First European Conference on Earthquake Engineering and Seismology
(a joint event of the 13th ECEE & 30th General Assembly of the ESC)
Geneva, Switzerland, 3-8 September 2006
Paper Number: 656

SIMPLIFIED PARAMETERS FOR THE EVALUATION OF SITE EFFECTS IN THE SEISMIC RISK ANALYSES OF MONUMENTS

Giuseppe DI CAPUA[1], Emanuela CURTI[2], Alberto LEMME[3], Silvia PEPPOLONI[1], Stefano PODESTÀ[2]

SUMMARY

In autumn 2002 two moderate energy earthquakes (31 October, 10:32 GMT, M_W = 5.4, and 1 November, 15:08 GMT, M_W = 5.0) struck the provinces of Campobasso and Foggia (southern Italy). The earthquakes attained an intensity VII (Modified Mercalli scale) throughout the epicentral area, except for the village of San Giuliano di Puglia, that suffered an intensity VIII-IX.
Damage and vulnerability surveys on monuments (churches) suggested that the geomorphological site conditions greatly affected the damage level. In particular we found that, for a comparable intrinsic vulnerability of the building, the structural damage level is directly correlated to local amplification phenomena related to the different morphological and lithological characteristics of each church site.
The assessment of damage increase related to local amplification of the ground shaking is made possible by evaluating the damage and seismic vulnerability of each church (e.g., the lack of antiseismic protection, the presence of vulnerability indicators). The damage increase was compared to the morpho-lithological characteristics of each site, schematized with a few simplified parameters. This methodology allowed us to evaluate separately a morphological hazard, related to the topographic characteristics of the site and the building location, and a lithological hazard, evaluated on the basis of the Italian Seismic Code.
Our research goal was to set up an expected damage evaluation method, that considers not only the building vulnerability, but also the additional vulnerability related to the morphological conditions of the church site. The methodology can be effectively used in preventive analyses, targeted to define a priority list of historic buildings and monuments at high seismic risk.

1. INTRODUCTION

After the 2002 earthquakes, that struck the southern Italy provinces of Campobasso (Molise) and Foggia (Apulia), the safety assessment of buildings has allowed 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 Mixed Operating Centre (COM) in Larino (a village in the epicentral area), coordinated by the "*Working Group for the Safeguard of the Cultural Heritage from Natural Risks"* (Italy's Gazzetta Ufficiale n. 116, 21 May 2001 - PCM-DPC Decree, 3 May 2001)*"*.
For this survey activity, the churches were investigated with a specific form proposed by the same Working Group (Ministerial Decree n. 133, 23th January 2001), adopting different forms for other kinds of buildings. The surveyors were organized in teams, called NOPSA (*Nuclei Operativi Patrimonio Storico Artistico*), composed by officials of the Regional board of the Ministry of Cultural Heritage and Environmental Conservation (architects and art historians), an engineer and a Fire Brigade technician. The first phase of the safety assessment has been

[1] Istituto Nazionale di Geofisica e Vulcanologia, via Nizza 128, 00198 ROMA, Italy
Email : giuseppe.dicapua@ingv.it; silvia.peppoloni@ingv.it
[2] Dipartimento di Ingegneria Strutturale e Geotecnica, Università degli Studi di Genova, via Montallegro 1, 16145 GENOVA, Italy
Email: curti@diseg.unige.it; podesta@diseg.unige.it
[3] Freelance, S.S. n. 17 - km 178, 86170 ISERNIA, Italy
Email: albertolemme1@virgilio.it

developed on the basis of the warnings received by the Larino COM, and most of the surveyed buildings were churches. The damage assessment of public or private buildings began, initially, near the earthquake epicentre (area 1 - I_{MCS} between 6 and 8.5*)* and subsequently was carried out for all the villages from which inspection requests arrived. At the same time a vulnerability survey was carried out for the churches, using the II level form (Lagomarsino *et al.*, 2004) proposed in the SAVE Project ("Updated Tools for the Seismic Vulnerability Evaluation of the Italian Real Estate and of Urban Systems" – http://gndt.ingv.it). The damage and vulnerability survey has allowed to verify and optimize the procedures for damage assessment immediately after a seismic event (emergency phase) and to obtain useful indications for the reconstruction phase. On the whole 379 monumental buildings in 101 Molise villages and 207 monumental buildings in 44 Apulia villages were investigated. Figure 1 shows the number of monumental buildings surveyed after the earthquakes for each Molise village, subdividing the region according to the seismic classification proposed by the recent Italian Seismic Code (OPCM n. 3274, 2003 – http://zonesismiche.mi.ingv.it).

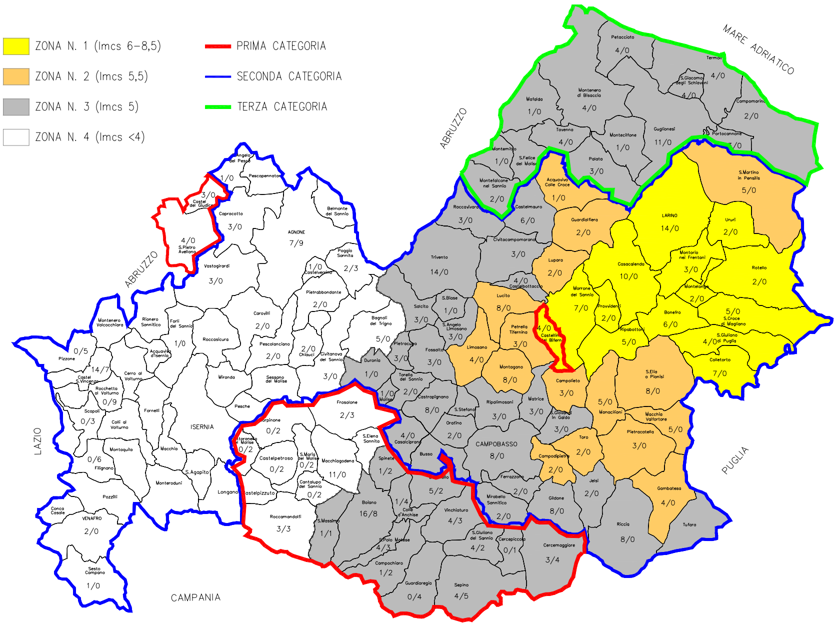

Figure 1: Number of monumental buildings surveyed in the Molise region after the 2002 earthquakes

The methodology used in the II level vulnerability assessment has allowed us to obtain a detailed survey that is useful to describe, in addition to the damage level, the intrinsic vulnerability of every church. In fact, a list of vulnerability indicators and anti-seismic devices is reported for each collapse kinematism. This allows the identification of 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 post-earthquake damage assessment and the definition of the macroseismic scale (EMS98) allow us to state the observational vulnerability model, through a correlation between the intensity of the earthquake (I) and the mean damage grade (μ_D, varying between 0 to 5). This represents the mean value of the probability histogram of the damage grades D_k (k=0,1,2,3,4,5), typical of easily observable damage levels, in terms of cracks and deformations. The vulnerability curves (Lagomarsino and Podestà, 2004a) are:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{3}\right)\right] \qquad (1)$$

where V (vulnerability index) ranges between 0.67 and 1.22 (for the more vulnerable churches).
The statistical analysis of the data after the Molise earthquakes and the comparison with the values obtained from previous earthquakes (Lagomarsino and Podestà 2004b) confirm the robustness of the used methodology. Table 1 reports the mean damage grades μ_D for the whole population of churches; notice that the set of 296 churches surveyed in Molise has been split into four sets according to macroseismic intensity (Modified Mercalli Scale): I_{MCS} = IV, V, VI and VII-VIII. In order to obtain a large enough and hence statistically significant dataset, the latter two intensity classes are considered together in order (Lagomarsino and Podestà, 2004b).

Table 1: Binomial coefficient (μ_D - mean damage grade) for the DPM of churches

	Macroseismic Intensity (MCS)				
	IV	V	VI	VII	VIII
Previous earthquakes	-	1.025	1.385	2.015	3
Molise	0.4	0.54	1.28	2.9	-

The detailed analysis of damage to monumental buildings, showed that in some cases the observed damage level cannot be explained with reference to the intrinsic vulnerability building only.
The damage level observed in some churches appeared particularly significant in relation to the moderate energy of the Molise earthquakes (respectively of magnitude M_W = 5.4 at 10.32 G.M.T. and M_W = 5.0 at 15.08 G.M.T.) We believe that this was due to the activation of damage mechanisms that are difficult to predict and not so common for these monumental typologies.
Seismic amplification phenomena that have locally increased the observed damage have been pointed out for various inhabited centres. In San Giuliano di Puglia a strong shaking increase has been observed along the morphological saddle on which a large part of the village is developed, with I_{MCS} = VIII-IX (Sanò et al., 2005). In Ripabottoni greater damage has been observed in buildings located close to the steep morphological scarp that bounds the built-up area (among these, S. Maria della Concezione church), despite the homogeneity of the building structural characteristics and of lithological subsurface conditions (Cevasco et al., 2005; Di Capua and Peppoloni, 2005; Martinelli et al., 2005). In particular, damage due to the crushing of the nave pillars (Isella et al., 2004) was observed in churches with a nave and two side aisles (for example at S. Maria Assunta church in Ripabottoni, S. Giacomo church in S. Croce di Magliano, S. Giuliano church in S. Giuliano di Puglia). The cracks were seen on each of the four sides of the pillars and developed from the central part to the base and to the top of the columns. This damage conditions are not correlated to the horizontal seismic action only, but we verified that in some cases (for example at S. Maria Assunta church in Ripabottoni) the vertical component played a leading role in the seismic response evaluation (Podestà et al., 2006).

2. SITE AND MORPHOLOGICAL EFFECTS

The classification of the building soil foundation in the Italian Seismic Code (OPCM n. 3274, 2003) is based on lithological categories characterized by different values of V_{s30}. At the same time a morphological site characterization has been provided in this Code: two characteristic situations have been envisioned, essentially distinguished on the basis of the slope height and the slope angle.
The elastic response spectrum branches of each site are determined on the basis of the associated soil foundation category. The spectrum anchorage value (T = 0) coincides with the design seismic action and is calculated by this product:

$$a_g \cdot S \cdot S_T \qquad (2)$$

where a_g is the peak ground acceleration (PGA) calculated at the top of the bedrock (return period = 475 years), S and S_T are coefficients that multiply the PGA, taking into account local lithological and morphological characteristics that may produce seismic amplification effects.
Concerning S_T (topographic coefficient), it is important to stress that a good correlation between the S_T values and the amplification factors has been found in some 2D and 3D local seismic response analyses (Paolucci, 2002). Over the past 30 years several investigators have pointed out that local seismic amplification phenomena due to topographical causes occurred on the occasion of earthquakes (Boore, 1972; Jibson, 1987; Geli et al., 1988; Bouchon et al. 1996; Spudich et al., 1996; Ashford et al., 1997a; 1997b; Chávez-García et al., 1997; Paolucci et al., 1999; Havenith et al., 2003). The topographical effect has produced a distinct damage increase in various documented cases (Çelebi, 1987; Kawase et al., 1990; Hartzell et al., 1994; Gazetas et al., 2002; Assimaki et al., 2005). Unfortunately, there are still very few systematic recordings carried out on ridges, scarp edges and slopes that can be used to quantify physical phenomena related to the geometric characteristics of the morphological shapes. A greater number of instrumental data would permit a comparison between the amplification factors, determinated in an experimental way, and the S_T values, provided in the morphological categories of the Italian Seismic Code, in order to obtain a more accurate safety degree in the structural design of buildings.

After the Molise earthquake, seismic microzonation studies have been carried out in the villages of the epicentral area. These studies have involved geological and geomorphological surveys, and site and laboratory geognostic investigations. On account of this analysis, the inhabited centres territory have been separated into areas characterized by different S values, fixed on the basis of V_{s30} through down-hole tests. Then, these values have been corrected taking into account the results obtained by 1D numerical analysis of the local seismic response. For some inhabited centres the morphological site settings provided in the Italian Seismic Code and liable of seismic amplifications have been identified. Hence the S_T value has been introduced beside the S value, even if it has been empirically modified on the basis of the observed damage.
The results, although preliminary and still unpublished, suggest low seismic amplification levels due to lithological causes, as there are not strong V_S contrasts in the subsurface, at least in the uppermost 30 m. In contrast, in many cases at least part of the observed damage seems to be more easily related to the topographic features of the same inhabited centres.
In a territorial vulnerability analysis, that is the aim of this study, a correlation between the intrinsic vulnerability of the building and the vulnerability connected to the site geomorphology seems preferable and conceptually more correct than computing the topographic conditions as an increase of the seismic hazard. In a preventive vulnerability analysis targeted to the definition of damage scenarios, if the seismic input is defined according to the expected intensity (macro-seismic approach), the local amplification cannot correctly be computed with a new hazard parameter, because the seismic intensity evaluation is a mean value that already averages out these phenomena over the investigated area. Therefore, according to recent approach (Lagomarsino and Giovinazzi, 2004), we propose the definition of a new behaviour modifier that can be used to assess the church vulnerability increase due to a possible morphological site effect.

2.1 The methodology adopted for the topographic analysis

In order to analyse the existing relationships between the buildings damage and the local morpho-lithological conditions, it has been necessary to acquire information about the observed damage on a large area. While the information available on lithology is incomplete and unpublished, topographic data could be easily obtained from the Technical Map to scale 1: 5,000 edited by Molise Region. The topographic analysis allowed profiles to be carried out along significant directions, and hence allowed us to characterize each site in morphological terms.
Three topographic model situations have been identified and schematized with a few simplified geometrical parameters that can be easily calculated on the same profiles (figure 2): *α* is the mean slope angle; *H* is the slope height, considered from the top of the slope to the first significant break in slope moving downhill; *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.

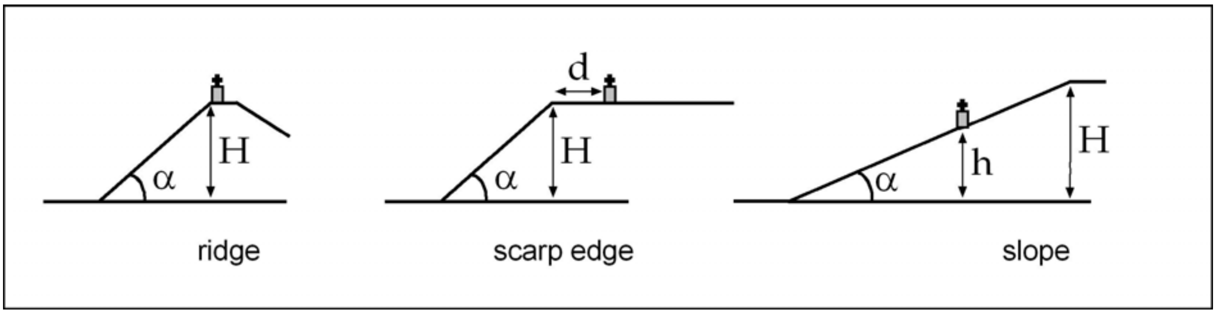

Figure 2: The topographic model situations and the associated geometrical parameters

Figure 3 shows an example of a topographic analysis, obtained for two churches in Castellino del Biferno, a village located in the Molise earthquake epicentral area that suffered an intensity VIII (Modified Mercalli Scale).

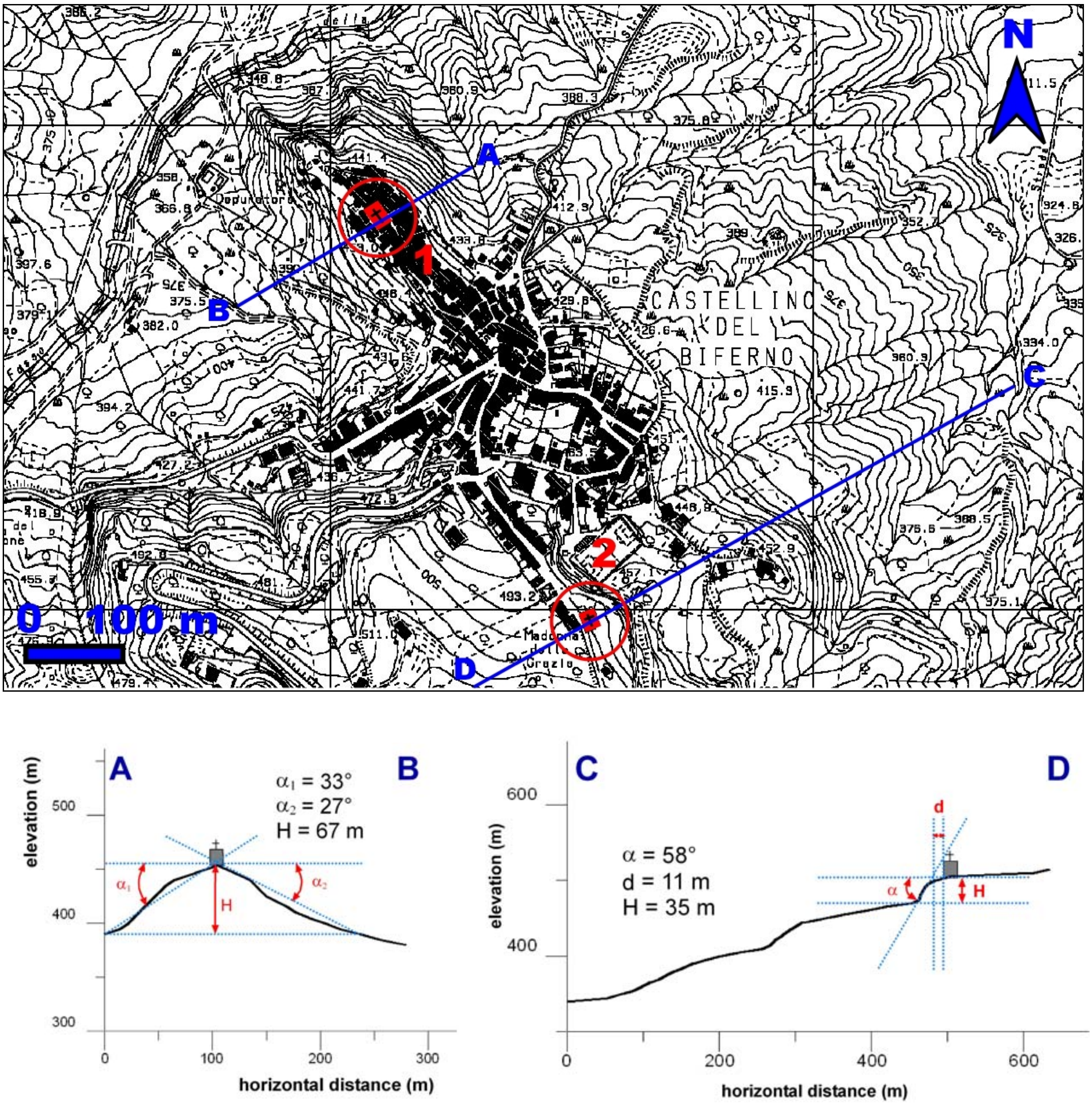

Figure 3: Topographic profiles carried out for the S. Pietro in Vincoli church (on the left) and Madonna delle Grazie church (on the right) in Castellino del Biferno (Campobasso, Italy)

The geometrical parameters related to the morphological characteristics of each site have been analysed for 38 churches, all damaged by the earthquake. The results of these analysis are shown in table 2.
We wish to stress that in some instances several profiles were been carried out for a single site. If different morphological situations were encountered, we associated the most dangerous model with the considered site. Hence the highest morphological hazard has been 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 has been considered irrelevant in relation to the seismic amplification due to topographic effect.
If the same morphological situation was found for a single site along several profiles, we considered the geometric parameters related to the more dangerous condition.
Churches located on the ridges represent the largest sample (more than 50 %), whereas churches located on the scarp edges or on the slopes together represent only 22 % of the whole sample. For this reason our analysis has been mainly oriented to study the morphological condition of the ridges.

Table 2: Topographic characteristics of the churches site and the associated geometric parameters

Village	Church	I_{MCS}	Site morphology	H (m)	α (°)	d (m)	h (m)
BONEFRO	S. Nicola	7.00	Slope	47.0	9.0	-	20.0
BONEFRO	S. Maria delle Rose	7.00	Slope	47.0	9.0	-	10.0
CAMPODIPIETRA	S. Bonaventura	5.50	Slope	47.0	5.0	-	23.0
CAMPODIPIETRA	S. Martino	5.50	Slope	47.0	5.0	-	7.0
CAMPOLIETO	S. Michele Arcangelo	5.50	Ridge	43.0	22.5	-	-
CASACALENDA	S. Maria Maggiore	6.00	Scarp edge	54.0	28.0	-	-
CASACALENDA	Chiesa dell'Addolorata	6.00	Scarp edge	86.0	18.0	91.0	-
CASTELLINO DEL BIFERNO	S. Pietro in Vincoli	7.00	Ridge	67.0	30.0	-	-
CASTELLINO DEL BIFERNO	Madonna delle Grazie	7.00	Scarp edge	35.0	58.0	11.0	-
COLLETORTO	S.Giovanni Battista	6.50	Ridge	147.0	15.0	-	-
COLLETORTO	S.Alfonso dei Liguori	6.50	Slope	60.0	13.0	-	7.0
COLLETORTO	Purgatorio	6.50	Ridge	117.0	14.0	-	-
GUARDIALFIERA	Santa Maria Assunta	5.50	Ridge	77.0	27.0	-	-
LARINO	Cattedrale di S.Pardo	6.00	Ridge	60.0	13.0	-	-
LARINO	S. Francesco	6.00	Ridge	60.0	13.0	-	-
LARINO	S. Stefano	6.00	Ridge	43.0	14.5	-	-
LARINO	S. Maria della Pietà	6.00	Scarp edge	18.0	9.0	0.0	-
LIMOSANO	S. Maria Maggiore	5.50	Ridge	70.0	24.5	-	-
LIMOSANO	S. Francesco	5.50	Ridge	63.0	8.5	-	-
MONTAGANO	SS. Nome di Maria o della Congrega	5.50	Ridge	87.0	12.0	-	-
MONTAGANO	S. Maria Assunta	5.50	Ridge	127.0	13.5	-	-
MONTECILFONE	S. Giorgio	5.00	Ridge	100.0	9.5	-	-
MONTELONGO	S. Maria ad Nives	6.50	Ridge	67.0	10.5	-	-
MONTELONGO	S. Rocco	6.50	Scarp edge	100.0	10.0	83.0	-
MONTORIO NEI FRENTANI	S. Maria Assunta	6.00	Ridge	198.0	10.5	-	-
MONTORIO NEI FRENTANI	Madonna del Carmine	6.00	Ridge	107.0	14.5	-	-
MORRONE DEL SANNIO	S. Maria Maggiore	6.00	Ridge	180.0	23.0	-	-
MORRONE DEL SANNIO	S. Roberto	6.00	Slope	150.0	12.0	-	110.0
PROVVIDENTI	S. Maria Assunta	6.00	Ridge	47.0	22.5	-	-
RIPABOTTONI	S. Maria della Concezione	7.00	Scarp edge	39.0	28.0	23.0	-
RIPABOTTONI	S. Maria Assunta	7.00	Scarp edge	47.0	27.0	51.0	-
ROTELLO	S. Maria degli Angeli	6.00	Scarp edge	33.0	15.0	0.0	-
ROTELLO	S. Rocco	6.00	Slope	27.0	10.0	-	20.0
SAN GIOVANNI IN GALDO	S. Giovanni Battista	5.00	Scarp edge	25.0	35.0	7.0	-
SANTA CROCE DI MAGLIANO	S. Giacomo	7.00	Slope	110.0	8.0	-	85.0
SANTA CROCE DI MAGLIANO	S. Antonio	7.00	Slope	105.0	8.0	-	70.0
URURI	S. Maria delle Grazie	6.00	Ridge	100.0	11.5	-	-
URURI	SS. Trinità	6.00	Ridge	104.0	10.5	-	-

3. CORRELATION BETWEEN DAMAGE AND MORPHOLOGY

In order to identify a quantitative correlation between the observed damage level and the morphological site conditions, the expected damage level (mean damage grade μ_{De}) has been calculated through the vulnerability index, obtained by the vulnerability form for all the churches reported in table 2. This value has been compared to the damage level (mean damage grade μ_{Do}), directly observed after the earthquake.

The ratio between these two indices allows us to define two different samples of churches: sample A (about 63%), where the expected damage level (through the proposed vulnerability model) is greater than the observed damage level; sample B (37%), where the damage level directly observed after the Molise earthquake is not foreseeable with the vulnerability model previously described. This different behaviour is problematic, mainly for the sample B. It is worth noticing that usually a predictive territorial vulnerability model is calibrated to ensure the safety. In this way it is possible to foresee the expected damage level without an underestimate of the earthquake impact. In fact, the used vulnerability model takes into account the local amplification phenomena, computing on average in the same vulnerability curves. The damage suffered by the Umbria and Marche churches following the 26 September 1997 earthquakes was certainly affected by site effects, which were indirectly considered in the definition of the vulnerability curves.

The detailed analysis of the site morphology, carried out on the sample B churches, has highlighted that more than 50% of the buildings, characterized by an observed damage higher than the expected damage, are located on ridges; for buildings located on the scarp edges and on the slopes this percentage respectively decrease to 33% and 11%.

Once the observed damage index and the vulnerability index are known, the vulnerability increase can be 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 3: Individuation of the ΔV_{ml} value connected to the site morphology.

Village	Denomination	Morphology	Intensity	Vulnerability index	Expected damage [$\mu_{\Delta\varepsilon}$]	Observed damage [μ_{Do}]	Ratio (observed - expected damage)	ΔV_{ml}
CAMPOLIETO	S. Michele Arcangelo	Ridge	5.5	0.96	1.28	1.855	1.455	0.131
CASTELLINO DEL BIFERNO	S.Pietro in Vincoli	Ridge	7.0	1.02	2.75	4.110	1.495	0.319
COLLETORTO	S.Alfonso dei Liguori	Slope	6.5	1.06	2.53	2.625	1.037	0.018
COLLETORTO	S.Giovanni Battista	Ridge	6.5	1.09	2.70	2.845	1.055	0.029
GUARDIALFIERA	Santa Maria Assunta	Ridge	5.5	0.96	1.26	1.355	1.072	0.023
LIMOSANO	Santa Maria Maggiore	Ridge	5.5	0.91	1.09	2.222	2.039	0.253
MONTAGANO	S.S. Nome di Maria o della Congrega	Ridge	5.5	1.00	1.45	1.460	1.010	0.003
MONTAGANO	S. Maria Assunta	Ridge	5.5	0.91	1.09	1.360	1.252	0.071
MONTECILFONE	S. Giorgio	Ridge	5.0	1.00	1.12	1.412	1.256	0.073
MONTELONGO	S. Rocco	Scarp edge	6.5	1.05	2.44	2.635	1.079	0.037
MORRONE DEL SANNIO	S. Maria Maggiore	Ridge	6.0	1.05	2.04	2.165	1.063	0.025
PROVVIDENTI	S. Maria Assunta	Ridge	6.0	1.02	1.90	3.065	1.614	0.228
RIPABOTTONI	S. Maria della Concezione	Scarp edge	7.0	1.00	2.62	3.500	1.333	0.179
RIPABOTTONI	S. Maria Assunta	Scarp edge	7.0	1.00	2.62	3.315	1.263	0.138

Therefore, the geometric parameters measured on the topographic profiles has been used to determine a regression curve fitting the experimental data. The *local morphological behaviour modifier* (ΔV_{ml}) allows the morphological information to be summarized in a single parameter. Adopting a value of the *local morphological behaviour modifier* equal to zero for flat surface conditions and for the other morphological conditions where the parameter H is lower than 30 m, the function proposed for the ridge condition is:

$$\Delta V_{ml} = 7.89 \cdot 10^{-3} \cdot H^{\delta} \cdot tg\alpha + 0.0148 \qquad (3)$$

where H is the ridge height, α is the mean slope angle. δ is 1 for $H \le 70$ m and 0.5 for $H > 70$ m.

Figure 4 shows the good agreement between the vulnerability increase necessary to obtain the mean observed damage level and the value of the behaviour modifier, calculated by the proposed formulation, obtained for the churches reported in table 3 (ridge condition).

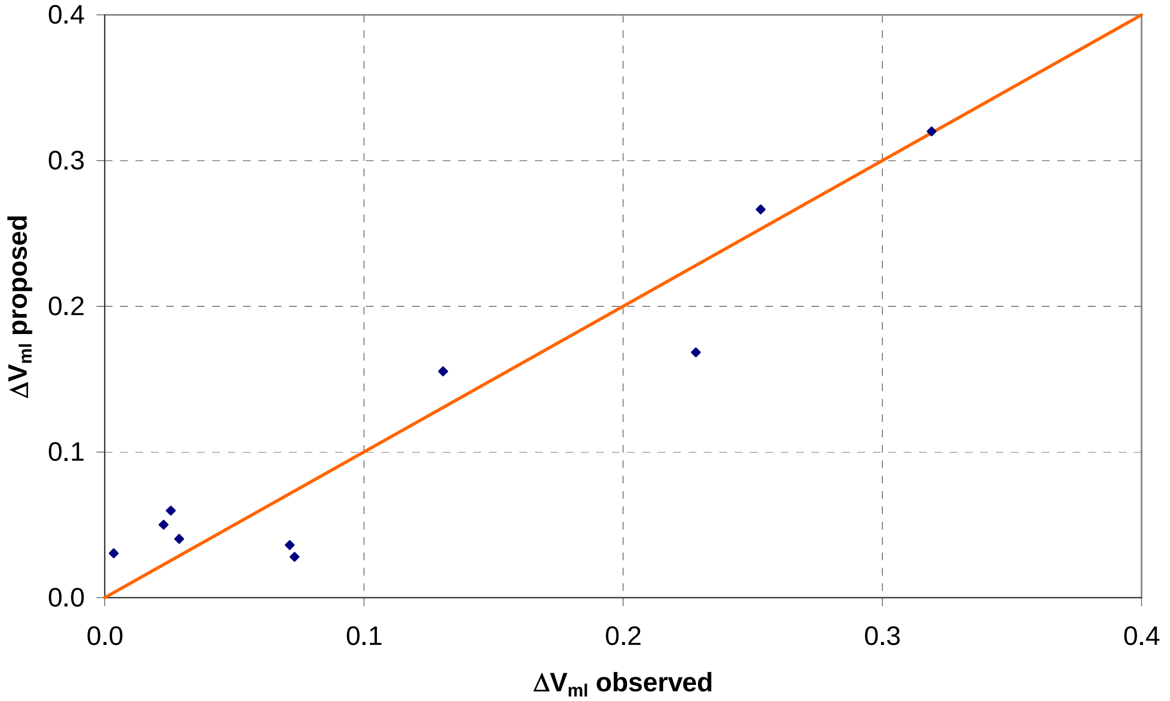

Figure 4: Comparison between observed ΔV_{ml} and proposed ΔV_{ml}

Function (3) provides the vulnerability increase value to consider in a preventive analysis of a particular building typology like the churches, when H > 30 m; nevertheless, as previously described on the whole sample, the vulnerability model takes already into account, on average, a vulnerability increase connected to the site effects. Therefore, according to the limit slope angle ($\alpha = 15°$) proposed by the Italian Seismic Code, we have adopted this value as threshold to select the situations where the ratio between the observed and the expected damage is higher than 1. So, the correlation proposed can be used in all those morphological site conditions where α is higher than 15°.

It is worth noticing that the possibility to take into account this parameter plays a fundamental role in a preventive vulnerability analysis. Although the mean value of ΔV_{ml} is equal to 0.11 (table 3), there are three churches (S. Maria Assunta church, Provvidenti; S. Maria Maggiore church, Limosano; S. Pietro in Vincoli church, Castellino del Biferno) that exceed the threshold value of ΔV_k (0.16 - Giovinazzi and Lagomarsino, 2004). In fact, this value determines a mean damage grade (μ_D) increase equal to the value resulting from a one-degree seismic intensity increment.

Figure 5: S. Pietro in Vincoli church – Castellino del Biferno (CB): overall view and observed damage

4. CONCLUSION

After the Molise earthquakes (2002), the vulnerability analysis carried out on the churches, together with the macroseismic studies, pointed out that at least part of the damage suffered could not be directly related to the intrinsic seismic vulnerability of the buildings. In all these cases the S_T value, assigned on the basis of geometric parameters measured on the topographic profiles is always equal to 1.2, with slope angle higher than 15°. This fact confirms the influence of the site topographic factor on the observed damage. 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 have been synthetized in a local morphological vulnerability modifier (ΔV_{ml}), that represents an additional parameter of the seismic vulnerability calculated for the church.

It is important to point out that the ΔV_{ml} could effectively support or improve other indices, for example related to local lithological conditions, that can be used in seismic risk analysis at larger scale.

The results obtained in this study suggest to update and improve the form used in Italy for surveying the damage to churches and their seismic vulnerability (Lagomarsino et al., 2004). We propose to insert in the churches form a new box that collects simplified geometric parameters related to the morphological features of churches site (figure 5).

Even if it has been not possible to find a direct correlation between the observed damage and the local seismic amplification phenomena for the other two model situations (slope and scarp edge), also these morphological conditions have been schematized with geometric parameters gathered from literature information (Jibson, 1987; Paolucci et al. 1999; Gazetas et al., 2002; Assimaki et al., 2005).

MORPHOLOGYCAL FEATURES OF THE SITE

SITE SETTING		PARAMETERS						ΔV_{ml}
flat surface	☐							
ridge	☐	slope angle (degrees)	——	slope height (meters)	——			———
scarp edge	☐	scarp angle (degrees)	——	scarp height (meters)	——	distance from the edge (meters)	——	———
slope	☐	slope angle (degrees)	——	slope height (meters)	——	height from the bottom of the slope (meters)	——	———

Figure 5: Proposed box for the churches seismic vulnerability form, used in Italy

5. REFERENCES

OPCM (Prime Minister Decree) n. 3274 - 20th March 2003 (2003), First elements about general criteria for the seismic classification of the national Italian territory and technical norms for the construction in seismic zone, Supplemento ordinario alla Gazzetta Ufficiale della Repubblica Italiana, n. 105, 8th May 2003, Serie Generale – Parte prima, *Istituto Poligrafico e Zecca dello Stato*, Roma (in Italian).

Ashford, S.A. and Sitar, N. (1997a), Analyses of topographic amplification of inclined shear waves in a steep coastal bluff, *Bulletin of the Seismological Society of America*, Vol. 87, No. 3, 692-700.

Ashford, S.A., Sitar, N., Lysmer, J. and Deng, N. (1997b), Topographic effects on the seismic response of steep slopes, *Bulletin of the Seismological Society of America*, Vol. 87, No. 3, 701-709.

Assimaki, D., Kausel, E. and Gazetas, G. (2005), Soil-dependent topographic effects: a case study from the 1999 Athens earthquake, *Earthquake Spectra*, Vol. 21, No. 4, 929-966.

Boore, D. (1972), A note on the effect of simply topography on seismic SH waves, *Bulletin of the Seismological Society of America*, Vol. 62, No. 1, 275-284.

Boore, D. (1973), The effect of simple topography on seismic waves: implications for the accelerations recorded at Pacoima Dam, San Fernando Valley, California, *Bulletin of the Seismological Society of America*, Vol. 63, No. 5, 1603-1609.

Bouchon, M. and Barker, S. (1996), Seismic response of a hill: the example of Tarzana, California, *Bulletin of the Seismological Society of America*, Vol. 86, No. 1A, 66-72.

Chávez-García, F.I., Rodríguez, M., Field, E.H. and Hatzfeld, D. (1997), Topographic site effects. A comparison of two nonreference methods, *Bulletin of the Seismological Society of America*, Vol. 87, No. 6, 1667-1673.

Çelebi, M. (1987), Topographical and geological amplifications determined from strong-motion and aftershock records of the 3rd March 1985 Chile earthquake, *Bulletin of the Seismological Society of America*, Vol. 77, No. 4, 1147-1167.

Cevasco, A., Di Capua, G., Eva, C., Ferretti, G., Isella, L., Massa, M. and Peppoloni, S. (2005), Local effects analysis of the seismic amplification at Ripabottoni (Molise, Italia), *Proceedings of XI National Congress "Ingegneria sismica in Italia",* Genova, January 25-29 2004 (CD-ROM, in Italian).

Di Capua, G. and Peppoloni, S. (2005), Molise earthquake 2002: morphological and geolithological study, preliminary to the seismic microzonation of the Ripabottoni inhabited centre (Campobasso), *Proceedings of XI National Congress "Ingegneria sismica in Italia",* Genova, January 25-29 2004 (CD-ROM, in Italian).

Gazetas, G., Kallou, P.V. and Psarropoulos, P.N. (2002), Topography and soil effects in the M_s 5.9 Parnitha (Athens) earthquake: the case of Adámes, *Natural Hazards*, 27, 133-169.

Geli, L., Bard, P.-Y. and Jullien, B. (1988), The effect of topography on earthquake ground motion: a review and new results, *Bulletin of the Seismological Society of America*, Vol. 78, No. 1, 42-63.

Giovinazzi S. and Lagomarsino S. (2004), A macroseismic method for the vulnerability assessment of building, *13th World Conference on the Earthquake Engineering*, Vancouver, B.C., August 1-6 2004, paper no. 896.

Hartzell, S.H., Carver, D.L. and King, K.W. (1994), Initial investigation of site and topographic effects at Robinwood Ridge, California, *Bulletin of the Seismological Society of America*, Vol. 84, No. 5, 1336-1349.

Havenith, H.-B., Vanini, M., Jongmans, D. and Faccioli, E. (2003), Initiation of earthquake-induced slope failure: influence of topographical and other site specific amplification effects, *Journal of Seismology*, 7, 397-412.

Isella, L., Podestà, S., Resemini, S., Pasta, M. and Eva, C. (2004), The relationship between damage and peak accelerations in Ripabottoni during the 2002 Molise, Italy, earthquake, *Earthquake Spectra 20,* Issue S1, 119-130.

Jibson, R. (1987), Summary of research on the effects of topographic amplification of earthquakes shaking on slope stability, Open File Report*, 87-268*, *U.S. Geological Survey*, Menlo Park, California.

Lagomarsino, S., Podestà, S., Cifani, G. and Lemme, A. (2004), The 31st October 2002 earthquake in Molise (Italy): a new methodology for the damage and the seismic vulnerability survey of the churches", *13th World Conference on the Earthquake Engineering*, Vancouver, B.C., August 1-6 2004.

Lagomarsino, S. and Podestà, S. (2004a), Seismic vulnerability of ancient churches. Part 1: damage assessment and emergency planning, *Earthquake Spectra 20,* 377-394, ISSN-8755-2930.

Lagomarsino, S. and Podestà, S. (2004b), Damage and vulnerability assessment of the churches after the 2002 Molise, Italy, earthquake, *Earthquake Spectra, 20*, (Special Issue 1, *2002 Molise Italy Earthquake Reconnaissance Report,* edited by P. Bazzurro and J. Maffei), S271-S283. ISBN: 1-932884-03-3.

Lagomarsino, S., Podestà, S., Resemini, S., Eva, C., Frisenda, M., Spallarossa, D. and Bindi, D. (2005), Molise earthquake 2002: correlation between monumental buildings damage and seismic shaking characteristics, *Proceedings of XI National Congress "Ingegneria sismica in Italia",* Genova, January 25-29 2004 (CD-ROM, in Italian).

Kawase, H. and Aki, K. (1990), Topography effect at the critical SV-wave incidence: possible explanation of damage pattern by the Whittier Narrows, California, earthquake of 1 October 1987, *Bulletin of the Seismological Society of America*, Vol. 80, No. 1, 1-22.

Martinelli, A., Lemme, A., Peppoloni, S. and Di Capua, G. (2005), Seismic vulnerability and masonry buildings damage of historical centres: the case study of Ripabottoni (CB). An example of integration between structural and geological data, in: Rischio sismico, territorio e centri storici, *FrancoAngeli*, Milano, Italy (in Italian).

Paolucci, R. (2002), Amplification of earthquake ground motion by steep topographic irregularities, *Earthquake Engineering and Structural Dynamics*, vol. 31, 1831-1853.

Paolucci, R., Faccioli, E. and Maggio, F. (1999), 3D response analyses of an instrumented hill at Matsuzaki, Japan, by a spectral method, *Journal of Seismology*, 3, 191-209.

Podestà, S., Resemini, S., Bindi, D. and Spallarossa, D., (*in press*), Influence of ground motion characteristics on monumental building damage: the 2002 Molise earthquake (Southern Italy), *Journal of Earthquake Engineering*.

Sanò, T., Di Pasquale, G. and Naso, G. (2005), Influence of the motion intensity, geology and morphology on seismic amplification at San Giuliano di Puglia (CB), *Proceedings of XI National Congress "Ingegneria sismica in Italia",* Genova, January 25-29 2004 (CD-ROM, in Italian).

Spudich, P., Hellweg, M. and Lee, W.H.K. (1996), Directional topographic site response at Tarzana observed in aftershocks of the 1994 Northridge, California, earthquake: implications for mainshock motions, *Bulletin of the Seismological Society of America*, Vol. 86, No. 1B, S193-S208.