzielli et al 2015; Peduto et al. 2017a,  
124 b). The qualitative analyses, though, result in curves that account only for the grade of  
125 structural damage, irrespective of the type of damage and of its correlation with the direction

126 of the foundation settlement causing that damage. Hence, it is evident the need for a new  
127 procedure that, starting from the mechanical analysis of the structural behavior of a building,  
128 evaluates the potential damage that it may undergo when subjected to foundation settlements  
129 due to landsliding.

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

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

144

## 145 **LANDSLIDE DAMAGE ASSESSMENT AT THE URBAN SCALE**

146

### 147 **Key features of the methodology**

148 As shown in the framework in Fig. 1, the proposed methodology starts with the definition of a  
149 new classification of reference for the damage assessment (Phase 2.1). This draws inspiration  
150 from the most relevant classifications of structural damage due to foundation settlements

151 reported in the literature, which, though, have never been related to landslide effects.

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

174 The methodology has been prompted by the study of landsliding in urban centers where  
175 landsliding is peculiarly slow, so it benefited by this particular circumstance, although it is

176 applicable also to other landslide conditions/activity.

177

178 **Building damage classification**

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

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

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

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

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

201 1998), a new building damage classification has been developed, with the specific aim to  
202 address it to landslide damage assessment at the urban scale.

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

220 The proposed classification is reported in Figs. 3 and 4; it defines six grades of damage, from  
221 0 to 3c, as the severity of the damage increases. Grades 0 and 1 relate to serviceability limit  
222 state, grade 2 to serviceability/ultimate limit state, grade 3a, 3b and 3c refer to ultimate limit  
223 state, ultimate limit state/collapse and collapse, respectively. As it can be noticed from Fig. 4,  
224 each grade of damage depends not only on its level, but also on its extension.

225 Differently from the classification by Burland et al. (1977) and from others that deal with

226 foundation settlements (e.g., Cooper 2008), the proposed classification introduces quantitative  
227 descriptions of both the level and the extension of the damage (Fig. 4) to have an evaluation  
228 of the damage grade as objective as possible trying to reduce at the minimum the subjective  
229 interpretation of the surveyor.

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

234

### 235 **1<sup>st</sup> level damage survey forms and diagnosis of the damage patterns**

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

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

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

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

- 251 • Section 1: building identification.
- 252 • Section 2: building description.
- 253 • Section 3: structural typology.
- 254 • Section 4: damage to structural elements and partition walls, existing emergency  
255 measures.
- 256 • Section 5: damage to non-structural elements (partition walls excluded) and existing  
257 emergency measures.
- 258 • Section 6: external danger and existing emergency measures.
- 259 • Section 7: further notes.
- 260 • Section 8: damage grade.

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

262 It is worth noting that even if the forms here proposed have been inspired by those by DPC  
263 (2009), they can be considered as completely different from them mainly for the following  
264 reasons:

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

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

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

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

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

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

296 In Section 2, the most important data about the building should be collected: dimensions, age,  
297 current usability, type of use and ownership, etc. It is worth noting that data to be collected in  
298 the forms should be easily found out by visual inspections. In this respect, the age of the  
299 building is a non-robust piece of information, as it can be obtained only by means of  
300 interviews, either of the owners or of the tenants of the building. The 'construction age'

301 periods indicated in the forms are relevant to the most important changes in the Italian  
302 technical standards. If the form is used in another Country, the 'construction age' periods  
303 should be updated accordingly.

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

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

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

322 Regarding masonry composed by artificial units (columns *E*, *F*, *G* in Section 3 of the masonry  
323 building form), solid units are those having hole percentage not higher than 15%, perforated  
324 units from 15% to 45% and hollow units higher than 45%. Without in-situ tests, it is quite  
325 impossible to understand the unit typology. Hence, in this case, the surveyor team should

326 select the type of worst performance (i.e., hollow units), provided that this choice is declared  
327 in Section 7. Section 3 of the forms is completed by a matrix concerning the roof structure  
328 typology.

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

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

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

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

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

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

351 even from the unsafety of distribution networks.

352 In the first part of Section 7, information about the accuracy of the survey has to be given.

353 The second part of this section is dedicated to free notes, sketches and/or further comments  
354 about the degree of reliability of the gathered information.

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

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

371 The second part of Section 8 deals with the possible causes of the damage. To this aim,  
372 according to the approach proposed (Step 1 in Fig. 1), the surveyor team becomes able to  
373 assess whether the damage is caused by foundation settlements. If this is the case, the  
374 corresponding box should be marked and a sketch of the building plan also providing  
375 indication of the direction of the settlement causing the damage is to be provided. This sketch

376 should be done only when it is possible to associate, in an objective way, the observed  
377 damage with the direction settlement. In the Supplemental Data of the online release of this  
378 article the graphic lexicon to indicate, on the building plan, the pattern of differential building  
379 settlements is shown. This lexicon applies to buildings whose cracks are evident along the  
380 boundary walls. When the damaged portion is inside, the arrows indicative of the settlement  
381 direction should be drawn inside the perimeter of the building plan. In Section 8, the box  
382 ‘undecided’ can be used either if the surveyor team is not sure if the damage is due to  
383 foundation settlements or if it can be ascribed not only to foundation settlements.

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

389

#### 390 **The landslide damage geotechnical chart**

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

399 The integration of topographic, geological, geomorphological and geotechnical survey data,  
400 along with the results of geotechnical modelling of the equilibrium of the landslide bodies

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

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

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

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

426 body and the direction of the landslide movement.

427

## 428 **APPLICATION OF THE METHODOLOGY TO THE TEST SITE**

429

### 430 **Geomorphological and geotechnical setting**

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

435 As for most of the urban centers in the Daunia Apennines, it lies on a promontory whose  
436 slopes are location of several ancient slow-moving landslides that have, ever since, affected  
437 the economic development of the town. As discussed in some detail by Cotecchia et al. (2014,  
438 2015) and Cafaro et al. (2017) most of the landslides are roto-translational, from medium  
439 depth to deep and from very slow to slow. The geo-morphological map of the southern  
440 portion of the town is shown in Fig. 5. The toes of the larger landslides emerge along the river  
441 Biletra located at the bottom of the valley. The landslide activity is often made evident by  
442 cracks visible on structures and infrastructures located upslope, about the landslide rear  
443 scarps, whereas bulging is frequently noticed during spring, within the lower-middle portion  
444 of the unstable slopes.

445 The Apennine sector where Bovino is located is mostly made up of Meso-Cenozoic tectonic  
446 units (Sannio, Fortore and Daunia Units), that include turbiditic formations, in which  
447 limestones and sandstones are found interbedded with clayey strata. In particular, at Bovino  
448 the Faeto Flysch outcrops across the whole promontory, from North to South (Fig. 5). Only  
449 the old part of the town is founded on the Synthem of Bovino, a sequence of conglomerates  
450 interlayered with medium-coarse arenaceous strata. In general, the tectonic events have

451 modified the original sedimentary set-up of the geological formations and often even the soil  
452 micro- to meso-structures (Nardelli et al. 2016; Silvestri et al. 2007; Vitone and Cotecchia  
453 2011; Vitone et al. 2013a,b; Cotecchia et al. 2014). Consequently, at Bovino the clays may be  
454 locally found to be fissured and, in general, the rock strata are fractured and float as  
455 disarranged rock masses within the fine soils (Cotecchia et al. 2015).

456 The Pianello suburb, in the south-western part of the town, is location of the highest  
457 concentration of landslides and of the most relevant damages to structures. The largest one,  
458 i.e., body A in Fig. 5, extends from the top of the Pianello slope, where its main scarp almost  
459 overlaps the slope crest, to the toe of the slope, at the Biletra river. The geotechnical model  
460 has been derived on the basis of laboratory tests (physical characterizations and mechanical  
461 tests, i.e., oedometers, consolidated undrained triaxial tests, Bromhead ring shear tests) carried  
462 out in the laboratory on undisturbed samples taken down three boreholes during the in-situ  
463 campaign of the four year research Project PS\_119 (Cotecchia et al., 2016). The experimental  
464 investigation allowed for the characterization of the weakest portion of the Faeto Flysch (FAE  
465 in the following), i.e., mainly clays of both medium to high plasticity ( $PI \cong 35-55\%$ ) and  
466 activity ( $A \cong 0.8-1.1$ ) of rather poor strength (peak parameters:  $c'_{\min-\max} = 0-25$  kPa,  $\phi'_{p \min-\max}$   
467  $= 13^\circ-26^\circ$ ; residual strength, Bromhead ring-shear:  $\phi'_r = 8.5^\circ$ ).

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

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

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

493

#### 494 **Landslide damage assessment**

495 As recurrently observed in the urban centers of the Daunia Apennines, the Bovino historical  
496 centre benefits from being founded on the most stable outcropping, here represented by the  
497 Synthem, a formation of cemented conglomerates (Cotecchia et al. 2014). The most recent  
498 urbanization, instead, has usually compelled the founding of buildings on the clay  
499 outcroppings and, in the case of Bovino, the new town is founded not only on high plasticity

500 clay outcroppings of FAE, but also on soils either part of the landslide bodies shown in the  
501 map (Fig. 5), or in interaction with the landslide bodies (e.g., back of the rear scarps). As in  
502 Bovino, other common feature among the urban centers within the Daunia Apennines is the  
503 major concentration of the building damages in the depletion zones of the landslides. This  
504 seems to occur despite the different structural typologies of the buildings that, in Bovino, are  
505 mainly represented by:

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

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

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

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

525 2008 and 2013 and included all the buildings located in Bovino. The surveys cannot be  
526 considered fully exhaustive because the surveyors could not enter many buildings and  
527 because buildings were restored/repainted during the damage monitoring and crack patterns  
528 were hidden for long. For the last reason, some surveys had to be repeated 2-3 times. Among  
529 the buildings reported as damaged in Fig. 6, the surveyors could enter only those marked with  
530 the asterisk '\*' in the figure. No documentation was given by the municipality and, hence,  
531 general data of the buildings were acquired by interviewing the inhabitants. If the survey was  
532 limited to the external part of the buildings, it was possible to fill in about 20-25 forms per  
533 day. For complete surveys, instead, the time spent to fill in the forms depended on the  
534 dimension of the building (never more than one hour per building).

535 Among the damaged buildings in Fig. 6, those numbered as 10-13, 15-18, 23-24, 27 have  
536 R.C. structure while the others have masonry structure. Moreover, buildings 10-12, 15-17, 23  
537 are public while the others are residential buildings. At the time of the surveys, buildings 16-  
538 17, 20, 26 were declared unusable by the municipality while in building 12 some retrofitting  
539 works were in progress.

540 According to recent information obtained by the Technical Office of the municipality, after  
541 2013 some of the most damaged buildings in Fig. 6 were retrofitted (buildings 11 and 17),  
542 declared unusable by the municipality (buildings 8 and 15) or demolished (20 and 26). It  
543 should be specified that the retrofitting carried out on buildings 11 and 17 regarded only  
544 seismic actions and not differential settlements induced by landsliding.

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

550 different structural typology, is again exhibiting crack patterns relevant to foundation  
551 settlements.

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

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

570 In some cases, the landslide damage geotechnical chart (Fig. 6) shows a strict correlation  
571 between the settlement direction and the main landslide movement (for instance see buildings  
572 6, 11-12, 20, 23, 28 in Fig. 6). Moreover, when buildings are located on the lateral borders of  
573 the landslides some torsional movement is testified by the crack patterns (e.g., buildings 16-  
574 18, 26 in Fig. 6).

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

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

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

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

599

600 **CONCLUSIONS**

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

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

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

618

619

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623

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729

### 730 **FIGURE CAPTIONS**

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

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

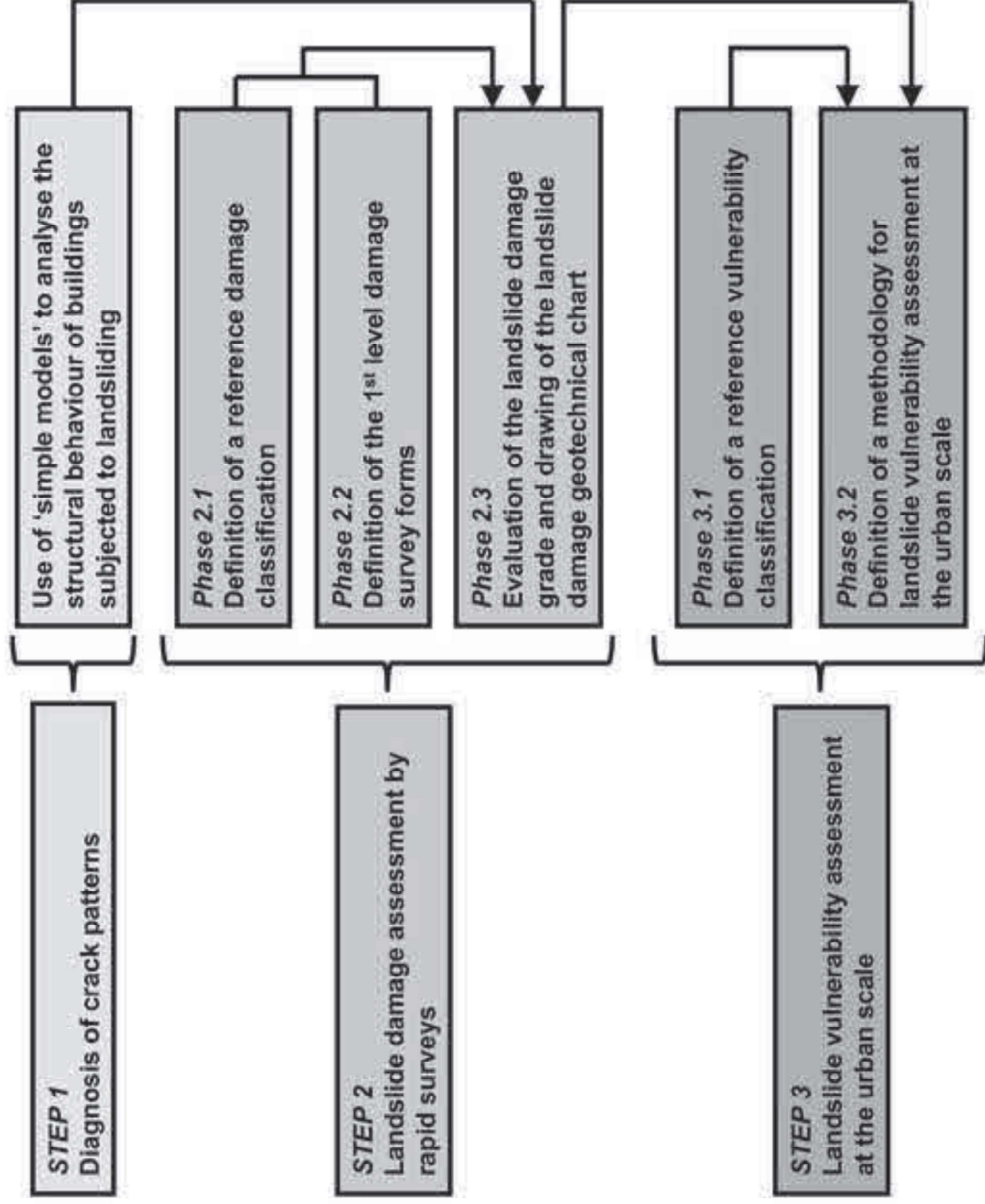
736 Figure 3. Comparison of the proposed classification with those by Burland et al. (1977) and  
737 Grüntal (1998).

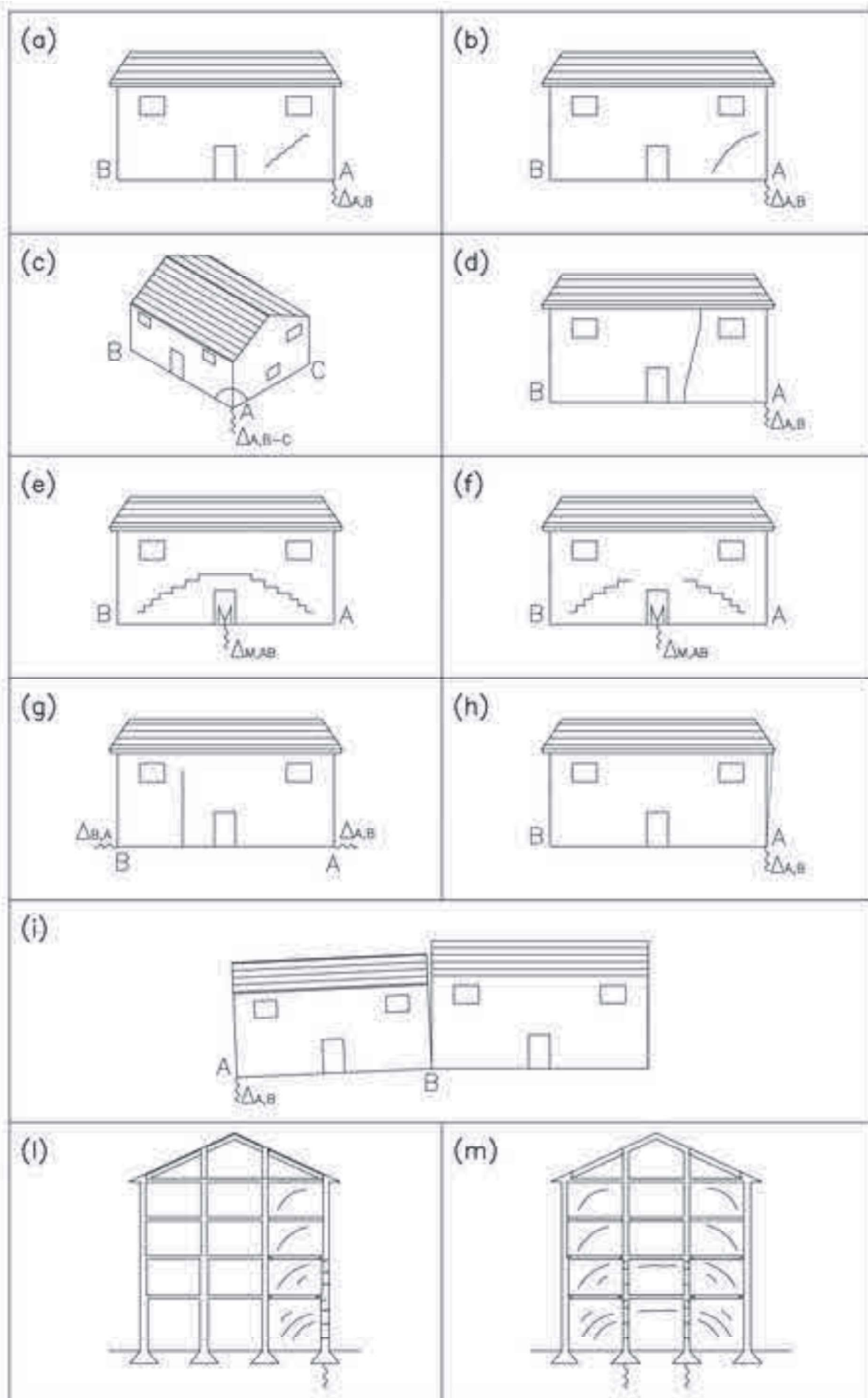
738 Figure 4. Proposed damage classification.







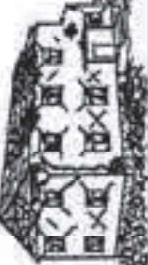



739 Figure 5. Geological and geomorphological map of Bovino. 1) Debris, 2) Sinthem of Bovino,  
740 3) Toppo Capuana marls, 4) Faeto Flysch (a: clayey strata), 5) geological contact (a:  
741 stratigraphic, b: tectonic), 6) landslide (a: crown, b: body), 7) continuously cored  
742 boreholes (PS\_119; a: inclinometers, b: piezometers); b) inclinometer readings along  
743 borehole I2.

744 Figure 6. Landslide damage geotechnical chart of Bovino.

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





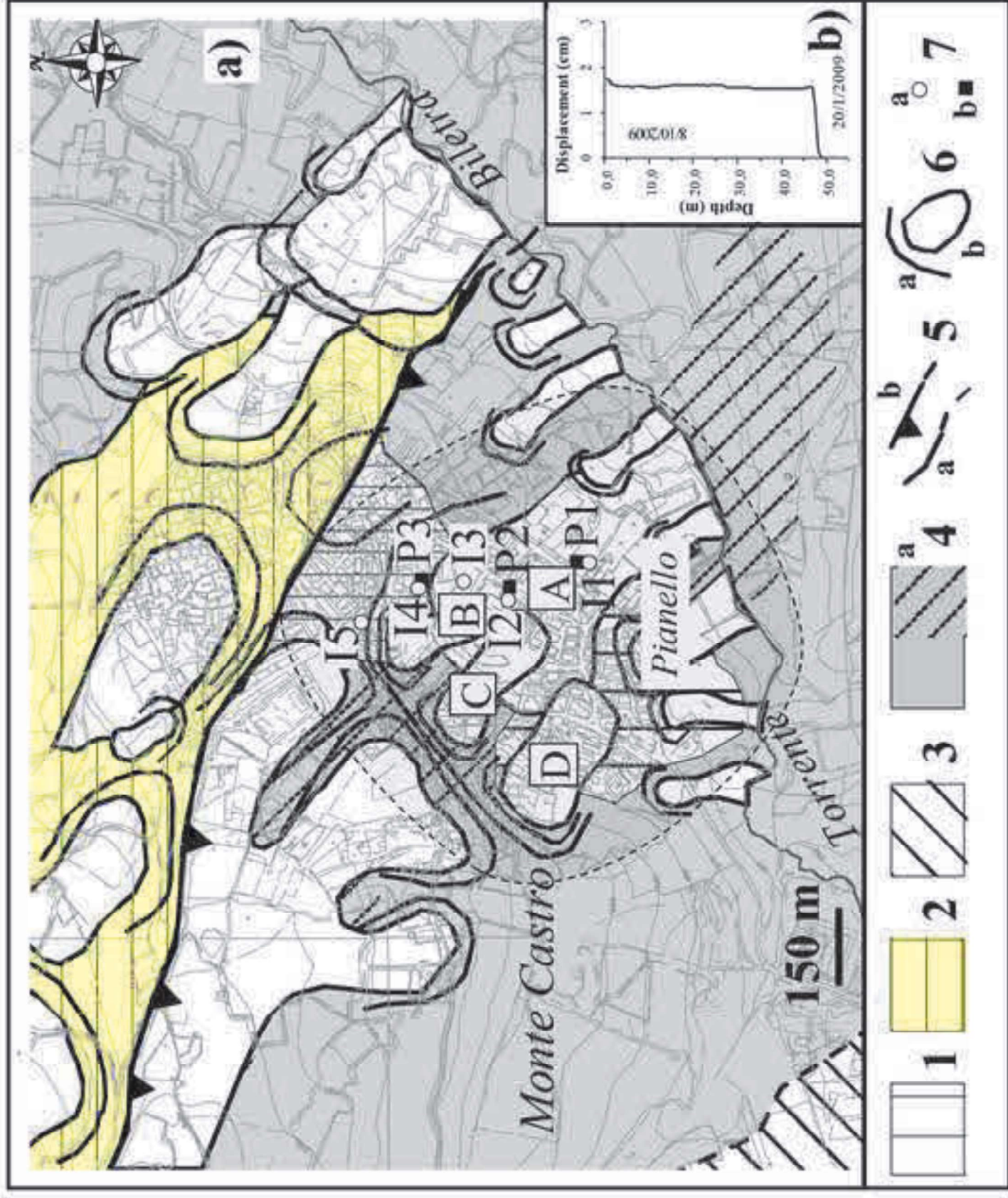
Burland et al. (1977) Classification		EMS 98 Classification (Grüntal 1998)		Proposed Classification	
0	Negligible			0	Negligible damage
1	Very slight			1	Negligible to slight damage
2	Slight			2	Moderate damage
3	Moderate			3a	Substantial to heavy damage
4	Severe			3b	Very heavy damage
5	Very severe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

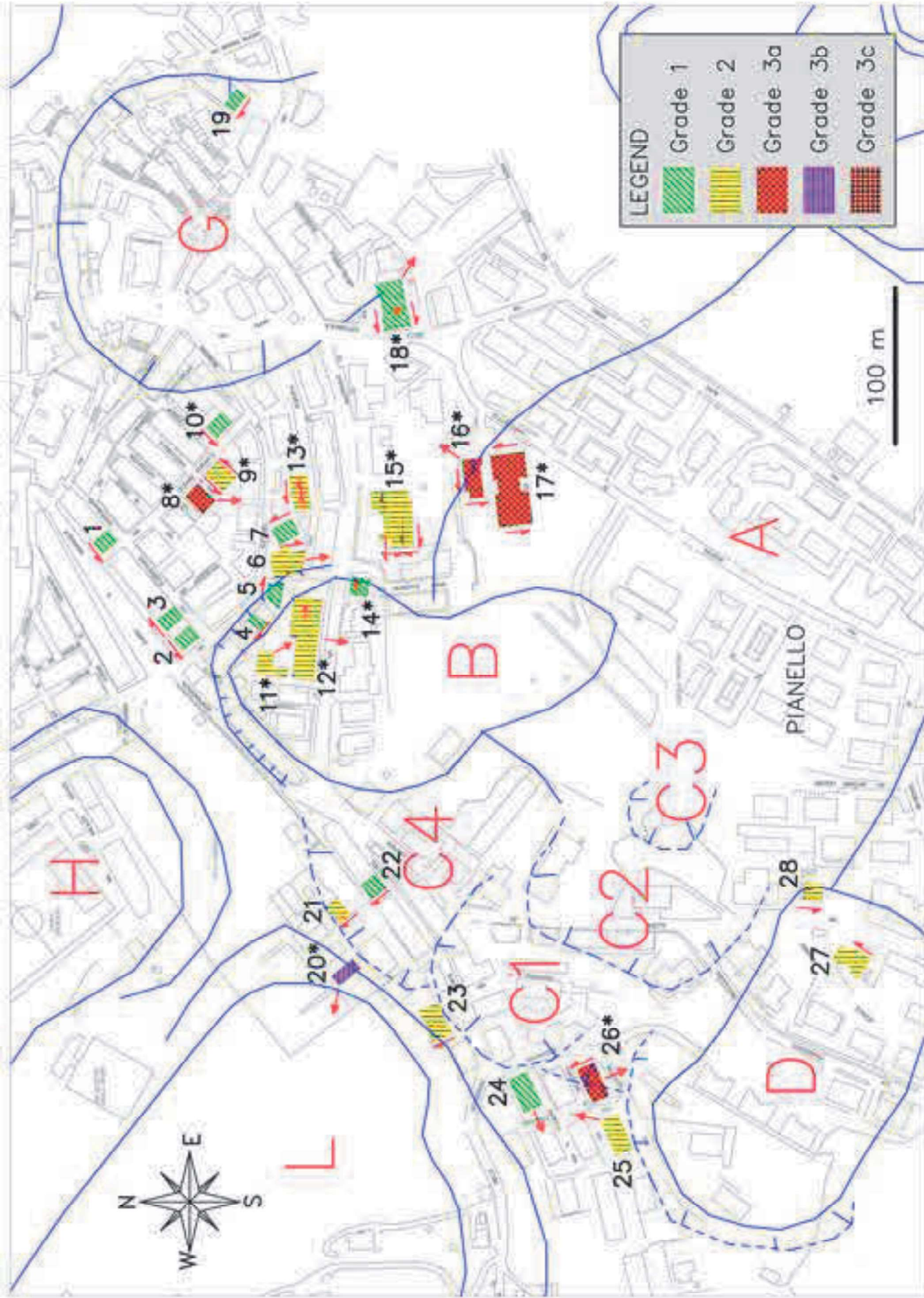
LEVEL OF DAMAGE		EXTENSION OF DAMAGE	
Level of damage	Description	Extension of damage	Description
0	No damage; crack width in masonry elements $\leq 0.1$ mm; crack width in R.C. beams and floors $\leq 0.3$ mm; crack width in R.C. columns, walls, nodes $\leq 0.3$ mm; out of plumb of vertical elements $\leq 0.1\%$ ; reduction of steel bar diameter due to oxidation $\leq 5\%$ of the nominal diameter.	few	Not more than 1/3 of the elements are damaged.
1	Crack width in masonry elements $> 0.1$ mm and $\leq 1$ mm; crack width in R.C. beams and floors $> 0.3$ mm and $\leq 1$ mm; crack width in R.C. columns, walls, nodes $> 0.3$ mm and $\leq 0.5$ mm; out of plumb of vertical elements $> 0.1\%$ and $\leq 0.2\%$ ; reduction of steel bar diameter due to oxidation $> 5\%$ and $\leq 10\%$ of the nominal diameter.	many	More than 1/3 and not more than 2/3 of the elements are damaged.
2	Crack width in masonry elements $> 1$ mm $\leq 5$ mm; crack width in R.C. beams and floors $> 1$ mm and $\leq 4$ mm; crack width in R.C. columns, walls, nodes $> 0.5$ mm and $\leq 2$ mm; out of plumb of vertical elements $> 0.2\%$ and $\leq 1\%$ ; reduction of steel bar diameter due to oxidation $> 10\%$ and $\leq 20\%$ of the nominal diameter.	most	More than 2/3 of the elements are damaged.
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.		

+

## DAMAGE GRADES

Grade of damage	Description of grade of damage for masonry buildings	Description of grade of damage for R.C. buildings
0	<i>Negligible damage</i> Damage of level 0 or damage of level 1 in few elements.	<i>Negligible damage</i> Damage of level 0 or damage of level 1 in few elements.
1	<i>Slight damage</i> 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.	<i>Slight damage</i> Damage of level 1 in many elements or damage of level 2 in few elements.
2	<i>Moderate damage</i> 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.	<i>Moderate damage</i> 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	<i>Heavy damage</i> Damage of level 2 in most elements or damage of level 3 in many elements or failure of individual non-structural elements (partition walls).	<i>Heavy damage</i> 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	<i>Very heavy damage</i> Damage of level 3 in most elements or serious failure of walls or partial structural failure of roofs and floors.	<i>Very heavy damage</i> 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	<i>Destruction</i> Total or near total collapse.	<i>Destruction</i> Collapse of ground floor or parts (e.g. wings, floors) of buildings.







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



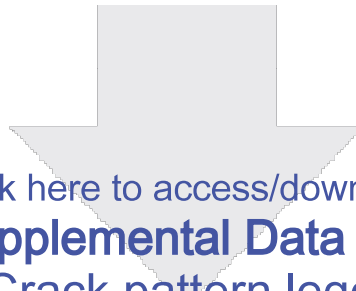
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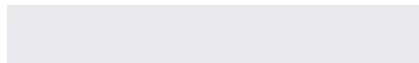
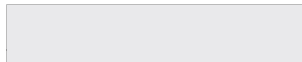


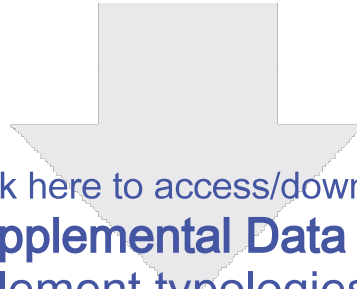
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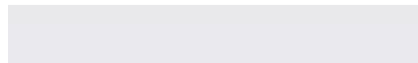
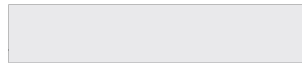


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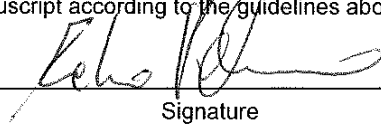
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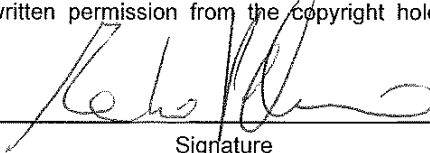
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