Real Time damage scenario: case study for the L'Aquila earthquake.

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SUMMARY:
In this paper we describe the methodology developed to calculate real time damage scenario for a seismic event, using a mechanical based method for the vulnerability assessment of buildings, Ground Motion Prediction Equations, exposure data and local site effects. The methodology has been developed for rapid assessment at regional scales, and is tested here by comparing the results with real damage data collected after the L'Aquila earthquake. In the followings we compare the results of scenarios obtained with information of different level of detail and accuracy, from national exposure and soil data used in conjunction with first hand earthquake information, to exposure data and site effects coming from detailed survey that have become available in the months following the event.

Keywords: Real time, damage scenario, vulnerability, site effects.

1. INTRODUCTION

The real time damage scenarios presented in this work are developed by integrating a routine for seismic risk assessment with a set of GMPEs which provide the ground shaking information. The routine evaluates the seismic vulnerability of a building in term of the probability to reach or exceed a certain level of structural damage for a given level of shaking. The building capacity is evaluated through a mechanical based method called in the literature SP-BELA (Borzi et al., 2008), that requires as fundamental data the height and structural typology of a building to perform a Monte Carlo simulation and produce a set of pushover curves. The building capacity is then compared with the level of shaking to evaluate the probability of damage. The comparison is done in term of capacity and displacement demand corresponding to the spectral ordinate at the fundamental period of the considered building. The degree of damage is classified in three level, namely light damage (SL1), severe damage (SL2) and collapse (SL3). In this work we consider how better quality data affect the calculated scenario, focusing in particular on the variables influencing the level of shaking, such as the type of GMPE used, site effects, fault information, and on the exposure data. We will discuss three set of scenarios produced introducing increasing level of complexity in the data utilised, starting from basic earthquake information and nationwide site effects and exposure data, to improved earthquake information, finally adding detailed exposure and microzonation data for the L'Aquila historical centre.

1.1. The L'Aquila earthquake

The damage scenario has been produced for the main shock of the L'Aquila earthquake, which occurred on the 6th of April 2009 in southern Italy. The epicentre was recorded at longitude 13.334, latitude 42.3, at a depth of 8.8 km and had a moment magnitude of 6.3. The normal fault activated in this earthquake was not immediately recognised, and several hypotheses were done in the first few days after the event. Therefore the data available in the first few days were the location of the event and the focal mechanism. The Department of Civil Protection in the following months carried out a survey for the safety assessment of buildings, classifying the damage in 6 classes, from A (safe buildings with no damage) to E (unsafe for high structural damage), with a further class utilised for buildings unsafe for external risk. The results of this survey for the private buildings are shown in Table 1.1

Table 1.1. Damage survey and safety assessment of private buildings.

Percentage	Number of buildings	Safety class
51,0%	36997	A SAFE (Small damage can be present, but negligible risk for human life)
12,5%	9056	B SAFE WITH QUICK INTERVENTIONS (temporarily unsafe)
2,7%	1958	C PARTIALLY SAFE (Only a part of the building can be safely used)
2.4%	1741	D TEMPORARILY UNSAFE (to be carefully reviewed)
26,4%	19151	E UNSAFE (high structural or geotechnical risk for human life)
5%	3642	F UNSAFE FOR EXT. RISK (heavy damaged adjacent buildings, possible rock falls, etc.)

To compare the results of this survey with the level of structural damage calculated by the real time scenario we associated each level of structural damage with different classes of building safety, as illustrated in Table 1.2

Table 1.1. Damage Correlation between structural damage grade and safety classes of the damage survey.

SL1 light damage	B	9056	12.5%
SL2 severe damage	C + D	3699	5.1%
SL3 collapse	E	19151	26.4%

Class F is not associated to any structural damage level as it is not possible to know whether the buildings unsafe for external risk where actually damaged or not, therefore the comparison of the results will be biased by the 5% buildings falling in this class.

1.2. Ground Motion Prediction Equations

We selected a set of Ground Motion Prediction Equations (GMPE) based on their goodness of fit with Italian data from the accelerometric network and satisfying the following requirements: 1) applicability in the first aftermath of the event with the minimum information available, such as earthquake location, depth and magnitude; 2) applicability of the site effects coefficients to the Italian Building Code soil classes; 3) applicability to a range of spectral ordinates and possibly calibrated for ground displacement. Based on the above requirements the chosen equations are the Cauzzi & Faccioli (2008), the Akkar & Bommer (2010) and the Sabetta & Pugliese (1996). In the followings these will be referred to as respectively the CF, AB and SP.

2. REAL TIME SCENARIO AT THE REGIONAL SCALE

2.1. Exposure data and site effects

Exposure data for this level of analysis come from the national census data (ISTAT). This database provides information on the number buildings present in each municipality subdivided by structural type (masonry or Reinforced Concrete), number of storeys and construction period in a range of ten year. By using the information present in this database we can infer the vulnerability class of masonry buildings, subdividing them in masonry of class A, B and C for high, average and low vulnerability respectively. For RC buildings we can assume seismically designed and not seismically designed buildings by comparing their construction period with the year in which the municipality they belong to was assigned to a given seismic zone by the Italian law.

Site effects were considered by using a national soil map at 1:100k scale produced by the INGV (National Institute of Geophysic and Vulcanology), that classifies soil type according to Italian building code soil categories and provides also the percentage of different soil type within the inhabited areas of each Italian municipality, following the methodology of Di Capua and Peppoloni (2009). As it is not possible to know where the single buildings are within the municipalities and on which soil type they are located, we evenly divide the masonry and RC buildings between the different soil types and calculate the scenarios by using the correspondent amplification coefficients of the GMPE of interest. Where the amplification coefficients are provided for different ranges of Vs30 rather than for soil categories, an average Vs30 for each soil class is assumed (Michelini et al.2008).

2.2. Damage scenario with first-hand earthquake information

A first example is given here of rapid damage assessment showing a scenario that can be calculated in the immediate aftermath of the earthquake with the first data available, that is epicentre location, depth and magnitude of the event. The calculated scenarios are for a fault of unknown type, and a comparison is made between results on rock and soil.

We produced different scenarios on rock and soil using three GMPEs, i.e. CF, AB and SP (the latter available only on rock), and we compare the results with the data for unusable buildings from the damage survey. Unusable buildings are the ones classified as agibility class E or F, and they can be compared with buildings reaching or exceeding the structural limit state 2. Figure 2.1 shows the comparison between the results obtained with the three GMPEs and the real data considering rock condition (a), and soil amplification effects (b).

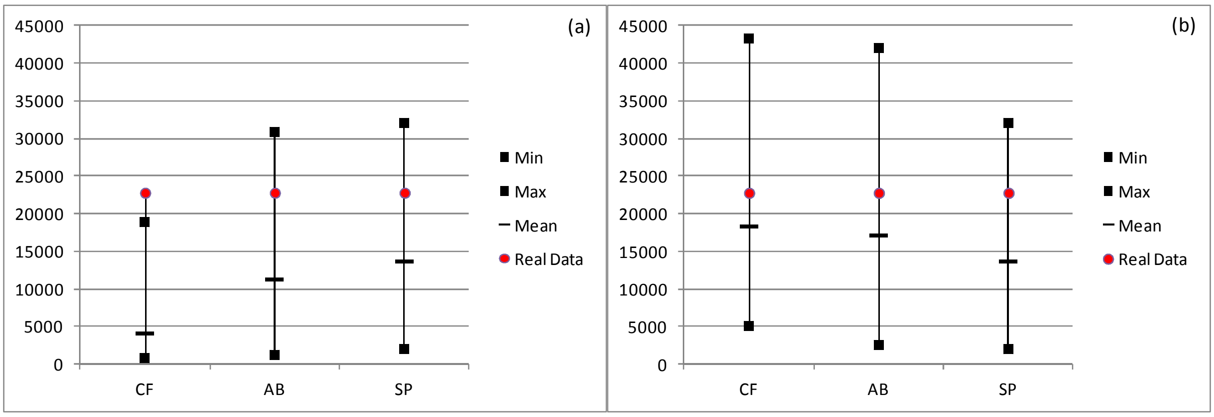

Figure 2.1. Comparison between the real time damage scenario on rock (a) and soil (b) and the real data for unusable buildings (class E + F) coming from the agibility survey. CF = Cauzzi Faccioli, AB = Akkar Bommer, SP = Sabetta Pugliese

As it can be seen the real damage data fall between the mean and maximum scenario results on rock for the AB and SP equations, while they are higher than the maximum of the CF data on rock. When using soil amplification data the damage figures on the ground are nearer to the mean values of the scenario obtained with the CF and AB equations, although they always fall above the mean. The type of site amplification coefficients used in the SP96 equation does not allow its use with the kind of soil information available in this work, and the results are repeated in the graph only for completeness.
Although the figures from the simulation scenario provide a good agreement with the damage data, the

spatial damage distribution is somewhat different. The modelled scenario shows that 95% of the damage reaching or exceeding limit state 1 occurs within 80 km from the epicentre. The real data showed that that the municipalities reaching Intensities greater or equal to 6 of the MCS scale are as far as 70 km from the epicentre, but the damage distribution is asymmetric and concentrated along a narrow band elongated roughly WNW-ESE, east of the main shock location (Figure 2.2), while west of it the damage decrease rapidly within about 20 km of the epicentre. This feature is characteristic of the L’Aquila earthquake and is probably related to directivity and near fault effects that have been recognised for this earthquake, effects that are not easily modelled with the usual GMPEs.

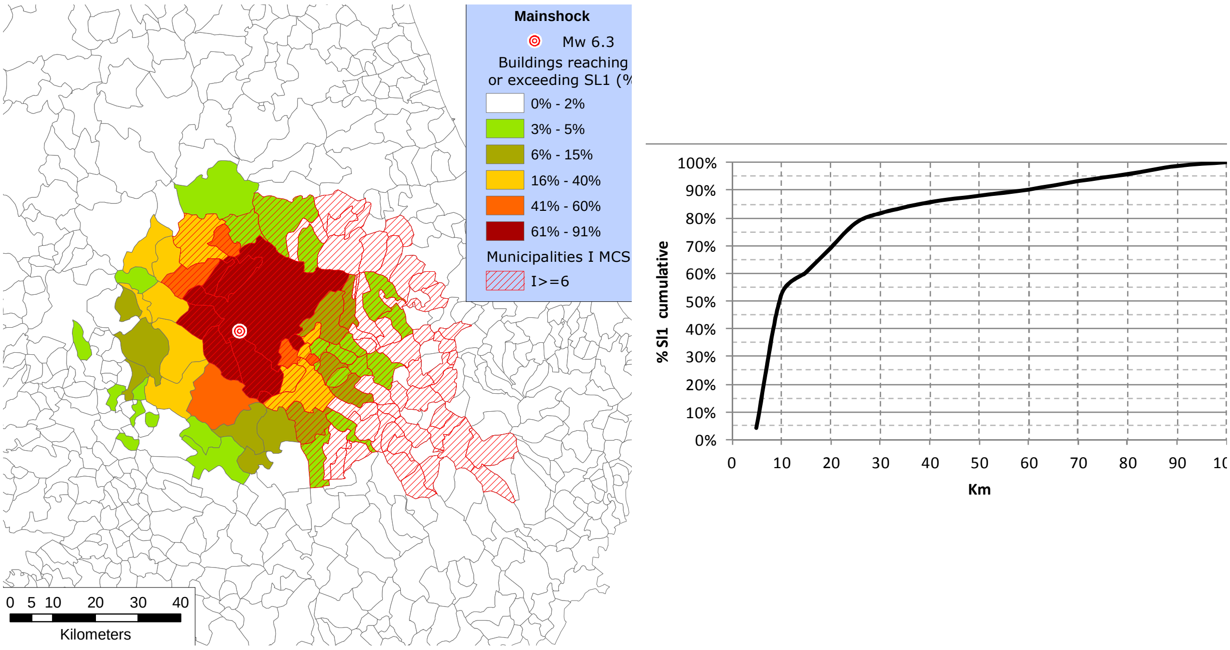

Figure 2.2. Damage scenario calculated with the CF on soil, expressed as percentage of buildings reaching or exceeding SL1 (left) in each municipality. On the right the cumulative distribution of the percentage of buildings reaching or exceeding SL1 with respect to the total damage within 100 km from the epicentre

2.3. Damage scenario with fault data

In our second example we utilised the fault mechanism and geometry that has been defined in the months following the earthquake event. The two attenuation equations that utilise the Joyner-Boore distance as metric are the AB and the SP, while the results for the CF will remain the same as such equation utilise the hypocentral distance and is not affected by the fault geometry.

The graphs in Figure 2.4 show the comparison between the real data and the scenarios produced with the selected GMPEs for the median and plus or minus one standard deviation of ground motion, expressed as percentage of the total buildings considered. The real data are obtained from the damage survey carried out in the municipalities that experienced intensities greater or equal to 6, displayed in Figure 2.2. The results of the scenarios obtained with the median of the GMPEs are lower then the real data for light damage and especially for collapse for all the three attenuation equations, with better results for the SP (in green) and CF (in blue).

All three GMPEs perform better for the three damage state when considering the 84th percentile of the ground motion, with very good fit for the light damage, and slightly higher results for severe damage and collapse. Using the 16th percentile of the GMPES the results are always underestimated, except for the light damage calculated with the SP equation. It is to be noticed that while the AB and CF ground motions are calculated using soil conditions, the SP is considered only for rock conditions.

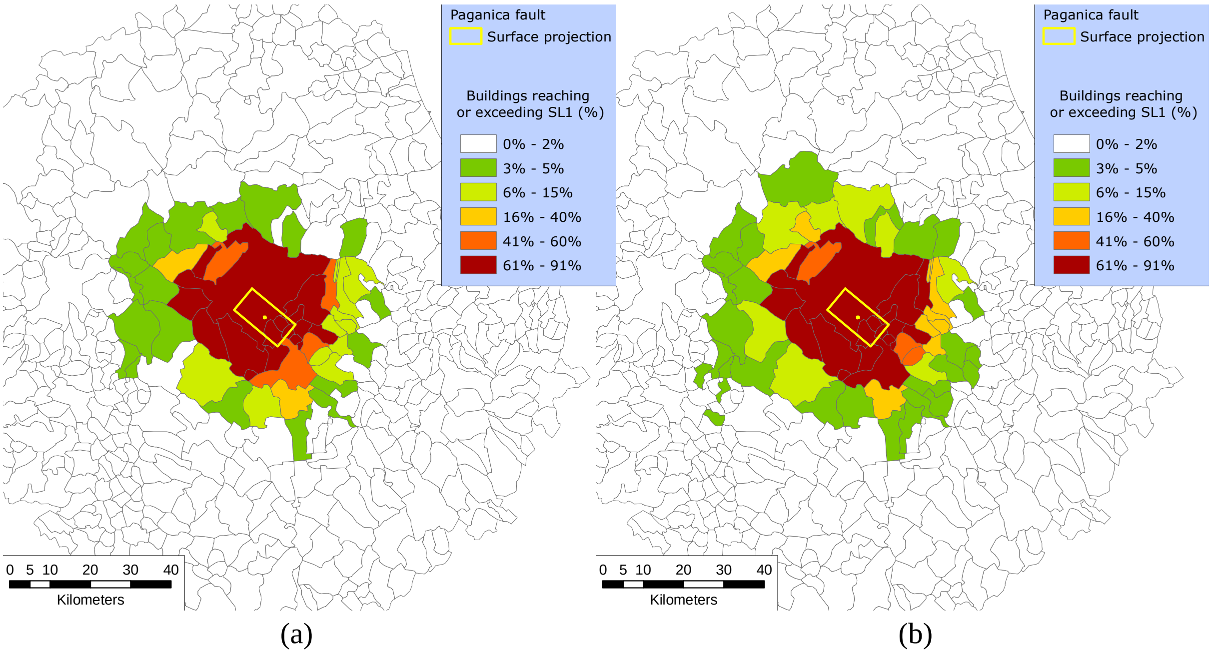

Figure 2.3. Real time damage scenario calculated using the AB10 (a) and SP96 (b) GMPEs, on soil and rock respectively, using the distance from the surface projection of the Paganica fault, recognised as the source of the L'Aquila 2009 earthquake

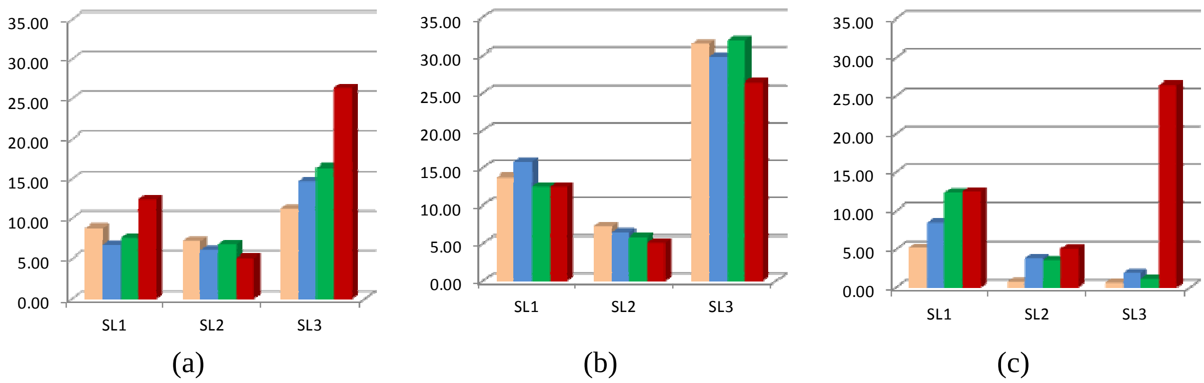

Figure 2.4. Results of scenarios obtained with three GMPEs using the median (a), +1STD (b), - 1STD (c) compared with the real data for the municipalities with I >=6, expressed as percentage of buildings experiencing the damage states SL1, Sl2 and SL3. Pink = CF, Blue = AB, Green = SP, Red = real data.

3. DAMAGE SCENARIOS AT THE LOCAL SCALE - HISTORICAL TOWN CENTRE

Detailed vulnerability data were collected for L'Aquila historical town centre by Tertulliani et al. (2011) during a damage survey of L'Aquila downtown carried out after the 2009 earthquake. We used these data to calculate a damage scenario at the local scale and compared the results with the real data coming from the cited damage survey. The scenario was modelled using the AB GMPE, and site effects coefficient were considered by taking into account both the national soil map and the results of a recent microzonation study carried out by the department of civil protection (Gruppo di Lavoro MS–AQ, 2010)

3.1. Buildings vulnerability

The vulnerability map available from the work of Tertulliani classified masonry buildings in three classes, A, B and C with increasing degree of quality, and two type of Reinforced Concrete, classified as vulnerability class C, for RC buildings without anti-seismic design and D, for seismically designed RC buildings. These data were used to assign to each building the structural type required to calculate the capacity with SP-BELA: We used the vulnerability map, together with detailed aerial photographs available for the town, to digitise the buildings and assign them the structural type corresponding to the vulnerability class, which is straightforward for classes A, B and D. To assign a structural type to the buildings belonging to the class C of Tertulliani required instead some assumptions, as both good quality masonry and RC without seismic design are classified as "C". We decided therefore to assign the buildings of more than 5 storeys to the class RC not seismically designed, while the remaining buildings with 5 or less floors would be considered as masonry. The number of storey for each building was estimated by overlaying the vulnerability layer with the service 'Edificato' provided by the Portale Cartografico Nazionale (PCN) for the main Italian towns, which has information on the building height, and we calculated it by assuming an inter-storey height of 3.4 metres for masonry and of 3 metres for RC. The building distribution obtained by all these data is shown in Figure 3.1.

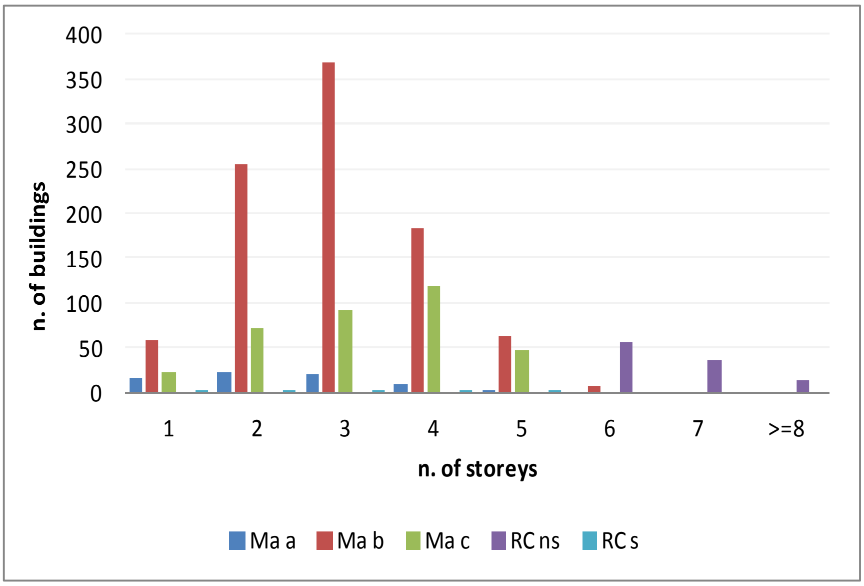

Figure 3.1. Building distribution in vulnerability classes and number of storeys for the L'Aquila historical centre. "Ma a" = Masonry - high vulnerability, "Ma b" = Masonry – average vulnerability, "Ma c = Masonry – low vulnerability", "RC ns" = Reinforced Concrete not seismically designed, "RC s" = Reinforced Concrete seismically designed.

3.2. Site effects

To consider local scale site effects we overlaid in a GIS the buildings map with the national soil map and with the microzonation map. When a regional scale scenario is performed, the information on the location of single buildings is usually not available, but only the number of buildings for each structural class within a given area is known. At the local scale we can instead assign exactly the soil class for each building considered in the calculation. For each building we therefore assigned a soil class and a Vs30 from the 100k map, called respectively soil_100k and vs30_100k. The soil class was derived directly from the soil map, while the Vs30 was inferred by using an average Vs30 for each soil class, as described in §2.1.

The microzonation data do not classify the territory in soil categories, but provide for each zone recognised as characteristic a stratigraphic log with its Vs profile, and the amplification factors FA calculated with numeric analysis performed for the characteristic profiles. As we cannot directly use the FA with the chosen GMPEs, we decided to estimate a Vs30 from the representative profiles defined for each zone. The L'Aquila town centre has been divided, in terms of FA, in two zones. The first one, in the northern part of town, comprises two zones with similar FA (Zs6 and Zs7), characterised by 20 to 50 metres of breccias with Vs = 800 m/s, followed by less than 100 to 200 metres of silts with Vs of 600 m/s. The second zone (Zs8) can be found mainly in the southern part of town and is characterised by 20 m of silts with Vs = 300 - 500 m/s, on 50 m of Brecce with Vs = 800 m/s, followed again by silts with Vs = 600 m/s. According to the Italian building code (NTC 2008) the soil category for Zs6 and 7 could be A (bedrock) or B, while Zs8 could be classified as soil E. In terms of Vs30, this could range between 700 and 800 m/s in ZS6 and Zs7, and between roughly 380 to 570 m/s in Zs8. For the purpose of the real time damage scenario we assigned a Vs30 = 700 m/s to Zs6+Zs7, and a Vs30 of 480 m/s to Zs8.

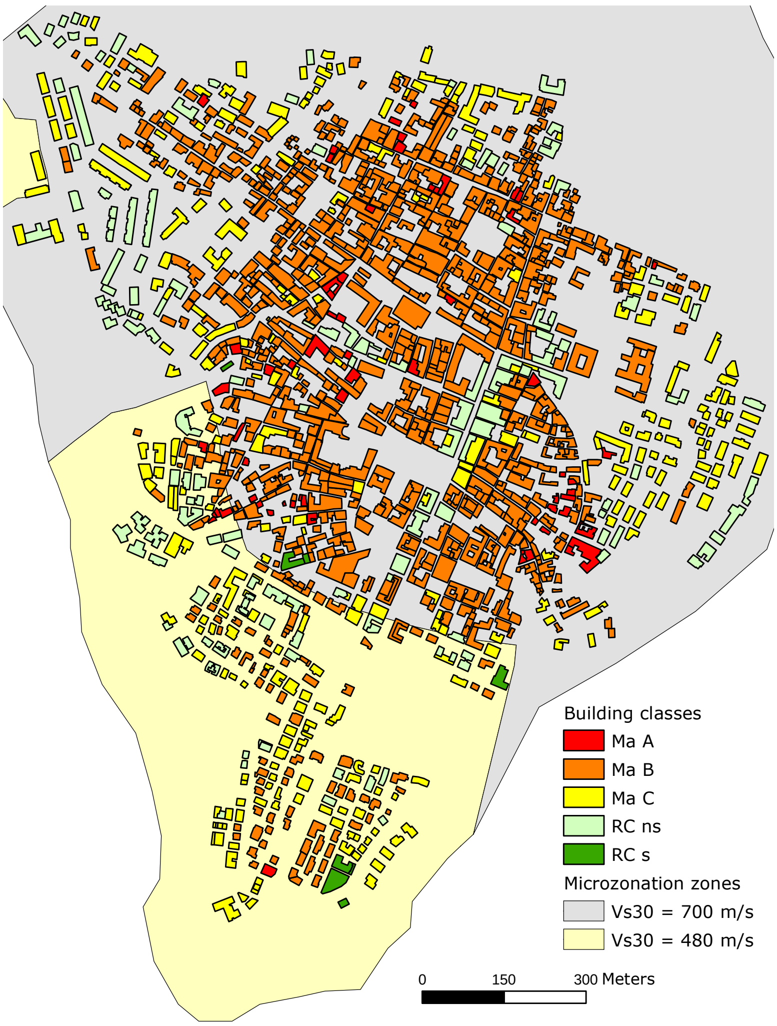

Figure 3.2. Vulnerability of the L'Aquila town centre, present study, modified by Tertulliani et al. (2011), and microzonation modified by Gruppo di Lavoro MS–AQ (2010).

The national soil map classified instead the northern part of town, more or less corresponding to Zs 6 and 7 (Vs30 = 700 m/s in Figure 3.2) as soil C, while the southern area was classified as soil B, more in agreement with the Vs30 assigned in this work.

3.3. Damage scenario results

Damage scenarios for the historical town centre were calculated using the AB equation for the median of ground shaking, considering the extended fault used in § 2.2 and with soil information as described above. The results are shown in Figure 3.3 and Figure 3.4, and compared with the real damage data collected by Tertulliani. In Figure 3.3 we see the scenario calculated using the 1:100k soil map for site effects. As we can see the buildings that experienced damage grades 4 and 5 are less in number than the buildings having a high probability (greater than 80%) of reaching the limit state of collapse SL3 in the modelled scenario. Looking at the vulnerability map of Figure 3.2 we can see that such buildings are mostly masonry of class A, B and C, while in the real scenario also a RC building in class D collapsed.

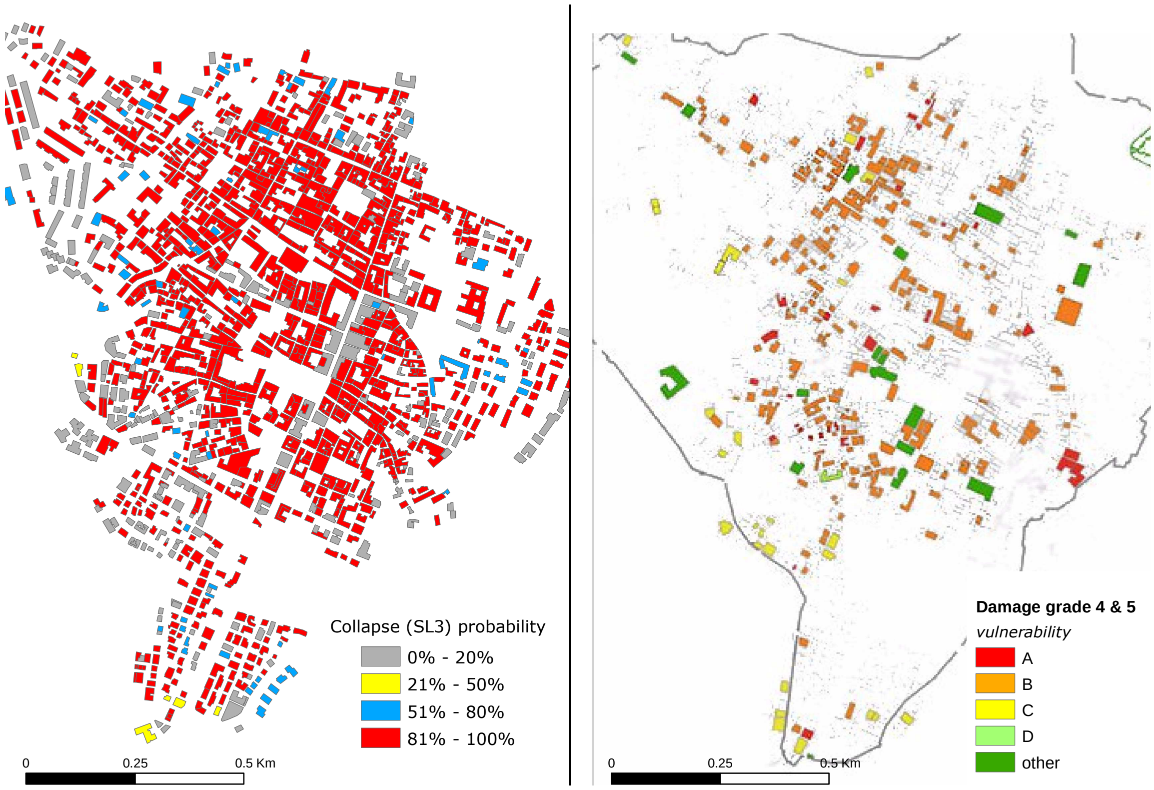

Figura 3.3. Left, damage scenario expressed in terms of probability of reaching the limit state of collapse (SL3), with site effects from the national soil map. Right, the real damage data showing the buildings experiencing damage grade 4 and 5, classified by vulnerability class (modified bye Tertulliani et al., 2011).

When using the more detailed information deriving from the microzonation study to evaluate the site effects the modelled scenario results are a better approximation of the real damage data. In Figure 3.4 we see in fact that even if we have still a higher degree of damage, compared to the real data collected, there is a better fit in the damage distribution. The buildings with high probability of reaching SL3 are mostly masonry of class A and B, with fewer C, while all RC buildings have a probability of reaching SL3 lower than 20%.

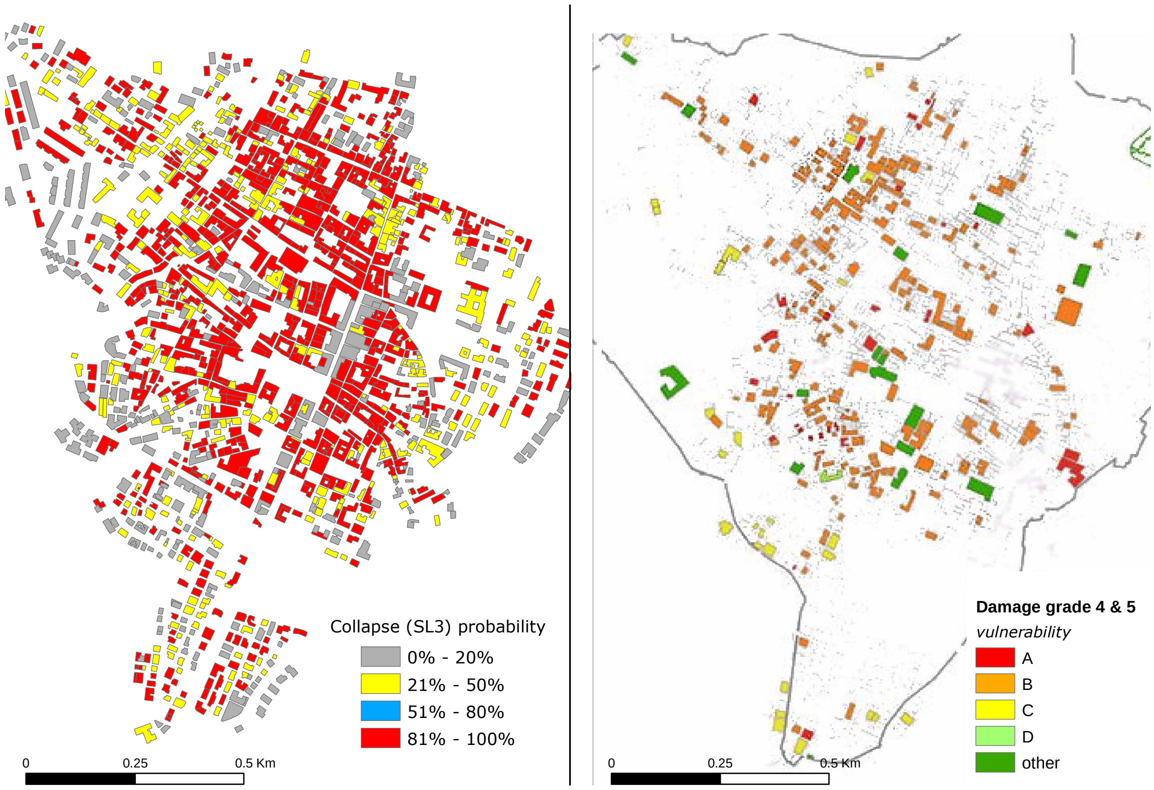

Figure 3.4. Left, damage scenario expressed in terms of probability of reaching the limit state of collapse (SL3), with site effects from the microzonation study. Right, the real damage data showing the buildings experiencing damage grade 4 and 5, classified by vulnerability class (modified bye Tertulliani et al., 2011).

4. CONCLUSIONS

We developed a routine to calculate real time damage scenarios that integrates a mechanical based method for the vulnerability assessment of buildings, exposure data, ground shaking information and soil conditions and we tested it by comparing the results with the real damage data of the L'Aquila earthquake of 6 April 2009.

We used three GMPEs, national scale exposure data and soil information to produce two scenarios that could be run in real time, with minimum information on the event required. The results of a first test run on rock and soil with the three GMPEs has shown that soil information, although with a low level of detail as the ones available at the national scale, are important to adequately quantify the damage. In fact the comparison done in terms of number of unusable buildings displays a better fit with the real data when producing a scenario taking into account site effects.

Although there is a good agreement between scenario and real data in terms of general figures, the spatial distribution of damage and the comparison with the municipalities that experienced damage intensities equal or greater than 6 are quite different, even when introducing in the calculation the extended fault and fault mechanism rather than only the epicentral location available in the first test. The comparison with the municipalities with I >=6 show the better fit for the scenarios produced with the 84th percentile of the GMPEs.

The scenarios produced with more detailed information on exposure and site conditions calculated for the historical city centre has evidenced again the importance of good quality data for site effect evaluation, as better results are obtained when using microzonation data. The comparisons have been made for the limit state of collapse and the results are overestimated by the model, contrary to the results obtained for the median of all GMPES for the regional scale scenarios.

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