13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2637

POST-EARTHQUAKE SITE EFFECT EVALUATION FROM DAMAGE AND BUILDING TYPE DATA: AN OVERVIEW OF ITALIAN RECENT APPLICATIONS

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SUMMARY

Microzonation is a crucial step in any post-earthquake reconstruction strategy in order to guarantee homogeneous safety levels. It involves the collection of a huge amount of data from several disciplines: topography, geology, seismology, geophysics and geotechnique. These data are usually costly to collect, while their collection, harmonization and analysis require a length of time, which is, often, not compatible with the reconstruction process. Recently one more discipline has been involved in microzonation, namely structural engineering. It uses the typological and damage data collected in the post-earthquake building damage and usability assessment. Different methodologies have been successfully implemented in the microzonation of several sites stricken by 1997 Umbria-Marche earthquake, 1998 Pollino earthquake and 2002 Molise earthquake. In the paper the different approaches are summarized and discussed, highlighting their advantages and limits.

INTRODUCTION

After all the recent Italian moderate earthquakes, as 1997 Umbria-Marche (Capotorti [1]), 1998 Pollino (Gullà [2]), 2002 Molise-Puglia (Casciello [3]) and 2002 Etna earthquakes (Goretti [4]), damage surveys in epicentral areas and in situ tests have shown the importance of the soil conditions on the local seismic intensity. Other European and world wide earthquakes have confirmed the importance of the phenomenon. Hence, in order to guarantee homogenous safety levels, microzonation should be one of the first steps in any post earthquake repair and reconstruction strategy. This is even more important if the strategy enforces the building upgrade or retrofitting, as occurs in Italy as a result of government financial contributions.

Site effect evaluation involves the collection of a huge amount of data of several disciplines: topography, geology, seismology, geophysics and geotechnique. These data are usually costly to collect, while their collection, harmonization and analysis require a length of time, which is, often, not compatible with the reconstruction process. The proposed solution after 1997 Umbria-Marche earthquake was a “quick” site effect evaluation based on geologic, geomorphologic, hydrogeologic and seismostratigrafic conditions and on numerical analysis on a reduced set of selected cases. The study regarded 465 urban areas and provided

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(CNR-IRRS, [5]) the local amplification to be used in the design of long term seismic countermeasures. A more detailed microzonation concerned the historic core of Fabriano, Nocera and Sellano (Marcellini [6]), some recently constructed districts in Fabriano and some localities near Nocera. Similar studies have been performed after the Pollino 1998 earthquake (Dolce [7]) and Molise earthquake (AA.VV., [8]).
Recently one more discipline, namely structural engineering, has been introduced in microzonation analysis. Several methodologies that make uses of the vulnerability and damage data, collected in the post-event survey within few months after the event, have been proposed. Pioneering works in the field compared soil properties with the building damage map (Ambrosini [9]), thus considering damage as a direct measure of the seismic motion. However, in order to be an effective measure of the ground shaking, damage has to be filtered by the building type, as vulnerability affects the damage level.
On the contrary, the following methodologies consider each building as an instrument, where the quantity to be measured is the damage and the response curve of the instrument is the seismic vulnerability, which should be known in advance. The main drawback is that such an instrument is insensitive at low seismic intensity (null damage) and saturates at high intensity (collapse). Therefore, even in a deterministic approach, seismic vulnerability cannot provide a one-to-one relationship with the soil motion, due to the null damage and collapse thresholds. Another item to be taken into account is the high uncertainty of the seismic building vulnerability when dealing with classes of structures and/or 1st level accuracy data. A complete probabilistic approach requires also considering uncertainties on surveyed building type and observed damage, as well as on the spatial correlation of the ground motion. On the other hand the number of surveyed buildings can be huge giving statistical relevance to the analysis.
The building damage and constructional type data have been successfully used in the microzonation of different sites stricken by recent Italian events, as 1997 Umbria-Marche earthquake (Goretti [10]), 1998 Pollino earthquake (Dolce [11]) and 2002 Molise earthquake (Goretti [12]). Due to different survey forms, different survey procedures and different number of surveyed buildings, the methodologies slightly differ from earthquake to earthquake. In the paper the different approaches are summarized and discussed, highlighting benefits and limits of the proposed procedures.

SEISMIC INTENSITY FROM BUILDING DAMAGE

In order to estimate the seismic intensity from the building observed damage, that is to estimate the cause (seismic intensity) that produced the effect (observed damage), an inverse problem should be solved. The building vulnerability of the affected building stock, that is the observed damage, d, when building type T is affected by seismic intensity, q, will be supposed known and with the following general expression:

$$d=f(T, q)+\varepsilon \qquad (1)$$

The function f gives the deterministic part of the cause-effect law. For simplicity, seismic intensity will be considered a discrete variable, namely the macroseismic intensity. Extension to strong motion parameters is straightforward. If building detailed data, according to 2nd or 3rd level accuracy forms, are available, Eq (1) is sometimes assumed as a deterministic relationship. This is the case of indirect vulnerability methods (Benedetti [13]), where T represents the vulnerability index. If Eq (1) is also a one to one relationship, it can be inverted, once T is known, in order to obtain q. Generally, however, Eq (1) is not a one to one relationship, because, even in the deterministic case, vulnerability models predict the building collapse (or the null damage) for seismic intensities greater (or less) then a fixed level. From the observed damage it is then impossible to estimate seismic intensities higher or lower than the above mentioned limits. In other words, when the building is undamaged all the intensities below the lower limit are admissible, while all the intensities higher than the upper limit are admissible when the building is collapsed. The physical reason for the described drawback is that the instrument of measure, i.e. the building, is not sensible enough to small seismic intensities in relation to the quantity to be measured, i.e. the observed damage. And, at the same time, the instrument saturates for high seismic intensity, when the building collapses. The upper and lower intensity thresholds clearly depend on building type, so in order to have a greater chance to estimate seismic intensity, buildings in the stricken area should have different vulnerability. Luckily, at least in Italy, earthquakes are not so destructive, while damage, due to the high building vulnerability, is often heavy. So, in many cases, seismic intensities can be effectively estimated from the observed damage, although, from a methodological point of view, the mentioned difficulties still remain.

Going beyond the deterministic approach, the uncertainty in building behavior is taken into account through the error term in Eq (1), ε, that gives the observed damage distribution conditional upon building type and seismic intensity. When the damage is assumed as a discrete variable and all the damage distribution is known, Eq (1) gives the damage probability matrix, commonly used when classes of structures and post-earthquake 1st level typological and damage data are considered. A complete probabilistic approach requires also introducing uncertainties on the observed building type and the observed building damage. Generally, the building type can not be univocally classified, due to the lack of data and/or to the uncertain attribution to a specific vulnerability class. Also damage classification can be uncertain in relation to the extension and grade of the observed damage in several building components.

Once inverted Eq (1), the intensity that affected each building, q, is known. In order to estimate the site amplification the reference intensity, q_{ref}, is also required. It can be evaluated as the spatial average of the intensities that affected the only buildings located on flat homogeneous stiff soil. The amplification of the seismic intensity can then be assumed as $F_a=q/q_{ref}$. Being q and q_{ref} random variables, also F_a is a random variable. It can be characterized by its mean or modal value, $m_{Fa}=E[q/q_{ref}]$ or $M_{Fa}=M[q/q_{ref}]$. It is not pointless noting that the variance of the seismic intensity in the affected area is a measure of the spatial variation of the seismic amplification in the area.

If q is assumed equal to the macroseismic intensity, I, the amplification can be expressed in term of increment of macroseismic intensity $\Delta I=I-I_{ref}$,. If, however, the amplification is required in terms of strong motion parameters, as Y=PGA, EPA, I_H, we have to resort to conversion laws, usually cast in the form $\log_{10}(Y)=a+bI$, where a and b are parameters. The amplification is then:

$$F_a=Y/Y_{ref}=10^{b(I-Iref)}=10^{b\Delta Ii}$$

and depends also on the term b. Several strong motion parameters have been analyzed in the following case studies and the corresponding b values are listed in table I. The relationship between amplification and macroseismic increment, according to different conversion laws, is reported in figure 1.

Table 1. b values according to several conversion laws

	PGA	PGA	PGA	EPA	EPV	I_H
Author	Margottini Local [14]	Margottini Global [14]	Petrini [15]	Decanini [16]	Decanini [16]	Decanini [16]
b	0,220	0,179	0,202	0,197	0,225	0,29

BUILDING VULNERABILITY

The physical damage caused by earthquakes will be assumed as the damage to the vertical bearing structures measured, according to the MSK 76 (Medvedev [17]) and EMS 98 (Grunthal [18]) macroseismic scales, in a discrete scale ranging from 0, the null damage, to 5, the collapse of the building. In all the following case studies, the empirical (expected) damage distribution has been obtained from the 1980 Irpinia survey on more than 30,000 buildings (CNR [19]).

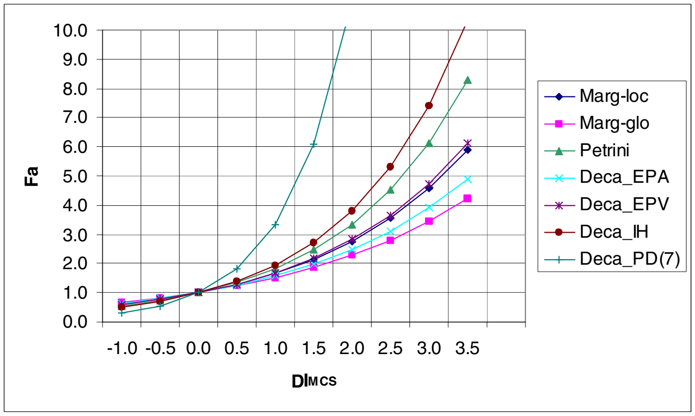

Figure 1. Relationship between amplification and macroseismic increment according to different conversion laws. PD(7) is the destructive potential evaluated for I_{MCS}=VII, according to Decanini, 2002 [16]).

Buildings have been grouped into vulnerability classes, according to the early work of Braga et al. [20], making use of the description of the vertical and horizontal building components. Macroseismic felt intensities, in MCS scale, have been re-evaluated within a Working Group recently established for the revision of the Italian building inventory and vulnerability (Angeletti [21]). From the empirical damage distribution, the empirical mean non dimensional damage has been obtained. It represents a scalar value, ranging from 0 (null damage) to 1 (building collapse), which is reported in table 2 for several intensities I_{MCS} and vulnerability classes T.

Table 2. Empirical mean non dimensional damage (1980 Irpinia earthquake)

T\\I_{MCS}	VI	VI-VII	VII	VII-VIII	VIII	VIII-IX	IX-X
A	0.209	0.245	0.296	0.372	0.396	0.506	0.725
B	0.124	0.174	0.198	0.230	0.266	0.285	0.426
C	0.030	0.093	0.104	0.102	0.094	0.076	0.185
Mixed	0.075	0.123	0.120	0.215	0.225	0.225	0.288
RC	0.023	0.035	0.062	0.067	0.091	0.060	0.267

Classes A, B and C are representative of poor, medium and good quality masonry buildings respectively, while the RC class is representative of RC buildings. In S.Giuliano case study also mixed structures have been included in the analysis, because of the local building type features. The mixed term refers only to buildings where, at the same or at different levels, masonry bearing walls are coupled with RC columns. In Castelluccio case study, vulnerability classes D, B/C and C/D, according to EMS 98 scale, have been added in order to better reproduce the non seismic RC building behavior.

Similar relationships have been used in the Fabriano case study, where the methodology requires to know in advance not only the mean damage, but also all the (expected) building damage distribution. Given vulnerability class T and macroseismic felt intensity I, it has been cast in the form:

$$P(d=k|T,I)=\{C(n,k)p(T,I)^k[1-p(T,I)]^{n-k}+\Gamma(k)g(T,I)\}/[1+g(T,I)] \quad (2)$$

where k=0,.., n=5, T=A,B, C, RC, $\Gamma=\{0\ 0\ 0\ 0\ 0\ 1\}$, C(n,k)=n!/[k!(n-k!)]. Expression (2) add up a binomial distribution and a collapse distribution. The latter one is a not null distribution only in the damage level that corresponds to the building collapse. This approach permits to accurately represent the damage distributions observed after the Italian destructive earthquakes, where the building collapse frequency is higher than the collapse frequency obtained from the binomial distribution that reproduces as best the mean observed damage. The two parameters in expression (2), p(T,I) and g(T,I), have been deduced from the empirical mean damage and collapse frequency.

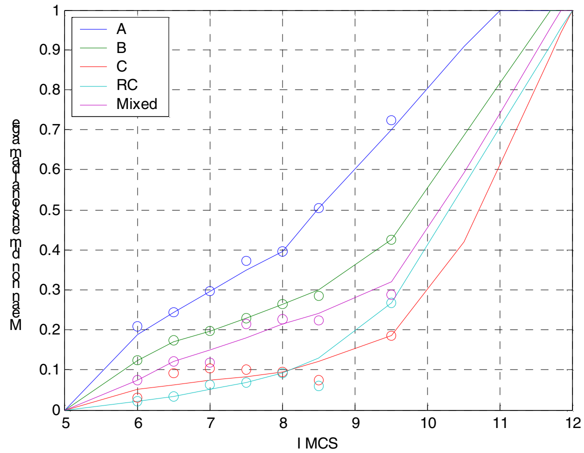

Figure 2. Mean non dimensional damage versus macroseismic intensity (MCS) for several vulnerability classes. Empirical values have been interpolated with solid lines and extrapolated to intensities up to I=XII

In RC buildings, the damage to external walls usually occurs earlier than the damage to vertical bearing structures and it can be significant also when the latter one is null. It has been shown (Masi [22]) that the damage distribution to external walls in RC buildings is very similar to the damage distribution to walls in good quality masonry buildings, at least up to an intensity of about VII MSK. For higher intensities, the parameter that better describe the RC building behavior becomes the damage to walls and columns. To take into account the aforesaid phenomenon, the following relationship has been introduced for RC buildings $P(d)=\alpha P(d_t)+(1-\alpha)P(d_s)$, where P(d) is the probability of observing damage d, d_s is the observed damage to vertical structures, d_t is the observed damage to external walls. The proposed observed damage distribution represents a continuous shifting from the observed damage distribution to infill walls to the observed damage distribution to vertical structures. The parameter α, on which the shifting is based, should be, in principle, based on the seismic intensity. However, being the damage a consequence of the seismic intensity, the parameter α will be assumed function of the observed damage to vertical structures, α=[1.0 0.9 0.5 0.2 0.1 0.0] when $E[d_s]$=[0 1 2 3 4 5]. Consequently also the vulnerability should shift from the vulnerability of good quality masonry buildings to the vulnerability of RC buildings. This is achieved assuming $P(T=C)=\alpha$ and $P(T=RC)=1-\alpha$. The described approach has been implemented only in Fabriano case study.

FABRIANO, 1997 UMBRIA-MARCHE EARTHQUAKE, CASE STUDY

Fabriano area has been stricken by the 1997 Umbria Marche earthquake (Dolce [23]). The post-earthquake damage and usability survey was performed with a preliminary draft of the form at present used by the Italian National Civil Protection. Although in Fabriano typological and damage data were collected in almost every building, data required to georefer buildings, as addresses or land register codes, were almost lacking. In order to have a complete and reliable data-base, to build up a GIS model, it has been reputed more effective to perform a new survey rather than to complete and/or modify the post-earthquake one, achieving also more homogeneous information. 883 buildings have been surveyed again (Larotonda [24]), in Fabriano historic core, where masonry buildings prevail, and in the districts of Spina Serraloggia and Borgo, where recent RC buildings prevail. All the buildings have been georeferred by means of the land register code. In the new survey, sections 1, 3 and 4 of the version 6.98 of the Italian post-earthquake damage and usability form have been filled.

Once known the observed damage d and the constructional type T of the surveyed buildings, a Bayesian approach (Benjamin [25]) can provide the probability that a building experienced a seismic intensity q:

$$P(q|d,T)=P(d|q,T)P(q_o)/[\sum_i P(d|q_i,T)P(q_{oi})] \quad (3)$$

where the summation is to be performed over the i=1,..,N_q discrete values of the seismic intensity introduced in the analysis. $P(q_o)$ is the a-priori probability that the building experienced an intensity q_o due to the occurred earthquake and does not have, obviously, any hazard meaning. It represents a local intensity distribution, but, as an a-priori estimate, it can be confused with the distribution of the seismic intensity in the whole area, $P(q_{co})$. A discussion on the possible choices of $P(q_{co})$ values will be postponed. $P(d|q,T)$ represents the building vulnerability in terms of probability of being in damage level d when building type T suffers an earthquake of intensity q. It is supposed known and given by equation (2).
If the observed building type T and the damage level d are uncertain, being all the possible damage levels and all the possible building type a complete and disjoint set of events, making use of the total probability theorem (Benjamin [25]), one gets:

$$P(q)=\sum_T\sum_d P(q|d,T)P(d)P(T) \quad (4)$$

where the uncertainties in damage and building type classification have been considered independent, although some correlation should probably exist. Then, inserting equation (3) in equation (4), one has for each building:

$$P(q)=\sum_d\sum_T P(d|q,T)P(d)P(T)P(q_{co})/[\sum_i P(d|q_i,T)P(q_{coi})] \quad (5)$$

The previous equation maps one distribution, the a priori felt intensity in the area, $P(q_{co})$, into many distributions, the a posteriori felt intensities, $P(q)$, one for each building. The main drawback of the present approach is that spatial correlation of the ground motion is neglected.
In case of deterministic building type classification, $P(T)$ should be set equal to 1 if T is the building type, while for deterministic damage classification $P(d)=1$ if d is the damage suffered by the building. The mean local intensity for each building can be assumed as $E[q]=\sum_j q_j P(q_j)$.
The a priori intensity distribution is an essential ingredient of the model and requires to be deeply analyzed. If the surveyed buildings are sufficiently uniformly spatially spaced and if they can be considered equally reliable, also the local seismic distributions $P(q)$ are uniformly spatially spaced and equally reliable. So the a posteriori distribution of the seismic intensity in the area, $P(q_c)$, can be assumed as the average distribution of the local intensities.
Neglecting the trivial assumption of non informative prior distribution, $P(q_{co})=1/N_q$, it seemed reasonable to select $P(q_{co})$ in order to reduce as much as possible the difference between the a priori and the a posteriori intensity distribution in the whole area. Moreover $P(q_{co})$ should also take into account the available strong motion recordings and/or the felt macroseismic intensity in the area. In the latter case, the felt intensity in the area, I_c, can be assumed as the mean of the a priori intensity distribution. Hence, the following integral constraint should be imposed to $P(q_{co})$: $E[q_{co}]=I_c\pm\varepsilon_I$, where ε_I is a possible error term associated to I_c. Therefore $P(q_{co})$ has been evaluated as solution of the following non linear constrained optimization:

$$\mathrm{Min}(\|1-(1/N_{tot})\sum_b\sum_d\sum_T P(d|q,T)P(d)P(T)/[\sum_i P(d|q_i,T)P(q_{coi})]\|) \quad (6)$$
$$P(q_{coi})>0,\ \sum_i P(q_{coi})=1,\ E[q_{co}]=I_c\pm\varepsilon_I$$

Buildings were grouped in four different vulnerability classes, A, B, C, and RC, according to description and performances of horizontal and vertical building components. The classification has been assumed uncertain both for lack of information on building components and for a non deterministic building classification, even when vertical and horizontal components were known. The observed damage distribution in each building, $P(d)$, has been assumed dependent on the observed damage level, D0,.., D5, and the damage extension, $e<1/3$, $1/3<e<2/3$; $e>2/3$, collected in the survey form.

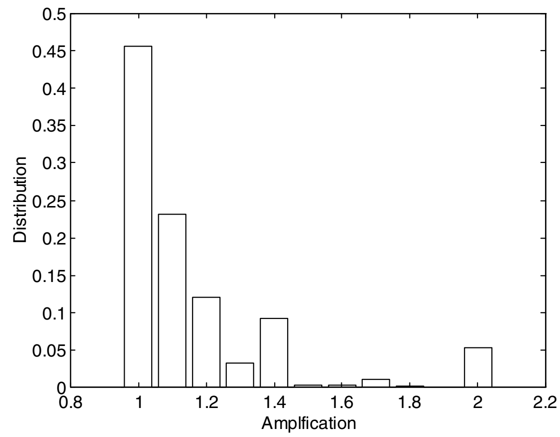

Figure 3. Distribution of the mean value of PGA amplification among Fabriano buildings.

The analysis has been limited to the following intensities I=[VI VII VIII IX] MCS. The felt macroseismic intensity in Fabriano has been assumed as I_c=VI-VII MCS (Camassi [26]), with a possible error of $\varepsilon_I=\pm0.25$. The following a priori intensity distribution has been obtained as a result of the constrained optimization in equations (6): $P(I_{co})$=[0.541 0.405 0.000 0.054] and hence $E[I_{co}]$=6.56 MCS. The distribution of the reference intensity in Fabriano has been evaluated by means of the probabilistic attenuation law proposed by Magri [27] and Albarello [28] for the following parameters: D=25 Km and I_o=VIII-IX MCS. $P(I_{ref})$=[0.633 0.291 0.069 0.007] was obtained. Hence $E[I_{ref}]$=6.45 MCS. Making use of the above a priori intensity, I_{co}, the macroseismic intensity felt by each building has been obtained. By comparison with the reference intensity, the increment of macroseismic intensity has been obtained for each building and then converted into PGA amplification (Margottini local in table 1).
The distribution of the mean amplification in terms of PGA is reported in Figure 3. For 93.3% of the buildings the mean amplification is not greater than 1.5, maximum value assigned in Fabriano detailed microzonation (Marcellini [6]). The mean value of the (mean) amplification turned out to be 1.20 and its variance 0.149, so that CV=32.2%. The mean amplification is also mapped in figure 4. The average of the mean amplification in different areas of Fabriano produced the following results: Historic core: Fa=1.16, CV=24.1% (816 buildings), Borgo Fa=2.15, CV=44.1% (8 buildings), Spina Serraloggia Fa=1.80, CV=43.2% (59 buildings).
In the detailed microzonation of Fabriano an amplification value Fa=1.5 was assigned to the new districts of Borgo and Spina Serraloggia, while amplification values ranging from 1.1 to 1.3 were assigned in the historic core, depending on the local soil properties. In particular in the SW part of downtown Fa=1.1, while in the NE part Fa=1.2. Only along the riverbed Fa=1.3 (Figure 4). Results from damage analysis seems then in good agreement with the microzonation results, especially in the historic core. In Borgo and Spina Serraloggia as well the agreement can be considered good if one takes into account that a) not all the buildings in these districts have been surveyed and b) results of detailed microzonation refer to an earthquake with 475 years return period, while the present analysis refers to a moderate magnitude earthquake. Amplifications obtained from the damage analysis have been then averaged over the areas were detailed microzonation assigned constant amplification. Then a) in the area were Fa=1.1 in the detailed microzonation, the average value of Fa=1.15 results from the damage analysis (350 buildings) and b) in the area where Fa=1.2 in the detailed microzonation, the average value of Fa=1.17 results from damage analysis (464 buildings). So the damage model does not predict any significant difference within Fabriano historical core. From figure 4, it is also evident that the spatial dispersion of the mean amplification does not permit to select areas with (almost) constant amplification. This result can be due

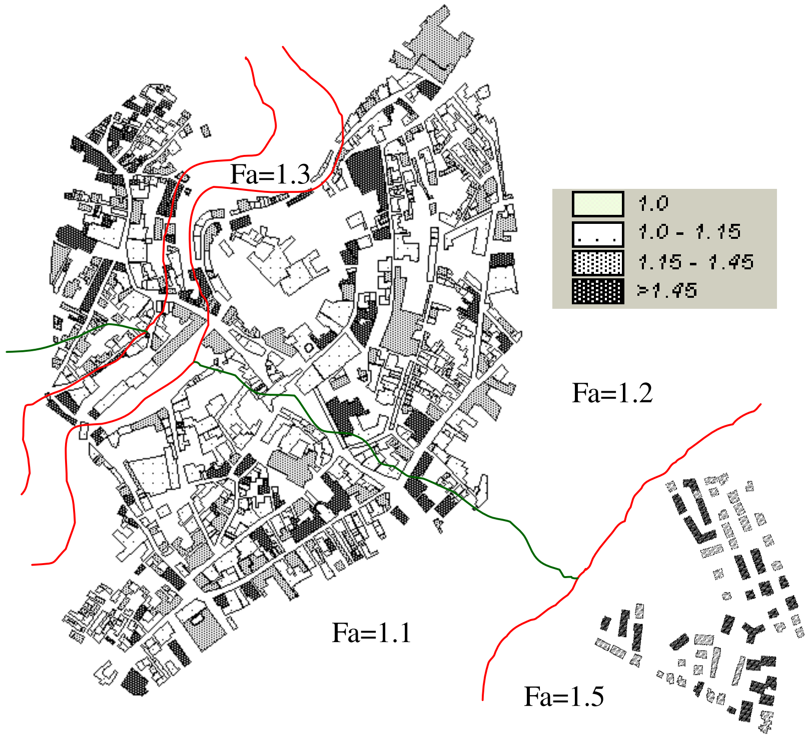

Figure 4. Map of the mean PGA amplification in Fabriano historic core and Spina Serraloggia district as result of the damage analysis. Fa values refer to Fabriano detailed microzonation.

to the lack of spatial correlation in the a priori intensity distribution as well as to building data inaccuracies.

CASTELLUCCIO, 1998 POLLINO EARTHQUAKE, CASE STUDY

Castelluccio Inferiore has been stricken by 1998 Pollino earthquake (Dolce [29]). After the event, the Basilicata Region promoted the microzonation in 27 Municipalities affected by the earthquake (Dolce [7]). The post-earthquake damage survey was performed with an updated version of the form used in 1997 Umbria-Marche earthquake.

In order to evaluate the areas with different levels of seismic intensity, an equivalent damage, d_{eq}, able to take into account the building type, has been introduced. More specifically the damage observed in each building has been transformed into the damage potentially suffered by a building belonging to the most vulnerable class, at the same site, and, hence, given the same seismic intensity. As the damage in a class of buildings is a random variable, the equivalence is obtained imposing the same non exceeding probability. The equivalent damage is then given by this integral equation:

$$F_d(d|T,I)=F_d(d_{eq}|T=A,I) \quad (7)$$

being d the observed damage in the building of type T affected by intensity I, A the most vulnerable class and F the damage cumulative distribution function (CDF). Hence to evaluate the equivalent damage, an average value of the seismic intensity and the vulnerability of the building stock should be known in advance, as in Fabriano case study.

The (expected) building vulnerability has been expressed in terms of damage probability matrices. The original DMP evaluated by Braga [20], in terms of MSK intensity, have been revised, adding vulnerability classes D, B/C and C/D in order to consider non seismic RC buildings, and extrapolated to I_{MSK}=V, an intensity not felt in the surveyed Irpinia municipalities. In contrast with Fabriano case study, the overall

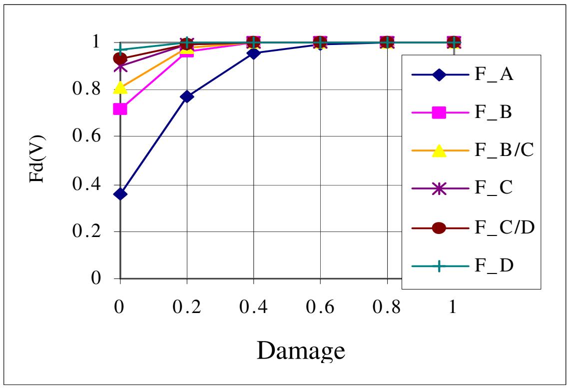

Figure 5. Damage distribution at I=V MSK

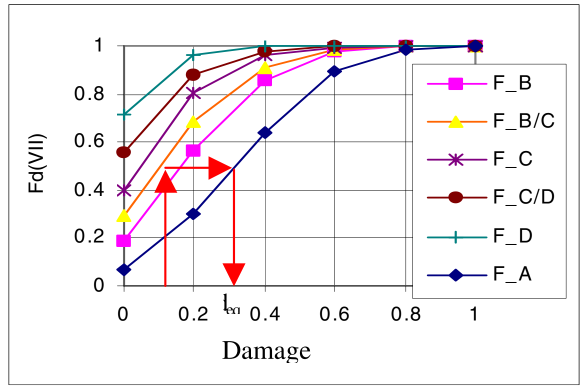

Figure 6. Damage distribution at I=VII MSK

building damage has been assumed dependent on the damage to every building component. In addition, the damage has been transformed into a continuous variable ranging from 0 (null damage) to 1 (building collapse). Hence the damage probability mass function (DPM) has been converted into a smoothed cumulative distribution function, reported in figure 5 and 6 for I_{MSK}=V and I_{MSK}=VII

In figure 6, the graphical procedure to get the equivalent damage is also highlighted. Entering with the observed damage (d=0.11) in the horizontal axis, one moves vertically up to the damage CDF relevant to the observed vulnerability class (B/C). Then one moves horizontally up to the damage CDF of the most vulnerable class (A), and finally, vertically to read the equivalent damage (d_{eq}=0.31) on the damage axis. When the building class is not the most vulnerable one and the damage is null, the model is not able to predict if a building of class A, at the same site, will be damaged or undamaged, as there is not a one-to-one relationship between the damage CDF. The same lack of uniqueness occurs if the observed damage is transformed into the damage potentially suffered by a building belonging to the less vulnerable class, when a vulnerable building collapses.

As the observed damage can be considered the effect of both building vulnerability and seismic intensity, it is not possible to establish any association between areas with heavier damage and areas with higher amplification. However, being the equivalent damage filtered by the building type, the areas with heavier equivalent damage are associated to higher amplification values.

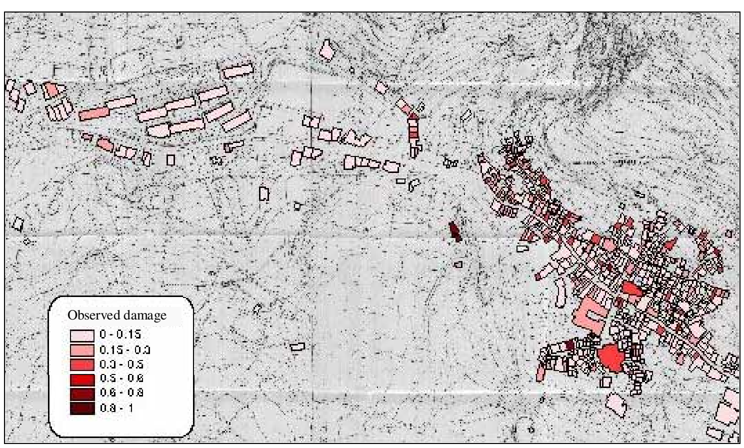

Figure 7. Map of the observed damage in Castelluccio

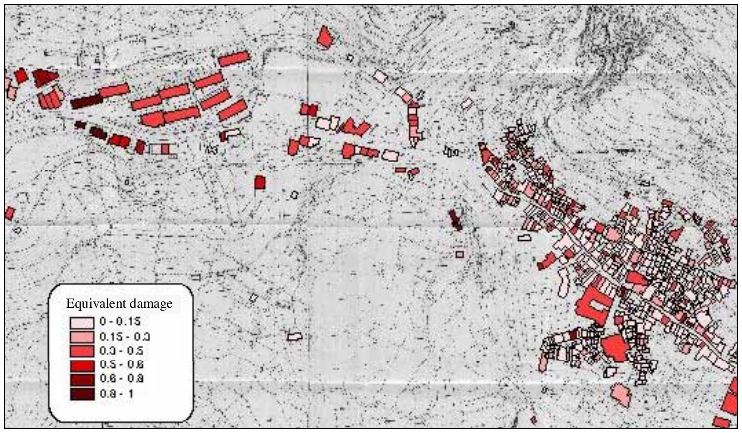

Figure 8. Equivalent damage map in Castelluccio.

This is confirmed by the damage maps of Castelluccio (Dolce [11]), reported in figure 7 (observed damage), and in figure 8 (equivalent damage). While the most damaged area is the historical core of Castelluccio, where old masonry buildings prevail (Figure 7), the area with heavier equivalent damage is a recent expansion area, where RC buildings prevail, located at the upper left part of the map (Figure 8).
The same procedure has been applied for the microzonation of two other municipalities of the same area, namely Rivello and Lauria, obtaining results consistent with the geological and geotechnical analyses.

SAN GIULIANO, 2002 MOLISE EARTHQUAKE, CASE STUDY

The area of S Giuliano municipality has been affected by the 2002 Molise earthquake, suffering an intensity of I=VIII-IX MCS (De Sortis [30]). The elementary school, built outside the historical core, collapsed producing the death of 26 children and 1 teacher.
Within the post earthquake damage and usability survey, building damage and building type data were collected on every building. Local authority and National Civil Protection technicians produced a GIS system of the urban area, where buildings were associated to the collected data. The GIS validation required additional building inspections, performed few months after the earthquake. The collapsed buildings, not inspected during the damage survey, were also inserted in the GIS.
The time restriction in delivering S. Giuliano microzonation required a simpler methodology. A deterministic approach, based on the completeness of the building survey, has been then assumed. However in order to take into account the variability in building type and damage and the spatial correlation of the soil motion, the seismic intensity experienced by the building located in $Q(x_i, y_i)$ has been evaluated by properly averaging the building type and the building damage observed in a proper neighborhood. Hence the damage distribution around each building has been assumed as:

$$f_{dli}=[\sum_j w_{ij}(x,y)\ I_{dj}]/[\sum_j w_{ij}(x,y)] \quad (8)$$

where i is the index of the generic building, I_{dj} is 0 but 1 when building j experienced damage level d and $w_{ij}(x,y)$ is a spatial weighting function depending on distance between building i and j, $\Delta_{ij.}$ As weighting functions, the constant one, the linear one and the gaussian one were possible choices in the model. From Eq (8) the mean non dimensional damage around building i can be evaluated as $p_i= m_{dli} /N_d = \sum_d d\ f_{dli} /N_d$ where N_d=5 is the number of damage levels.
Similarly the building type distribution, in the neighborhood of building i, has been evaluated as:

$$f_{Tli}=[\sum_j w_{ij}(x,y)\ I_{Tj}]/[\sum_j w_{ij}(x,y)] \quad (9)$$

where I_{Tj} is 0, but 1 when building j belongs to vulnerability class T.

The relationship reported in Figure 2, between non dimensional mean damage and macroseismic intensity, has been supposed to hold for the observed building types. It will be named $h(I_{MCS},T)$. Hence the expected mean non dimensional damage around building i, considering the observed building type distribution, can be assumed as:

$$g_i(I_{MCS})=\sum_T h(I_{MCS},T)\, f_{Ti} \qquad (10)$$

Equating the expected, g_i, and the observed, p_i, mean non dimensional damage, the felt intensity in the neighborhood of building i, I_i, can be obtained. The reference intensity has been evaluated as the spatial average of the intensities felt by buildings located on firm soil, near the historical core. This area has been deduced from geological and geotechnical results.
Data were collected with the AeDES form, rel. 5.2000 (Baggio [31]), partially different from the one used in Fabriano and Castelluccio. Hence the damage classification and the building type classification are slightly different from the previous ones. They have been based on the suggestion of the Working Group that established AeDES form (Baggio [31]). In case of unknown building type, vulnerability class A was assigned to the building. Following Di Pasquale [32], the physical damage has been assumed as an appropriate combination of damage grade and damage extension to vertical bearing structures.
Results of the model, in terms of the spatial average of the intensity, I, and amplification, F_a, over the whole urban area, are reported in Table.3. R is the radius within which local average (Eqns. 8 and 9) is performed, w_{ij} is the weighting function in R, I_{ref} the reference intensity, E[] and σ give mean value and standard deviation.

Table 3. Fa in terms of PGA using Margottini local intensity conversion law

R (m)	w_{ij}	I_{ref}	E[I]	σ_I	E[Fa]	σ_{Fa}
25	Linear	6.98	8.06	1.88	2.60	2.22
25	Uniform	7.02	8.10	1.78	2.49	2.04
50	Linear	7.10	8.19	1.65	2.37	1.76
50	Uniform	7.15	8.22	1.60	2.29	1.62
100	Linear	7.27	8.29	1.46	2.14	1.40
100	Uniform	7.43	8.36	1.38	1.99	1.24

It can be deduced that the mean value of I increases as R increases and/or when the weighting function is assumed uniform rather than linear. On the contrary the standard deviation of I reduces as R increases, obviously vanishing for extremely large values of R. Mean F_a behavior is a direct consequence of E[I] and I_{ref} behavior, and similarly σ_{Fa} follows σ_I. Again a large value of σ_{Fa} is evidence of areas with different amplification within S. Giuliano.
In figure 9 is reported the amplification map (Goretti [12]) in terms of EPA (Table 1), obtained for R=100 m, uniform weighting function within R and I_{ref} as the spatial average of intensities within the only historical core on firm soil. Several areas with different amplification can be highlighted. A small deamplification area is located at the upper left side of the historical core. Another small area of slight amplification is located at the right side of the historical core. Being this area located on firm soil and at the top of the hill, amplification can be due to topographic effects. A larger area with considerable amplification starts from the historical core and moves upward on the left and on the right sides of the new expansion area. Finally the area with stronger amplification is located outside the historical core, around the main road in the middle of the new expansion area where the school was located. A spatial averaging of the amplification within the above areas gives the values reported in the following table:

Table 4. Spatially averaged F_a values within the amplification areas

	R=50 m			R=100 m		
Fa	Mean	Std.dev	CoV	Mean	Std.dev	CoV
Area 2	1.34	0.27	19.85	1.13	0.09	7.55
Area 3	2.16	0.74	34.12	2.03	0.61	29.85
Area 4	3.36	0.77	22.86	3.20	0.37	11.69

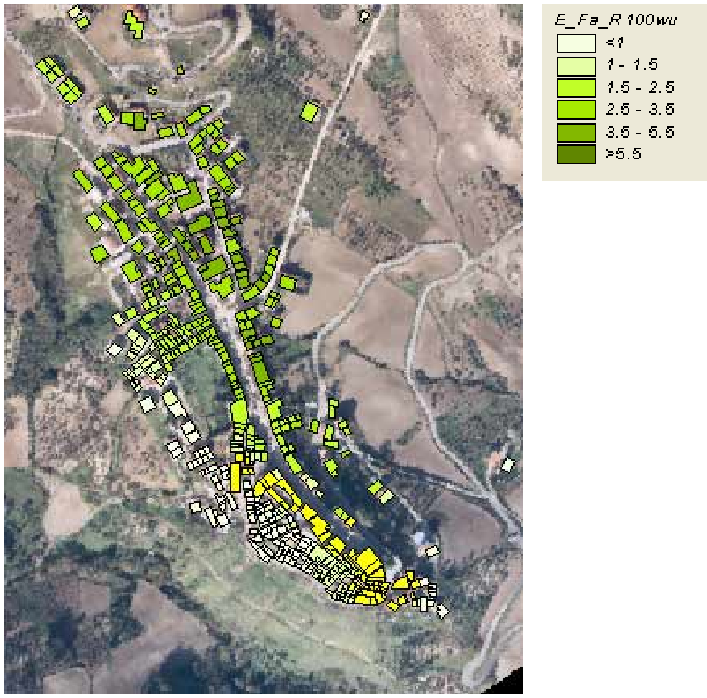

Figure 9. Map of the amplification in terms of EPA in S. Giuliano

The above results have been compared with the amplification provided by in situ measurements and numerical analysis (Baranello [33]), where the amplification has been defined as $F_A=SI/SI_{ref}$. $SI=\int PSV(T)dT$ is the spectral intensity and SI_{ref} is the same quantity measured or evaluated on a reference site (in this case the historical core). The integral has been performed between 0.1 and 0.5 sec in order to include most of the building natural period. Six seismometric stations, S#, were installed after the main shock. Results are summarized averaging Fa values in the same areas defined as above:

Area 2. S7 NS=2.2, EW=2.4; Mean 2.3

Area 3. S8 NS=2.3, EW=3.4; S9 NS=2.5,EW=1.7; S6,NS=3.2,EW=2.8;S3 NS=1.8,EW=3.0;Mean 2.5

Area 4. S10 NS=4.6, EW=3.9; SG11 NS=3.3, EW=3.2; Mean 3.7

Numerical analysis on a 2D linear equivalent model and moderate magnitude earthquake gave the following Fa values:

Area 1. A: Fa=1.05

Area 2. B: Fa=1.90, C: Fa=2.63, G: Fa=2.13, H: Fa=2.30, Mean 2.2

Area 3. D: Fa=2.50, E: Fa=2.88, F: Fa=3.24, Mean 2.87

Considering that a) recordings and numerical analysis provided Fa local values, b) seismic intensities in the different analysis were not exactly the same (aftershocks in recordings, moderate magnitude earthquake in numerical analysis and main shock in damage analysis) and c) building damage and type data were not very accurate, results from damage analysis are reputed to be in good agreement with other discipline results.

CONCLUSION

Post earthquake site effect evaluation is a necessary step in any reconstruction strategy. Although different approaches are today available, the time required for a detailed microzonation can be sometime incompatible with the reconstruction process. Hence, several complementary methodologies, aimed at evaluating seismic intensity from building damage and vulnerability data, are herein examined.

In all of them each building is considered as an instrument. The quantity to be measured is the damage and the response curve of the instrument is the seismic vulnerability, that should be known in advance. The main drawback is that buildings are insensitive at low seismic intensity (null damage) and saturates at high intensity (collapse). Another aspect to be taken into account is the considerable uncertainty of the seismic building vulnerability, when dealing with classes of structures and/or 1st level accuracy data. A complete probabilistic approach requires also to account for uncertainties on surveyed building type and observed damage, as well as the spatial correlation of the ground motion. On the other hand the number of surveyed buildings can be very high, giving relevance to the analysis.

The building damage and constructional type data have been successfully used in microzonation of several sites stricken by recent Italian events, as 1997 Umbria-Marche earthquake, 1998 Pollino earthquake and 2002 Molise earthquake. Due to different survey forms and procedures, the methodologies slightly differ from case to case. The different approaches seem powerful and promising for the following reasons:

- Observed damage and constructional building type data, collected during the post-earthquake usability and damage survey, are available few months after the events;
- The methodology can easily provide an estimate of site effects and is not as costly as other investigations;
- Results can be in terms of area with similar soil amplification or, directly, in terms of amplification;
- The high number of damaged (and undamaged) buildings gives statistical significance to the analysis;
- Results give information about the main shocks. It can be relevant in case of lack of accelerometric recordings.

On the other end some drawbacks appear:

- The (expected) building vulnerability should be known in advance. Often it has to be deduced from building surveys in occasion of other close earthquakes. In case of 1st level accuracy data, vulnerability is very uncertain. Even in case of deterministic vulnerability often a one-to one relationship between damage and seismic intensity is not guaranteed.
- The felt intensity or any other measure of the soil motion should be known in advance, at least as a prior estimate;
- The surveyed data are 1st level accuracy data. The accuracy and homogeneity of the data is then questionable.
- An extrapolation from the felt intensity to the design earthquake is required.

Considering the different proposed methodologies the following conclusion can be made:

- The equivalent damage approach is the simplest and quickest one. However it can just identify areas with different amplification, not providing any quantitative information about site amplification;
- The methodology used in Fabriano seems the most accurate one. It provides, via a bayesian approach, the spatial variation of the soil amplification, considered as random variables. However it requires the a priori estimate of the distribution of the soil motion. As the latter one has been obtained from a non linear constraint optimization, the computational effort is greater than in the equivalent damage approach;
- The approach used in S.Giuliano seems a good compromise between accuracy and simplicity. However it requires an exhaustive building survey in the affected area. The methodology is able to take into account, though in an approximate way, the spatial correlation of damage, building type and soil motion.

Future developments of the methodology will be devoted to introduce spectral accelerations as measure of the ground motion, to cast the problem in the framework of the theory of estimate and to take into account all the epistemic and aleatoric uncertainties and their (possible) spatial correlation. Finally, it is worth to mention that, due to the power of the methodology, the damage analysis has been strongly suggested, by Molise Region, as one of the disciplines to be considered in the microzonation of the municipalities affected by the Molise 2002 earthquake.

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