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SPATIAL CLUSTER ANALYSIS AND SITE EFFECTS IN SAN GIULIANO BASED ON BUILDING CONSTRUCTIONAL AND DAMAGE DATA COLLECTED AFTER 2002 MOLISE EARTHQUAKE

Abstract. The paper reports the methodology used to evaluate site effects in S. Giuliano based on constructional building type data and building damage data collected just after the 2002 Molise-Puglia earthquake. The analysis has been performed within the Working Group established by the Italian Civil Protection Department in order to deliver S. Giuliano microzonation map. Despite the necessary approximations within the proposed methodology and the data inaccuracies, results clearly show that in the historical core the seismic intensity (MCS) has been 2 degree less than in the new expansion area. In addition spatial cluster analysis on the soil motion amplification highlights a clear-cut boundary between the stiff soil in the historical core and the soft soil in the expansion area.

ANALISI DI CLUSTER SPAZIALE E VALUTAZIONE DEGLI EFFETTI DI SITO A SAN GIULIANO A PARTIRE DAI DATI TIPOLOGICI E DI DANNO DEGLI EDIFICI RILEVATI DOPO IL SISMA DEL MOLISE 2002

Riassunto. Il lavoro illustra la metodologia utilizzata per valutare gli effetti di sito a San Giuliano a partire dai dati tipologici e di danno degli edifici, raccolti in emergenza dopo il sisma di Molise-Puglia del 2002. Le analisi sono state condotte nell'ambito di un Gruppo di Lavoro istituito dal Dipartimento di Protezione Civile al fine di produrre le mappe di microzonazione sismica di San Giuliano. Malgrado le inevitabili approssimazioni nella metodologia proposta e le inaccuracy insite nei dati raccolti in emergenza, i risultati mostrano chiaramente che nel centro storico l'intensità risentita è stata di circa 2 gradi MCS inferiore a quella risentita nell'area di espansione. Analisi di cluster spaziale sull'amplificazione del moto del suolo hanno successivamente evidenziato un chiaro confine tra il suolo rigido del centro storico ed il suolo soffice dell'area di espansione.

INTRODUCTION

After all the recent Italian moderate earthquakes, as 1997 Umbria-Marche (Capotorti, 1997), 1998 Pollino (Gullà, 2001), 2002 Molise-Puglia (Casciello, 2003) and 2002 Etna earthquakes (Goretti and De Sortis, 2003), 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.

Site effect evaluation involves the collection, harmonisation and analysis of a huge amount of data coming from several disciplines: topography, geology, seismology, geophysics and geotechnique. Recently one more discipline, namely structural engineering, has been introduced in microzonation analysis and several methodologies that make uses of the vulnerability and damage data, collected few months after the event, have been proposed. Pioneering works in the field compared soil properties with the building damage in Rome (Ambrosini, 1986), thus considering the damage as a direct measure of the seismic motion. Brambati et al. (1980) compared building damage, period of the first natural mode of vibration and soil stratigraphy in Tarcento. More recently (Goretti and Dolce, 2004a), each building has
been considered 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. Only when filtered by the building type, damage can be considered an effective measure of the ground shaking. The main drawback of this approach is that building 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 1\textsuperscript{st} level accuracy data. A probabilistic approach that considers uncertainties on surveyed building type and observed damage was presented in Goretti and Dolce (Goretti and Dolce, 2004a). In order to reduce the computational demand of the model, that requires a non linear optimization, a simpler methodology has been than proposed (Goretti, 2004) within S. Giuliano microzonation (AA.VV, 2003), later applied also to Laino Borgo (Goretti, 2005). An overview of Italian recent applications is presented in Goretti and Dolce (2004b).

In the following the evaluation of site effects in S. Giuliano based on constructional and damage building data collected after 2002 Molise-Puglia earthquake will be presented. In addition, spatial cluster analysis based on the soil amplification is introduced, in order to provide information on the zones that can be considered homogeneous from the amplification point of view.

MODEL DESCRIPTION

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 any building will be evaluated by properly averaging the building type and the building damage observed in a neighbourhood of the building itself. More formally, the observed damage distribution in the neighbourhood of building i, \( f_{d|i} \), is evaluated as:

\[
\begin{align*}
fd|i = & \left[ \sum_j w_{ij}(x,y) I_{dj} \right] / \left[ \sum_j w_{ij}(x,y) \right] \\
\end{align*}
\]

where \( i \) is the building index, \( I_{dj} \) 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 \( j, \Delta_{ij} \). Three weighting functions were included as possible choices in the model: a) constant, b) linear and c) gaussian (Goretti, 2004). From Eq. (1) the mean non dimensional damage around building \( i \) can be evaluated as \( p_i = m_{d|i} / N_d = \sum_d d f_{d|i} / N_d \) where \( N_d = 5 \) is the number of not null damage levels. Note that the above approach is meaningful only, as in this case, if the survey is exhaustive.

Similarly the observed building type distribution in the neighbourhood of building \( i \), \( f_{T|i} \), is evaluated as:

\[
\begin{align*}
ft|i = & \left[ \sum_j w_{ij}(x,y) I_{Tj} \right] / \left[ \sum_j w_{ij}(x,y) \right] \\
\end{align*}
\]

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

The felt macroseismic intensity is then estimated comparing the observed and the expected mean non dimensional damage in the neighbourhood of any building. The latter one, considering the observed building type distribution, \( f_{T|i} \), in the building neighbourhood can be expressed as:
where $h(I_{MCS}, T)$ is the expected non dimensional mean damage when intensity $I_{MCS}$ affects building type $T$ and represents the vulnerability of the building stock. In the following $h(I_{MCS}, T)$ will be supposed known, for each building type, from post-earthquake surveys in similar regions or from numerical analysis on similar building types.

Equating the expected non dimensional mean damage, $g_i$, to the observed non dimensional mean damage, $p_i$, the felt intensity in the neighbourhood of building $i$, $I_{MCSi}$, can be obtained. In other words, the felt intensity is the intensity for which the mean expected damage and the mean observed damage coincide. For simplicity, in the following the subscript MCS will be omitted.

Site effects in terms of seismic intensity are then obtained comparing the felt intensity, $I_i$, with the reference intensity, $I_{ref}$. The latter one is the intensity expected at S. Giuliano in case of flat and stiff soil. The increment of intensity, felt by each building, is then:

$$\Delta I_i = I_i - I_{ref}$$

and is entirely attributable to site effects, being already depurated from building vulnerability.

In Goretti and Dolce (2004a) $I_{ref}$ has been deduced from a probabilistic attenuation law. In this case, there were geological and geotechnical evidences (AA.VV., 2003) of stiff soil, although not really flat, approximately where the historical core was located. Two alternative hypothesis were then considered: the first one assumes $I_{ref}$ as the spatial average of intensities associated to buildings located on the whole historical core, the second one averages intensities on buildings located on a pre-selected region, where stiff soil was assumed. In both cases $I_{ref}$ can be cast in the form:

$$I_{ref} = \frac{\sum_i I_i}{N_R}$$

where $i=1, \ldots, N_R$ are the buildings located on the reference soil.

In order to quantify site effects in terms of strong motion parameters, as EPA, PGA, etc., empirical conversion laws have been used. In general, said $Y$ the strong motion parameter to be estimated from the seismic intensity $I$, conversion laws are cast in the form of $\log_{10}(Y) = a + bI$, where $a$ and $b$ are parameters depending on the assumed law. The amplification in terms of $Y$, associated to each building, $F_{ai}$, can be expressed as:

$$F_{ai} = \frac{Y_i}{Y_{ref}} = 10^{b(I_i - I_{ref})} = 10^b I_i$$

and strongly depends on the $b$-value of the attenuation law, that is reported in Tab. 1 for several ground motion parameters (PGA, PGV, EPA, $I_i$).

**Tab. 1 - $b$-value for several ground motion parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PGA</th>
<th>PGA</th>
<th>PGA</th>
<th>EPA</th>
<th>EPV</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>0.220</td>
<td>0.179</td>
<td>0.202</td>
<td>0.197</td>
<td>0.225</td>
<td>0.29</td>
</tr>
</tbody>
</table>
The amplification in terms of ground motion parameters due to the increment of macroseismic intensity is then reported in Fig. 1.

**Fig. 1 - Amplification in terms of ground motion parameters. PD(7) is amplification in terms of Destructive Potential (Decanini, 2002) evaluated for $I_{MCS}=VII$.**

**BUILDING VULNERABILITY**

Building vulnerability has been quantified through a relationship between mean damage, constructional building type and macroseismic felt intensity. Following all the recent macroseismic scales, as MSK 76 (Medvedev, 1977) and EMS 98 (Granthal, 1998), observed physical damage to vertical bearing structures in a scale ranging from 0, the null damage, to 5 the building collapse, has been considered.

The mean damage has been evaluated from the damage distribution observed after 1980 Irpinia earthquake, when more than 30,000 buildings have been inspected (CNR, 1980). Buildings have been grouped in 5 vulnerability classes, following Braga et al. (1982), on the basis of the description of vertical and horizontal building components. Mas-A, B and C refers to masonry building of poor, medium and good quality, RC to reinforced concrete buildings and Mixed to buildings with both masonry and reinforced concrete vertical bearing structures. Macroseismic intensities, assigned just after the earthquake, have been re-evaluated within the Working Group established for the updating of building vulnerability in Italy (Angeletti et al., 2002). The mean damage observed after 1980 Irpinia earthquake, once divided by the number of damage levels, is reported in Tab. 2.

**Tab. 2 - Empirical mean non dimensional damage in terms of macroseismic intensity (after Irpinia 1980 earthquake).**

<table>
<thead>
<tr>
<th>$I_{MCS}$</th>
<th>VI</th>
<th>VI-VII</th>
<th>VII</th>
<th>VII-VIII</th>
<th>VIII</th>
<th>VIII-IX</th>
<th>IX-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mas-A</td>
<td>0.209</td>
<td>0.245</td>
<td>0.296</td>
<td>0.372</td>
<td>0.396</td>
<td>0.506</td>
<td>0.725</td>
</tr>
<tr>
<td>Mas-B</td>
<td>0.124</td>
<td>0.174</td>
<td>0.198</td>
<td>0.230</td>
<td>0.266</td>
<td>0.285</td>
<td>0.426</td>
</tr>
<tr>
<td>Mas-C</td>
<td>0.030</td>
<td>0.093</td>
<td>0.104</td>
<td>0.102</td>
<td>0.094</td>
<td>0.076</td>
<td>0.185</td>
</tr>
<tr>
<td>Mixed</td>
<td>0.075</td>
<td>0.123</td>
<td>0.120</td>
<td>0.215</td>
<td>0.225</td>
<td>0.225</td>
<td>0.288</td>
</tr>
<tr>
<td>RC</td>
<td>0.023</td>
<td>0.035</td>
<td>0.062</td>
<td>0.067</td>
<td>0.091</td>
<td>0.060</td>
<td>0.267</td>
</tr>
</tbody>
</table>

The non dimensional mean damage has been then smoothed and extrapolated to high intensities not felt in 1980 Irpinia earthquake, obtaining the solid lines reported in Fig. 1 Circles represent Irpinia observed values.
Fig. 2 - Relationship between nondimensional mean damage, vulnerability class and macroseismic intensity. Solid lines are adopted values, circles are 1980 Irpinia earthquake observed values.

Assumed observed vulnerability reported in Fig. 2 has been then compared with the vulnerability implicit in the MCS scale. The damage percentages reported in MCS scale have been attributed to class B masonry buildings, although this assumption is not always accepted. The mean non dimensional damage has been then obtained with the additional hypothesis of binomial damage distribution.

In Fig. 3, MCS (dashed line) and Irpinia (solid line) observed vulnerability are reported in term of mean non dimensional mean damage for class B Masonry buildings. In the same figure the mean non dimensional damage observed in 2002 Molise earthquake (squares) is presented.

Fig. 3 - Non dimensional mean damage versus macroseismic intensity for class B Masonry buildings: solid lines=assumed, dashed line=implicit in MCS scale, stars=observed after 1980 Irpinia earthquake, squares=observed after 2002 Molise earthquake.

From Fig. 3 it emerges that MCS scale assumes, for intensities $I_{MCS}=VI$ and VII, damage levels lower than the ones observed in Irpinia and in Molise. This is considered to be due to several items: a) the MCS description of $I=VI$ (Molin,
personal communication); b) inspections performed from outside do not allow to detect slight damage that are instead more visible from inside; c) the inspector’s trend to overestimate the damage.

In addition, the assumed vulnerability probably underestimates the mean non dimensional damage for high intensity, $I_{MCS}>X$, and hence gives, in this range, for the same observed damage, an high estimate of the felt intensity.

**SAN GIULIANO CASE STUDY**

S Giuliano municipality has been affected by 2002 Molise earthquake, suffering intensity $I_{MCS} = VIII-IX$ (Galli and Molin, 2004). The elementary school, built outside the historical core, collapsed producing the death of 27 children and 1 teacher (Foster and Kodama, 2004).

Within the post earthquake safety inspections, 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 the collected data were associated to the polygons of the inspected buildings. The GIS validation required additional building inspections, performed few months after the earthquake. The collapsed buildings, not inspected during the damage survey, were also included in the GIS.

Data were collected with the AeDES form, rel. 5.2000 (Baggio et al., 2000). The damage classification and the building type classification have been based on the final report of the Working Group that established AeDES form. In Tab. 3 is reported the used vulnerability classification (Mas-A, Mas-B, Mas-C and RC), based on the seismic performance of building components. In case of unknown building type, vulnerability class A was assigned to the building.

**Tab. 3 - Vulnerability classification and component performance.**

<table>
<thead>
<tr>
<th>Vertical structures</th>
<th>MASONRY</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular layout or bad quality, (hewn stone, pebble, HCT)</td>
<td>Irregular layout and good quality (squared stone, full bricks)</td>
</tr>
<tr>
<td>Horizontal structures</td>
<td>Without iron ties or beam ties</td>
<td>With iron ties or beam ties</td>
</tr>
<tr>
<td>Vault without ties</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Vault with iron ties</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Flexible floors</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Semi-rigid floors</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Rigid floors</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

Following Dolce et al. (1999) and Di Pasquale and Goretti (2001), the physical damage has been assumed as an appropriate combination of damage grade and damage extension to vertical bearing structures.

$$d = \sum_i d_i e_i$$
where \( d_i \) and \( e_i \) are determined from the conversion rules in Tab. 4. Damage grade (D0, D1, D2-D3, D4-D5) and damage extension \( E \) are observed values, reported in section 4 of the Aedes form. Summation is extended to all the damage levels in the building. Result is then rounded to the nearest greater integer and then non dimensionalised to the maximum number of damage levels, \( N_d = 5 \).

**Tab. 4** - Damage classification to vertical bearing structures.

<table>
<thead>
<tr>
<th>Level</th>
<th>Observed</th>
<th>( D_0 )</th>
<th>( D_1 )</th>
<th>( D_2-D3 )</th>
<th>( D_4-D5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed</td>
<td>( d=0 )</td>
<td>( d=1 )</td>
<td>( d=2.5 )</td>
<td>( d=4.5 )</td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>Observed</td>
<td>( E&lt;1/3 )</td>
<td>( 1/3&lt;E&lt;2/3 )</td>
<td>( E&gt;2/3 )</td>
<td></td>
</tr>
<tr>
<td>Assumed</td>
<td>( e=0.166 )</td>
<td>( e=0.500 )</td>
<td>( e=0.834 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4** - Building type distribution in S. Giuliano.
Fig. 4 and Fig. 5 show the constructional building type and the observed building damage in San Giuliano. Historical down-town is located SE, where buildings are closely spaced, while the new expansion area is located NW. The damage map, even in absence of the vulnerability filtering, highlights an area of more severe effects outside the historical core. The boundary is approximately a straight line oriented WNW-ESE.

According to the proposed methodology, the felt intensity in the neighbourhood of any building has been then evaluated for several choices of the model parameters. Once estimated the reference intensity, the felt intensity increment and amplification in term of ground motion parameters has been evaluated.

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 Tab. 5. $R$ is the radius of the area where local averages (Eqs. 8 and 9) are performed, $w_{ij}$ is the weighting function in $R$, $I_{ref}$ the reference intensity, $E \sigma$ and give mean value and standard deviation.

**Tab. 5 - $F_a$ in terms of PGA using Margottini local intensity conversion law.**

<table>
<thead>
<tr>
<th>$R$ (m)</th>
<th>$w_{ij}$</th>
<th>$I_{ref}$</th>
<th>$E[I]$</th>
<th>$\sigma_I$</th>
<th>$E[F_a]$</th>
<th>$\sigma_{F_a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Linear</td>
<td>6.98</td>
<td>8.06</td>
<td>1.88</td>
<td>2.60</td>
<td>2.22</td>
</tr>
<tr>
<td>25</td>
<td>Uniform</td>
<td>7.02</td>
<td>8.10</td>
<td>1.78</td>
<td>2.49</td>
<td>2.04</td>
</tr>
<tr>
<td>50</td>
<td>Linear</td>
<td>7.10</td>
<td>8.19</td>
<td>1.65</td>
<td>2.37</td>
<td>1.76</td>
</tr>
<tr>
<td>50</td>
<td>Uniform</td>
<td>7.15</td>
<td>8.22</td>
<td>1.60</td>
<td>2.29</td>
<td>1.62</td>
</tr>
<tr>
<td>100</td>
<td>Linear</td>
<td>7.27</td>
<td>8.29</td>
<td>1.46</td>
<td>2.14</td>
<td>1.40</td>
</tr>
<tr>
<td>100</td>
<td>Uniform</td>
<td>7.43</td>
<td>8.36</td>
<td>1.38</td>
<td>1.99</td>
<td>1.24</td>
</tr>
</tbody>
</table>
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 $R$. The trend of the mean $F_a$ value is a strictly related to the trend of $E[I]$ and $I_{\text{ref}}$, and, similarly, $\sigma_{F_a}$ is strongly correlated to $\sigma_I$. A large value of $\sigma_{F_a}$ is evidence of areas with different amplification within S. Giuliano.

Results of the model (Goretti, 2004) in terms of macroseismic intensity are reported in Fig. 6 for a suitable choice of the parameters: $R = 100$ m, uniform weighting function within $R$ and $I_{\text{ref}}$ as the spatial average of intensities within the only historical core on firm soil (that is excluding from the stiff soil buildings located on Area 1, see Fig. 6). Results show that, in the area of most severe effects, the felt macroseismic intensity has been approximately 2 degree (MCS scale) greater than in the historical core. Fig. 7 reports the amplification map in terms of EPA. Several areas with different amplification can be highlighted. A small slight deamplification area is located at the upper left side of the historical core (Area 1). A small area of slight amplification is located at the right side of the historical core (Area 2). 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 (Area 3). Finally the area with stronger amplification is located outside the historical core, around the main road, in the middle of the new expansion area, just where the school was located (Area 4). A spatial averaging of the amplification within the above areas gives the values reported in the Tab. 6.

**Tab. 6 - Spatially averaged $F_a$ values within amplification areas 2, 3 and 4.**

<table>
<thead>
<tr>
<th></th>
<th>$R = 50$ m</th>
<th></th>
<th></th>
<th>$R = 100$ m</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_a$</td>
<td>Mean</td>
<td>Std.dev</td>
<td>CoV</td>
<td>Mean</td>
<td>Std.dev</td>
<td>CoV</td>
</tr>
<tr>
<td>Area 2</td>
<td>1.34</td>
<td>0.27</td>
<td>19.85</td>
<td>1.13</td>
<td>0.09</td>
<td>7.55</td>
</tr>
<tr>
<td>Area 3</td>
<td>2.16</td>
<td>0.74</td>
<td>34.12</td>
<td>2.03</td>
<td>0.61</td>
<td>29.85</td>
</tr>
<tr>
<td>Area 4</td>
<td>3.36</td>
<td>0.77</td>
<td>22.86</td>
<td>3.20</td>
<td>0.37</td>
<td>11.69</td>
</tr>
</tbody>
</table>
The above results are compared with the amplification provided by in situ measurements and numerical analysis on a 2D soil model (Baranello, 2004). In both
cases the amplification was defined as $F_A = SI/\text{SI}_{\text{ref}}$, where $SI = \int \text{PSV}(T) dT$ is the spectral intensity and $\text{SI}_{\text{ref}}$ 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. Considering in situ measurements, six seismometric stations, $S\#$, were installed after the main shock. Results are summarized in Tab. 7 averaging $F_A$ values in the areas previously defined. Numerical analysis on a 2D soil linear equivalent model and moderate magnitude earthquake provided $F_A$ values on several point of the soil surface (Baranello, 2004). Point location is reported in (Baranello, 2004). Again, local $F_A$ values are averaged over the same areas as above and reported in Tab. 7.

**Tab. 7 - Average amplification in Area 2, 3 and 4.**

<table>
<thead>
<tr>
<th></th>
<th>In situ recordings</th>
<th>Numerical analysis</th>
<th>This model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 2</td>
<td>2.3 ($^{(1)}$)</td>
<td>1.05 ($^{(a)}$)</td>
<td>1.13</td>
</tr>
<tr>
<td>Area 3</td>
<td>2.5 ($^{(2)}$)</td>
<td>2.20 ($^{(b)}$)</td>
<td>2.03</td>
</tr>
<tr>
<td>Area 4</td>
<td>3.7 ($^{(3)}$)</td>
<td>2.87 ($^{(c)}$)</td>
<td>3.20</td>
</tr>
</tbody>
</table>

($^{(1)}$) $S7$; ($^{(2)}$) $S3, S6, S8, S9$; ($^{(3)}$) $S10, S11$
($^{(a)}$) Point A; ($^{(b)}$) Points B, C, G, H; ($^{(c)}$) Points D, E, F.

Considering that a) recordings and numerical analysis provide $F_A$ local values, while the proposed methodology provides averaged $F_A$ values; b) in each approach a different seismic intensity was considered (aftershocks in recordings, moderate magnitude earthquake in soil numerical analysis and main shock in damage analysis) and c) building damage and constructional type data were only I level accuracy data; results from damage analysis are reputed to be in good agreement with other discipline results. However, item b) is considered to have the most influence on the scatter of results, due to the different soil behaviour in case of different seismic input energy.

In order to have a more rational evaluation of areas with homogenous amplification, a spatial cluster analysis is then performed, where the number of groups was a-priori established. Each spatial group is defined by the coordinates of its centroid, $x_c$, $y_c$. Each building is then assigned to the group with minimum geometrical distance between the centroid and the building, that is:

Buildings $j$ belongs to group $k$ iff $D_{kj} = \min_i (D_{ij})$, where $D_{ij}^2 = (x_j - x_{ci})^2 + (y_j - y_{ci})^2$

Centroid coordinates are evaluated with a non linear optimization in which the objective function is the minimum of the within group variance of the amplification.

$$\sum_i \text{Var}(F_a)_i = \min \quad \text{Var}(F_a)_j = \text{E}_j [F_a^2] - (\text{E}_j [F_a])^2 \quad \text{if building } j \in \text{group } i$$

As the results strongly depends on the initial conditions, the solution is repeated many times, randomly selecting the initial position of the centroids. The solution with minimum variance within groups is then retained. In case of 3 centroids and 2000 different initial conditions, statistics are shown in Tab. 8 and the group’s location is reported in Fig. 8.
Tab. 8 - Amplification within groups from spatial cluster analysis.

<table>
<thead>
<tr>
<th>Group</th>
<th>$E[Fa]$</th>
<th>$Var[Fa]$</th>
<th>$CoV[Fa]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.02</td>
<td>0.13</td>
<td>35%</td>
</tr>
<tr>
<td>B</td>
<td>2.71</td>
<td>1.02</td>
<td>37%</td>
</tr>
<tr>
<td>C</td>
<td>0.47</td>
<td>0.008</td>
<td>18%</td>
</tr>
</tbody>
</table>

Although the assumed cluster analysis has some limitation in the geometry of the groups, i.e. it will not easily provide concentric areas, a clear-cut boundary between stiff and soft soil appears. This result is in very good agreement with geological evidences (AA.VV, 2003). The groups are also very similar to the ones reported in Fig. 7, and intuitively defined: Group A corresponds to the historical core that includes Area 2, Group B includes both Area 3 and Area 4 and Group C corresponds to Area 1.

From Tab. 8 it appears that the average amplification values within Area A and B are in good agreement with average amplification values within Area 2, 3 and 4 reported in Tab. 7. De-amplification values within Area 1 were not computed and reported in Tab. 7 as there were no recordings or results from numerical analysis to be compared with results of the proposed model. From cluster analysis it turns out that de-amplification can half the soil motion in Area C. In considering this results one must recognize i) the small number of buildings in Area C, ii) the inaccuracy of the model in case of negligible soil motion that do not trigger the building damage, iii) the assumed building vulnerability in comparison with the one implicit in the MCS scale (Fig. 3). With respect to the assumed vulnerability, the latter one provides an higher intensity for slight damage and a lower intensity for high damage, reducing the amplification difference among areas.
CONCLUSIONS

A methodology able to evaluate site effects form building type and damage data collected after an earthquake has been presented. 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 any building is evaluated by properly averaging the building type and the building damage observed in a neighbourhood of the building. Site effects in terms of seismic intensity are then obtained comparing the felt intensity, $I_i$, with the reference intensity, $I_{ref}$. In order to quantify site effects in terms of strong motion parameters, as EPA, PGA, etc., empirical conversion laws have been used.

In comparison with other approaches previously proposed by the same author, this one is simpler, faster and does not require any special computational effort. However the building survey must be exhaustive, that damage and constructional type data must be collected for all the buildings in the area of interest.

The model has been applied to S. Giuliano municipality, stricken by 2002 Molise- Puglia moderate earthquake. After some sensitivity analysis, model results for a suitable choice of the parameters show the presence of several amplification areas.

Despite the limitation inherent to the model and the building data (in)accuracies, peculiar to quick post-earthquake inspections, average amplification values within the different areas are in good agreement both with aftershock recorded values and results of numerical analysis on a 2D linear equivalent soil model.

In terms of macroseismic intensity, in the area of most severe effects, where the school collapsed, the felt macroseismic intensity has been approximately 2 degree (MCS scale) greater than in the historical core. Spatial cluster analysis on soil motion amplification provides a clear-cut boundary between the stiff soil in the historical core and the soft soil in the new expansion area. Again the boundary is in very good agreement with geological evidences.

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