CORRELATION BETWEEN LOCAL AMPLIFICATION EFFECTS AND DAMAGE MECHANISMS FOR MONUMENTAL BUILDINGS

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ABSTRACT

The damage and vulnerability survey of the monumental buildings, damaged by the 2002 earthquake in the Molise Region, has allowed singling out of a correlation between the observed damage of the churches and their morphological site conditions. The vulnerability model connected to the survey methodology provides an evaluation of the expected mean damage. Comparison with the observed damage determined the introduction of a local morphological behaviour modifier, able to take into account the vulnerability increase due to the site effects. In order to validate the previous results, a numerical 2-D analysis of the seismic local response has been performed. In particular, a numerical code, working with boundary elements, has been applied to the analyzed situations. The results, in terms of pseudo-acceleration response spectra and amplification factors, allow one to compare the numerical and the observed analyses. This comparison shows good agreement and allows one to find some correlations between the geometric characteristics of the sites, the values of the amplification coefficients and the damage mechanism activated.

Keywords: site-morphological amplification, monumental buildings, collapse mechanisms

INTRODUCTION

Vulnerability analysis for monumental buildings may be carried out at different levels of knowledge, that show a greater level of in-depth knowledge, as a function not so much of the method used (macroseismic or mechanical approach), but of the accuracy and the typology of the available information. Seismic action, for instance, is certainly one of the fundamental parameters used to define the vulnerability model. In fact, the seismic hazard map in a single town or in a larger area may be defined by different parameters:

- macroseismic intensity: this is a hybrid measure of the seismic input, since it indirectly depends on the building vulnerability (even though modern macroseismic scales try to overcome this restraint); the macroseismic intensity is useful when the hazard is derived from historical seismicity, both in deterministic or probabilistic scenarios; in principle, intensity is a discrete variable, evaluated through the macroseismic survey, but in a risk analysis it should be used as a continuous variable, if the vulnerability models are able to manage it properly;

- peak ground acceleration (PGA) and spectral values: with these parameters a mechanical representation of the seismic input is obtained, related to the structural response of an equivalent single degree of freedom system; since PGA is a continuous variable, the spatial variability may

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be represented better than using the macroseismic intensity; moreover, site effects may be taken into account both with a PGA amplification and with a spectral shape modification.

It is clear that, when physical parameters (peak acceleration, spectral velocity) are available it is possible to use mechanical models, closer to a purely engineering approach. On the other hand, when historical earthquakes are studied, the lack of instrumental information leads necessarily to a hazard description by means of an intensity scale. This scale is defined through a conventional size, that traces back the shock measure to its effects on objects, people and the natural environment. Nonetheless, such a dual approach does not determine a greater or lesser reliability of the obtained result, which shows the same approximation degree for the same information level.

From this point of view, for seismic risk scenarios of monumental buildings it seems useful to adopt a vulnerability model (Lagomarsino *et. al.*, 2004; Lagomarsino, 2006), based on three levels of knowledge, in relation to the accuracy and the meaningfulness of the collected data, both for the macroseismic and the mechanical approach:
- Level 0: the vulnerability analysis is traced back to a simple census, in which very few details are surveyed and a typological identification of the monument is used (church, convent or monastery, palace, tower, etc.);
- Level I: in the census phase the individual monuments are surveyed with quick forms, in which certain behaviour modifiers are introduced; these modifiers are linked to certain information of structural importance (for instance, the structural regularity, the material quality, the state of maintenance, etc.);
- Level II: a vulnerability estimate may be attributed to each building by means of a meticulous and detailed survey.

The two approaches are based respectively on the definition of a vulnerability index and of a capacity curve, that are refined on the individual building as a function of the analysis level adopted in the survey (Table 1).

The macroseismic model has the seismic intensity (in order to use the historical earthquake data) and the structural typology as reference parameters. This method leads to the determination of a vulnerability curve, in which the seismic intensity is correlated to the average expected damage. The damage is represented by means of damage probability matrices, through statistical elaborations: having fixed an intensity, it is possible to obtain the damage distribution among the various levels.

The mechanical model uses parameters such as geometrical, technological and dynamical aspects (fundamental period, ductility, peak acceleration, etc), so as to obtain a series of capacity curves able to forecast the response of the different macroelements in relation to the diverse actions, to which they may be subjected. The capacity curve is a spectral curve and the structural response is assessed as a demand spectrum. The damage is described by the fragility curves, which represent the probability of having the damage as a function of the peak acceleration.

Table 1. Resumptive draft of vulnerability model

	Macroseismic model	Mechanical model
Level 0	Vulnerability index: typology	Capacity curve: typology
Level I	Vulnerability index: single building	Capacity curve: single building
Level II	Vulnerability index: analysis by macroelements	Capacity curve: macroelement analysis

Despite the evident differences, the two methods and the results obtained are comparable to each other: it is indeed possible to pass from the variables of one method to those of the other by means of empirical correlations. The dual approach allows the definition of a risk scenario congruent with the analysis method adopted and the results obtainable are a function of the level of data knowledge. In particular, the authors wish to highlight how it is possible to take into consideration the local seismic amplification (Gazetas *et al.*, 2002; Paolucci, 2002; Havenith *et al.*, 2003; Assimaki *et al.*, 2005) in

both methods: in the mechanical approach it can be implicitly considered in the modelling, whereas in the macroseismic model the topographical amplification can be taken into account through the definition of a behaviour modifier, connected to the morphological site conditions (Di Capua *et al.*, 2006), since the seismic hazard is totally included in the single parameter "intensity".

THE 2002 MOLISE EARTHQUAKES

On October 31st and November 1st, 2002 two moderate-sized earthquakes (respectively of magnitude M_l = 5.4 at 10.32 G.M.T. and M_l = 5.0 at 15.08 G.M.T.), occurred in southern Italy and were felt in many municipalities of the area of Campobasso (Molise region) and Foggia (Apulia region). Focal mechanism solutions show that the fault rupture was almost a pure strike-slip rupture along the E-W plane. The foci depth was about 22 km (www.ingv.it/roma/reti/rms/terremoti/italia/molise/molise. html). In the epicentral area, the two earthquakes produced damage corresponding to the VII-VIII intensity degrees of the Mercalli-Cancani-Sieberg (MCS) scale, excluding the village of San Giuliano di Puglia, where the damage level matched the VIII-IX degrees.

As usually happens, after an earthquake, the safety assessment of the buildings was carried out and allowed us to evaluate, for different building typologies, the damage level caused by the seismic event; in particular, the survey of the damaged cultural heritage was carried out by the Task Cultural Heritage of the Larino COM, coordinated by the "Working Group for the Safeguard of Cultural Heritage from Natural Risks (G.U. no. 116, 21st May 2001 - PCM-DPC Decree, 3rd May 2001)".

Montelcilfone (CB) – Italy

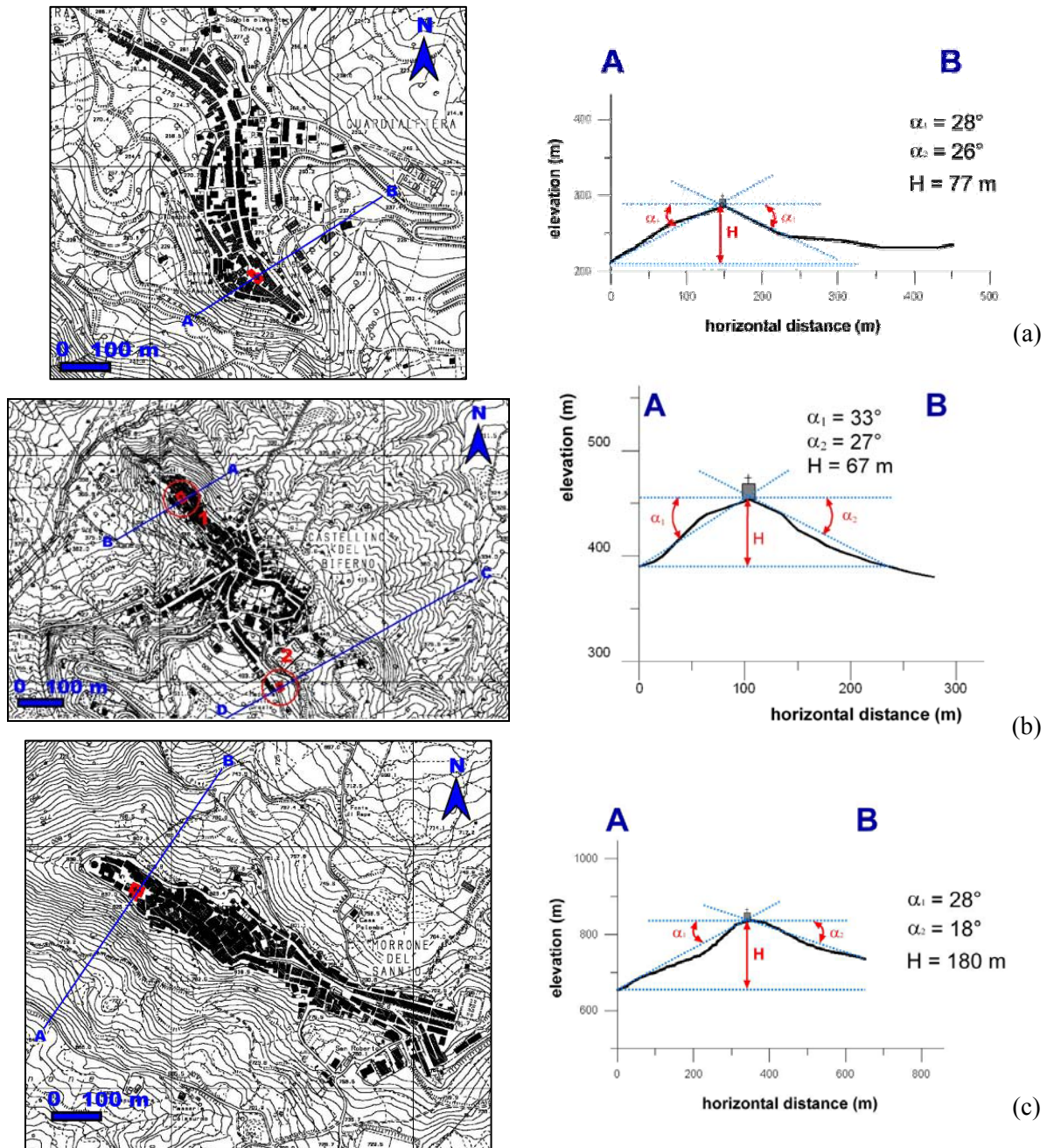

Castellino sul Biferno (CB) – Italy

Guardalfiera (CB) - Italy

Figure 1. Examples of ridge site conditions

The methodology used for the post-earthquake survey of churches provides a detailed description of the intrinsic vulnerability of every church, in addition to the damage level. In fact, for each collapse kinematism, a list of vulnerability indicators and a-seismic devices is reported, that allows one to single out those typological or constructive details, respectively able to facilitate or to contrast the

activation and the evolution of the 28 collapse mechanisms proposed (Lagomarsino *et al.*, 2004). The analysis of seismic behaviour of monumental buildings points out that the observed damage level cannot only be connected with the building's intrinsic vulnerability. In particular, during the survey activity, it was possible to notice the particular site morphology of several inhabited centres, often connected to the presence of a ridge or scarp edge condition (Figure 1).

Figure 2. Topographic profiles carried out for: S. Maria Assunta church, in Guardalfiera (Campobasso, Italy -a-); S. Pietro in Vincoli church, in Castellino del Biferno (Campobasso, Italy -b-); S. Maria Maggiore church, in Morrone del Sannio (Campobasso, Italy -c-)

In order to define relationships between the building damage and the local morpho-lithological conditions, the information regarding the observed damage was collected and processed. In particular, we focused our attention on the topographic effects, since the preliminary results of the seismic microzonation studies, carried out in the villages of epicentral area, show low seismic amplification levels due to lithological causes. Therefore, in order to characterize each church-site in morphological

terms, the topographic profiles along significant directions were easily obtained for 38 churches from the Technical Map to scale 1: 5000, edited by the Molise Region (Figure 2).

Three topographic model situations have been identified and schematized with a few simplified geometrical parameters, easily calculable on the same profiles: α is the mean slope angle; H is the slope height, considered from the top of the slope to the first significant breaking slope going down hill; h is the height of the church site from the bottom of the slope; d is the distance of the church from the scarp edge. It is important to emphasize that sometimes, for a single site, several profiles were carried out. If different morphological situations were found, in this case the most dangerous model was associated with the considered site: so the highest morphological hazard was associated with the ridge condition, the intermediate hazard with the scarp edge condition and the lower hazard with the slope condition.

Finally, the flat condition was considered irrelevant in relation to the seismic amplification due to topographic effect. When the same morphological situation along several profiles was found for a single site, in this case the geometric parameters related to the most dangerous condition were considered (Di Capua *et al.*, 2006).

SITE EFFECTS COMPUTATION: MACROSEISMIC AND MECHANICAL APPROACH

In order to take into account the site effects in a vulnerability analysis based on a macroseismic approach, a quantitative correlation between the observed damage level and the morphological site conditions has been performed.

Table 2. Individuation of the ΔV_{ml} value for the ridge site condition

Village	Denomination	Intensity	Vulnerability index	Expected damage [μ_{De}]	Observed damage [μ_{Do}]	ΔV_{ml}
CASTELLINO DEL BIFERNO	S. Pietro in Vincoli	7.0	1.02	2.75	4.11	0.319
LIMOSANO	S. Maria Maggiore	5.5	0.91	1.09	2.22	0.253
PROVVIDENTI	S. Maria Assunta	6.0	1.02	1.90	3.07	0.228
MORRONE DEL SANNIO	S. Maria Maggiore	6.0	1.05	2.04	2.17	0.140
CAMPOLIETO	S. Michele Arcangelo	5.5	0.96	1.28	1.86	0.131
MONTECILFONE	S. Giorgio	5.0	1.00	1.12	1.41	0.073
MONTAGANO	S. Maria Assunta	5.5	0.91	1.09	1.36	0.071
COLLETORTO	S. Giovanni Battista	6.5	1.09	2.70	2.85	0.029
GUARDIALFIERA	S. Maria Assunta	5.5	0.96	1.26	1.36	0.023
MONTAGANO	SS. Nome di Maria	5.5	1.00	1.45	1.46	0.003

The ratio between the expected damage level (mean damage grade μ_{De}) and the damage level (mean damage grade μ_{Do}) directly observed after the seismic event, allows one to define a church sample for which the damage level, directly observed after the Molise earthquake, is not foreseeable with the vulnerability model adopted (Lagomarsino and Podestà, 2004). Knowing the observed damage index and the vulnerability index, the vulnerability increase was calculated through the vulnerability curves, in order to reset the difference between the expected and the observed damage level. This increase can be considered as the value of the behaviour modifier ΔV_{ml} connected to the site morphology (Table 2) (Di Capua *et al*, 2006).

Taking into account the geometric parameters, individuated to describe the three different topographic model situations, the authors proposed a preliminary regression curve, able to fit the experimental data, for the ridge conditions. The equation, although based on a limited number of churches, provides the vulnerability increase value to consider in a preventive analysis, when the slope height (H) is greater than 30 m and the mean slope angle (α) is higher than 15° (Di Capua et al, 2006).

According to a mechanical approach, in order to evaluate the value of an amplification factor to adopt in the determination of the elastic response spectrum of each site, a numerical 2-D analysis of the seismic local response was performed. In particular, on the analyzed situations a numerical code, working with boundary element method (BEM, Brebbia, 1984), was applied; the choice is due to the characteristics of the situation that considers only the topographic effects in presence of homogeneous material with elastic behavior under seismic conditions.

The BEM approaches are divided into direct and indirect ones: in the first formulation, the most popular, the unknowns are the values of displacements and tractions; in the second, the problem is formulated in terms of force or moment boundary density; it is less popular in spite of the fact that such a distribution of forces can give a better insight into the physical phenomenon of wave propagation. The ELCO program (Callerio et al., 2000; Pergalani et al., 2003a) uses an indirect method (Sanchez-Sesma et al., 1993).

The base hypotheses are the following:
- plane motion: the soil particle velocities and displacements lie on a plane;
- the seismic source is so far from the site that even waves are plane;
- the elastic medium is divided into plane regions with homogeneous mechanical properties: density, share modulus and damping.

The BEM method considers, with linear segments, the only boundary of the real structure, reducing the computational time, using the Green function. The structure is characterized by an elastic and homogeneous material.

The BEM method is based on the equilibrium equation and on Hook's law to define the stresses and tractions according to the displacements: the displacement field at a generic internal point of the structure is described by the boundary integral, in the absence of body forces, due to the product from Green's tensor and the force density. Green's tensor is the displacement in the direction i at point r due to the unit force applied in the direction j at point r' and the force density is the force of the length unit on the boundary in direction j. This equation specifies that the displacement, in any point of the structure, is the sum of the displacements due to a distribution of the sources on the boundary and therefore this sum is null in the case of external points. When $r \rightarrow r'$ on the boundary, Green's function has a logarithm-type integrable singularity, that can be extracted and considered equal to zero outside the boundary.

The code considers a continuous displacement field and works in the frequency domain applying Fourier's transformation to the motion equation; imposing the continuity conditions over the boundary between adjacent homogeneous regions and the condition of null stress on the interface with the air, the integral equation can be transformed into a system of algebraic equations.

The code requires the following parameters:
- density and share wave velocity of the material;
- topographic section defined as a set of linear segments;
- frequency range used in the analyses;
- acceleration time-histories.

The seismic motions in terms of accelerograms are applied to the BEM model and the results are defined in terms of pseudo-acceleration response spectra and amplification factors, as a ratio between

spectral intensity (Housner, 1952), calculated using the pseudo-velocity spectra in the periods of 0.1-0.5 s and 0.5-1.5 s of output and input. These ranges can be considered representative of the dominant period of the typical building of the studied area: the first range is representative of small, regular and rigid structures, the second of high and flexible structures (Pergalani *et al.*, 2003b).

Because of the absence of strong motion recordings of analyzed seismic events, generated accelerograms were performed. On the basis of the magnitude and epicentral distance, using Sabetta-Pugliese's attenuation law (Sabetta & Pugliese, 1996), the pseudo-acceleration response spectra at the site have been obtained. These response spectra represent the target for the generation of the acceleration time-histories, using Sabetta-Pugliese's procedure (Sabetta & Pugliese, 1996). For each magnitude-epicentral distance couple, seven accelerograms have been generated, considering or not considering the standard deviation, and applied to BEM models of each analyzed situations. The final results represent the average of the values of the seven analyses.

From the two considered events (October 31st 2002 – magnitude 5.4; November 1st 2002 – magnitude 5.0) in accordance with the epicentral distance of each site, seven accelerograms were performed; in Figure 3 two samples of acceleration time-histories are shown.
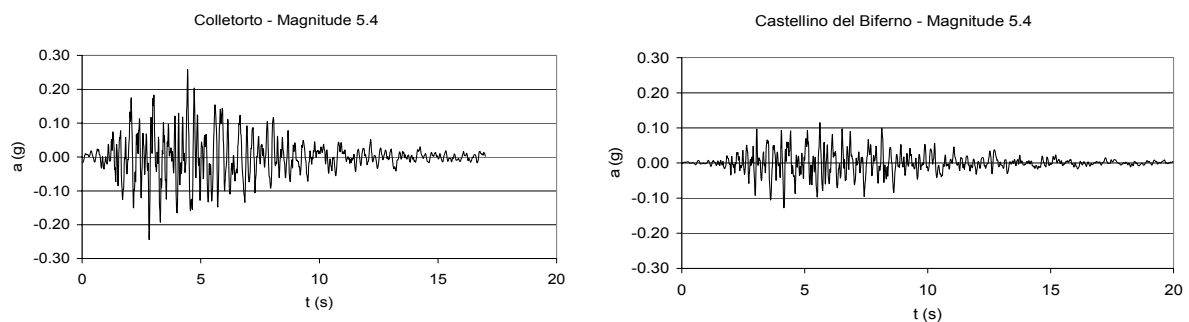

Figure 3. Samples of used acceleration time-histories

In Figure 4, two samples of topographic sections are represented, where H is the maximum height and L is the maximum width; the parameters used in the analyses are: density 2.2 gr/cm^3; share wave velocity 800 m/s; frequency range 0.2-15 Hz.
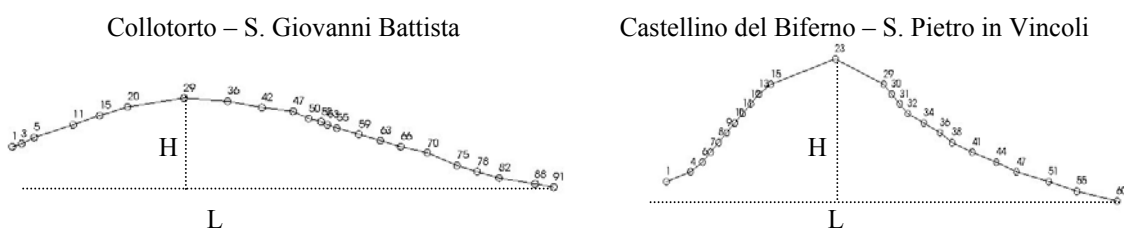
Figure 4. Samples of topographic sections

The results of two sites in terms of the pseudo-acceleration response spectra are illustrated in Figure 5, where the response spectra of the two events, the average of the results of the seven applied acceleration time-histories and the maximum values of all results are reported.
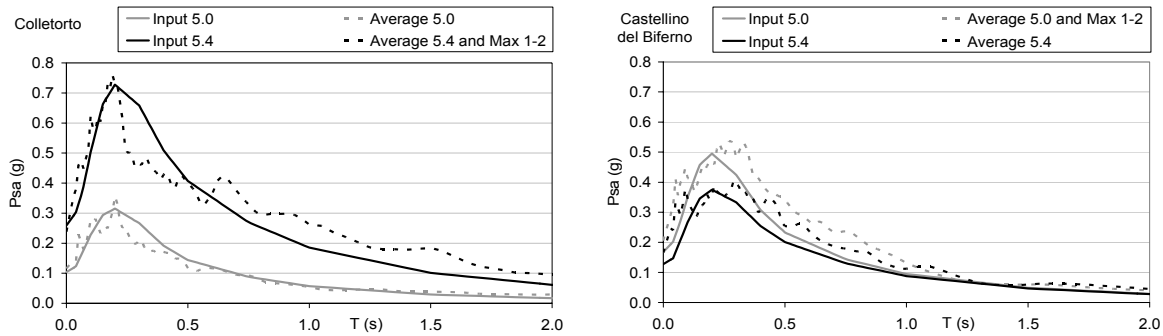
Figure 5. Samples of the results in term of pseudo-acceleration response spectra

As shown, in the case of Colletorto, the analyses give different results applying the two events and the maximum results are obtained considering the event characterized by magnitude of 5.4; in this case the level of amplification is zero. In the case of Castellino del Biferno the analyses give results quite similar applying the two events and the maximum results are obtained considering the event characterized by magnitude 5.0, because this event is nearer than the other and the level of amplification is not neglected.

The results in terms of amplification factors (Fa), calculated in the periods of 0.1-0.5 s, and H/L ratio for each analyzed site are shown in Table 3. The period 0.1-0.5 s has been considered representative of the dominant period of the analyzed churches. To obtain the value of Fa, for each site, the two sets of acceleration time-histories of the two events have been applied; then the average of the two sets has been calculated; finally the maximum value of the two averages has been selected.

Table 3. Results in terms of amplification factors for all sites

Sites	Church	H/L	Fa (0.1-0.5 s)
CASTELLINO DEL BIFERNO	S. Pietro in Vincoli	0.26	1.42
MORRONE DEL SANNIO	S. Maria Maggiore	0.28	1.26
GUARDIALFIERA	S. Maria Assunta	0.21	1.21
LIMOSANO	S. Maria Maggiore	0.17	1.20
CAMPOLIETO	S. Michele Arcangelo	0.17	1.16
PROVVIDENTI	S. Maria Assunta	0.14	1.09
COLLETORTO	S. Giovanni Battista	0.17	1.00
MONTAGANO	S. Maria Assunta	0.14	1.00
MONTAGANO	SS. Nome di Maria	0.12	1.00
MONTECILFONE	S.Giorgio	0.08	1.00

The analyzed sites are characterized by rounded and pointed ridges: the rounded present a large width at the top of the ridge (Pergalani & Compagnoni, 2006).

The results show the relationship between the H/L and Fa values; in particular, the high values of Fa are related to high values of H/L.

In two cases (Colletorto and Montagano sites - in grey) this relationship is not verified, because these sites are characterized by rounded ridges: consequently the Fa values are lower than the Fa values characterized by the same H/L ratio of the pointed ridges.

CONCLUSIONS

After the Molise earthquakes (2002), the vulnerability analysis carried out on the churches pointed out that at least part of the damage suffered could not directly be related to the intrinsic seismic vulnerability of the buildings. The topographic analysis carried out on several churches struck by the earthquake has allowed us to evaluate some geometric parameters for the more recurrent morphological situation (the ridge). They could be synthesized in a local morphological vulnerability modifier (ΔV_{ml}), that represents an additional parameter to take into account in vulnerability analyses (macroseismic approach).

In order to validate the previous results, a numerical 2-D analysis of the seismic local response has been performed. The comparison between the different approaches (Table 2 and 3) confirms a discrete agreement between the local morphological vulnerability modifier (ΔV_{ml}) and the amplification factor (Fa), although some unavoidable differences. In particular, it is worth noticing that, with the exclusion of the S. Maria Assunta church in Guardalfiera (CB), the two lists present the same site in the first five positions. Although the site number is very limited, the results appear independent from the seismic intensity value. In the case of Guardalfiera site the values of local morphological vulnerability modifier (ΔV_{ml}) and the amplification factor (Fa) do not match instead . The cause must be investigated more deeply, but it is important to remember that the vulnerability survey, performed in emergency phase immediately after the seismic event, could present some incongruence due to the need to survey a great number of buildings rapidly. This aspect could be avoided in a real vulnerability campaign, where the inspection time can be longer.

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