Damage mechanisms as seismic transducers in historic centres: the example of San Pio delle Camere after 2009 earthquake in Abruzzo (Italy)

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SUMMARY
A wide survey of the construction damages held in the nearby historic centres of San Pio delle Camere and Castelnuovo (AQ), after the 6 April 2009 earthquake in Abruzzo, have been done.
The soil of the upper part of San Pio delle Camere is characterised by high level of consistency, while the soil of the lower part of the village and of the Castelnuovo burg is generally highly compressible, performing relevant amplifications during the earthquake. Moreover the usual typology of constructions, made up by irregular stones masonry with poor mortar, assures a relative uniformity of the response to the earthquake.
From the numerous damage mechanisms on the facades and on the internal parts of the buildings, a map of the equivalent PGA experimented during the above seism has been determined.
In addition, the study of the signals recorded by some accelerometric stations around the epicentre, and processed with proper attenuation laws, furnishes further data for the seismic microzonation of the area.

Keywords: earthquake, damage mechanism, PGA, Abruzzo

1. INTRODUCTION

The earthquake occurred on 6th April 2009 in Abruzzo has been characterized by distinctive features in terms of macro-seismic intensity and local amplifications: the damages to similar buildings located in nearby areas were often substantially different.
In particular, one can note the presence of a consistent amount of vertical seismic component and a preferential direction of the ground movement, that is aligned SE-NW, with the projection of the main seismic source, the so-called Paganica fault. Moreover many amplification phenomena are due to the specific features of the soil, that consists mainly of a limestone bedrock and a layer of alluvial sediments with clay and silts, whose thickness reaches even values of 100 m.
In the case-study the macro-seismic intensity that was measured at Castelnuovo, that is 25 km far from L'Aquila, the epicentre, is largely higher than the values measured in places with similar distance from the epicentre such as San Pio delle Camere that is 2.5 km far from Castelnuovo. In the map reported in Figure 1 (Galli et al., 2009), the exceptional seismic intensity recorded at Castelnuovo is shown. This can be estimated about IX-X MCS, in comparison with the value of V-VI MCS relative to San Pio delle Camere. The damage amount depends surely on the quality of the buildings, but both villages and those located nearby are characterized by similar construction typologies whose quality is everywhere low and assures a relative uniformity of the response to the earthquake.
Hence, these different macro-seismic intensities are due to the presence of shake amplification phenomena that are caused by the lithostratigraphic and morphological features of the area and by instability and permanent deformation phenomena of the soil.
The start point of our technical assessments is the observation of building damages. Thanks to the financing of the Tuscany District, that in 2010 and 2011 founded stages for young graduating students in San Pio delle Camere, we had the possibility, as supervisors, to deeply analyse the buildings and to assess the damage and the seismic vulnerability. In this work, we use San Pio delle Camere as a real seismic transducer, that gives us the possibility to notice some correlation elements between the

damages and the local seismic response thanks to the great number of different specific damages.

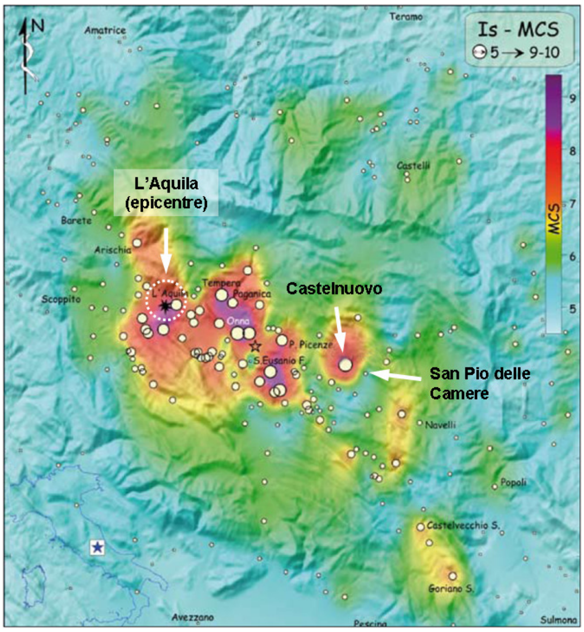

Figure 1. Synoptic map of the MCS intensity during the earthquake of April 2009.

At the first instance, the analysis of the large amounts of damage mechanisms has provided some possible values of the activation acceleration, that can be considered the minimum value of the peak soil acceleration (PGA) in San Pio delle Camere during the main shock. As further consideration, the conventional analysis of vulnerability in Castelnuovo, where the most part of the buildings have been destroyed and the collapse mechanisms have been overpassed, provides the upper limit of the PGA during the main shock. In this way, it is possible to assess the actual difference of the seismic actions in both villages.
These results can be used for the validation of the estimations of the recent seismic microzoning (2009). Indeed, on the basis of the records performed during the main shock by the nearby accelerometric stations of the National Accelerometric Net (the Italian RAN) and thanks to the signal-distance attenuation law, it has been possible to reconstruct the seismic action for both villages San Pio and Castelnuovo, and, consequently, to evaluate the amount of the seismic local amplification coefficient using the results of the assessment of the collapse mechanisms.
Undoubtedly, the knowledge of the main mechanisms can be considered particularly instructive and essential for the evaluation of the deficiencies of the most common typologies of buildings in sight of their consolidation.

2. THE EARTHQUAKE AT SAN PIO DELLE CAMERE AND CASTELNUOVO

San Pio delle Camere is a hill slope village located in the L'Aquila basin at the base of the Mount Gentile (Fig.2), 830 m o.s.l., on the south-east side of the valley of the Aterno river and 25 km far from the epicentre of the earthquake of 2009. The historic medieval centre is located in the higher part of the village and the build-up area is essentially along a main direction as the contour line. From the local geological point of view, the stratigraphy presents a carbonate bedrock overlayed by breccias in the upper part of the village and alternative layers of continental drifts of silts and clay with variable thicknesses in the lower part (Fig.3).
The historic centre of Castelnuovo is settled on an elliptical hill extended in direction WNW-ESE and made up of mainly fluvio-lacustrine deposits, at 860 m o.s.l., just 60 m above the surrounding valley, with an average slope of about 17°-18°. The centre of the village, concentric circles shaped, is located on the top of the hill.

Figure 2. Aerial view of Castelnuovo and San Pio delle Camere.

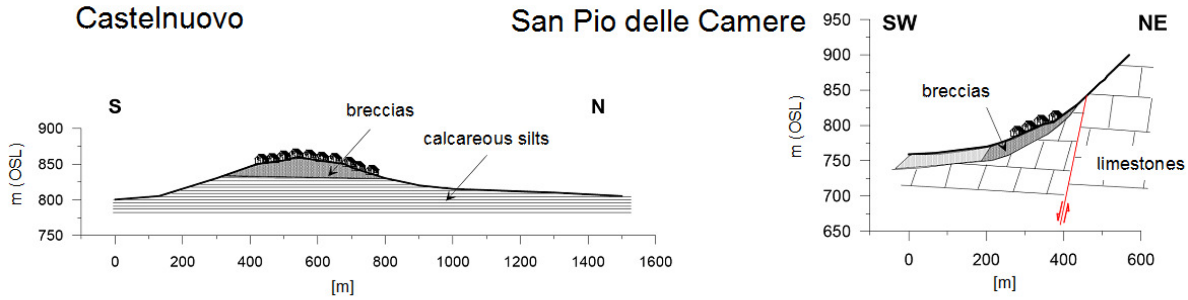

Figure 3. Approximate geological cross-sections of the two villages

As many villages around L'Aquila, San Pio delle Camere and Castelnuovo are characterised by underground chambers, under the buildings in both the rock and the sedimentary colluviums. Their shape and size are variable and the thickness of the vault is frequently very low. Many years ago these chambers, from which San Pio takes the name, were used as stall for the livestock and then as food cellar and storage. The exact impact of the presence of these underground chambers on the seismic amplification is still under evaluation.

The construction quality in both villages is quite low and their typologies are very similar. The 2 - 3 storey buildings are made up of masonry, the oldest ones of stone masonry, the more recent ones of concrete brick masonry too, often with no respect for the old construction rules. Somewhere one can observe curtain walls made up of not reinforced concrete with low quality. The oldest masonry is characterized by rough blocks and very poor mortar with irregular texture and no transversal connections. Moreover, the constructive evolutions such as rising, enlargement, refurbishments and change of functional use generated inhomogeneous structural systems with bad response to the earthquake. After the collapses it has been possible to understand the constructive evolution of many buildings, as one can see in Fig.6.

These situations occur largely at both villages, but Castelnuovo exhibits the heaviest damages, that are comparable only with those reported in the historical chronicles about the earthquake of 1461 (more than 550 years ago). This fact derives surely from the local amplification that were produced by the specific conformation of the village and by the soil nature: the large thickness of the lacustrine deposits has surely promoted the amplification of the seismic action at Castelnuovo and in the lower zone of San Pio delle Camere.

The features of the seismic shaking in homogeneous areas have been characterized with numerical descriptive parameters by the seismic microzonation studies, that have been performed for the whole surrounding zone of L’Aquila after 2009. In San Pio delle Camere the assessment has been executed using numerical models of the soil, whereas in Castelnuovo it has been possible to use also some experimental observations during the secondary shocks. In Fig. 4, the map of the local amplification is reported. As one can note, in San Pio delle Camere the local amplification coefficient is equal to 1-1.2 for the highest part of the village, where is located the historic centre and the rocks outcrop, and higher than 2, with a peak value of 2.5, elsewhere. In Castelnuovo, the coefficient is 2.2 at the top of the village and higher elsewhere, reaching values higher than 2.5. It is also noteworthy that the damage at the top of the village of Castelnuovo was considerably worse than at the base.

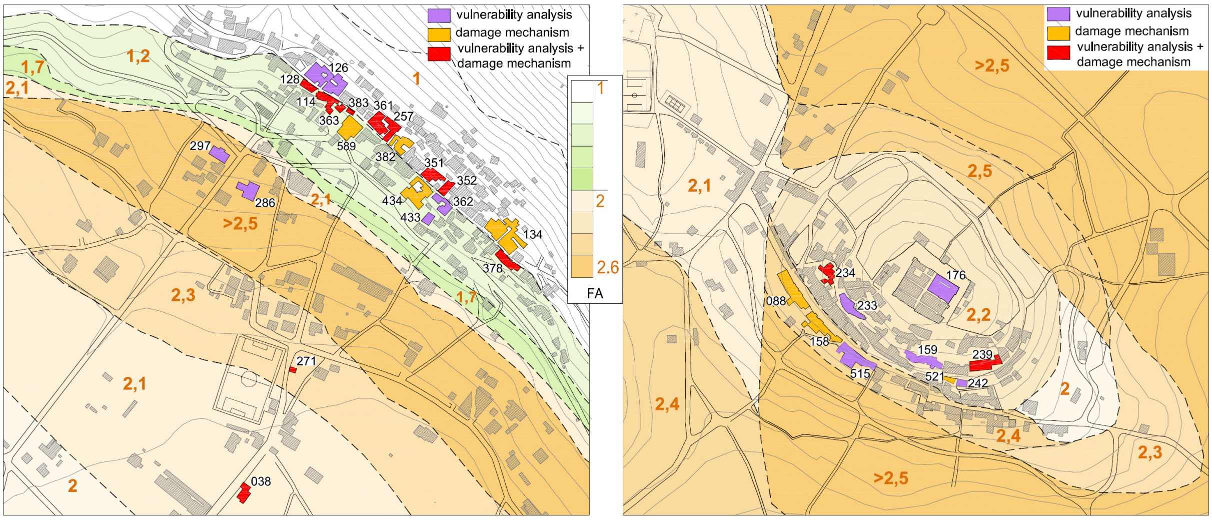

Figure 4. Building aggregates in San Pio delle Camere and Castelnuovo (on the left and on the right side, respectively) with the microzonation map.

3. THE ANALYSIS OF THE DAMAGES

In the historic centre of San Pio delle Camere the earthquake caused many damages with similar severity: it can be observed damage patterns on the facades and on the internal parts of the buildings and failures of thin brick vaults, mainly at the highest floors. Many mechanisms are well visible from the outside, as out-of-plane rotations of portion of walls, masonry corners or whole façades (Fig. 5) and, more infrequently, collapses of the outer leaf of the walls. A large amount of buildings, about 40%, has been declared unusable even if without significant failures.

On the contrary, in Castelnuovo many buildings are partially or totally collapsed, others exhibit overturning of facades and masonry corners. At the moment, the little village is abandoned, full of rubbles and debris, at the mercy of the invasive vegetation.

In this work, we have selected in San Pio and in Castelnuovo some building aggregates having meaningful damages or located in areas susceptible to high local amplifications (Fig. 4). In San Pio the analysis has been carried out on the area overlapping two zones where the local amplification factor is low, about 1 and 1.2. In Castelnuovo the area overlapping the zones with amplification factor 2.2 and 2.4 has been analysed. The selected case-studies consist essentially of stone masonry complex buildings, always representative of the usual typology, often resulting from many constructive evolution phases.

In order to deduce the value of the PGA attained during the main shock, many damage out-of-plane mechanisms have been analysed. As it is well known, it is possible to define three distinct limit states for the damage mechanisms with regard to the seismic action: (i) the state of *formation*, which involves the contribution of the cohesion on the detachment surface in the equilibrium balance with the inertial forces, (ii) the state of *activation* of oscillation (damage limit state), (iii) the state of *complete overturning* (collapse limit state).

Due to the uncertainties about the values of the mechanical characteristics of the masonry involved in the formation state, the only mechanisms considered are those in the state of activation.

Figure 5. Damage mechanisms in San Pio delle Camere (buildings aggregates n° 352, 038, 134, 434 - see Fig.4).

Mechanisms in state of complete overturning, that never occurred in San Pio delle Camere, are often present in Castelnuovo, where, due to the severe collapses, it is difficult to determinate the original shape of the macro-element. Moreover, in this case it is difficult to deduce the PGA, because the correct response of the mechanism can be assessed only through a dynamic non-linear analysis. Even if the problem is treated in an approximate form, it is not possible to refer to the forces: it is necessary to consider the displacement response spectrum and, in particular, the maximum ground displacement.

Figure 6. Collapsed buildings in Castelnuovo.

The methodology concerns the application of simple kinematic models, that make it possible to describe the mechanical behaviour of structural components and assemblages (macro-models). Thus, for every activated mechanism, the activation multiplier has been computed using simplified rocking block models and taking into account the stabiliser effect given by the weight of the macro-element and the horizontal inertial forces, that are proportional to the masses through an horizontal load multiplier α_0. If M_{RF} is the stabilising moment of the self weight, related to the shape of the macro-element, M_{RE} is the contribution of chains or tie beams and M_S is the overturning moment due to the seismic forces acting with acceleration g, the value of α_0 which leads to the mechanism activation can be obtained in the following way

$$\alpha_0 = \frac{M_{RE} + M_{RF}}{M_S}. \quad (1)$$

The spectral activation acceleration a* at the height of the hinge of the mechanism can be calculated from the multiplier α_0

$$a^* = \frac{\alpha_0}{e^*} g \quad (2)$$

where e* is the participating mass ratio and *g* is the gravity acceleration.
When the hinge of the macro-element is located at a certain height *z* from the base of the building, the value of the spectral acceleration at the soil a_0* which activates the mechanism is generally lower then a*. The evaluation of the soil acceleration a_0* has been carried out as suggested by the current Italian technical codes (Technical Standards for Constructions, 2008): the value of the soil acceleration capable to activate the mechanism is the minimum between a*, calculated for z = 0, and the anchor acceleration for the spectrum having spectral ordinate $S_e(T_1)$

$$S_e(T_1) = a^* /(z/h), \quad (3)$$

where *h* is the height of the building and T_1 is the natural period of the whole structure. As rough approximation, T_1 has been supposed proportional to $h^{3/4}$.
Dividing the spectral ordinate $S_e(T_1)$ by the maximum spectral amplification factor F_0 on the reference soil bedrock, the anchor acceleration of the response spectrum can be obtained

$$a_0^* = \min (a^*, a^* /(z/h\, F_0)). \quad (4)$$

As F_0 depends on the return period of the earthquake, it has been deduced trough an iterative process. Starting from the numerous mechanisms analysed, in Table 1 many results are reported. In Fig.7 the maps of the activation accelerations are presented.
The computed soil acceleration represents the minimum value needed for the activation of the mechanisms: as the mechanism is triggered, the macro-element also attains the collapse for higher values of the PGA.
From the map of San Pio in Fig.7, a relatively uniform distribution of activation accelerations can be observed in the historic centre of San Pio, with an average value of 0.094 g. Moving toward the valley, where the local amplification factor exceeds 2, values between 0.13 g and 0.15 g have been calculated. On the contrary, in Castelnuovo, the few cases we have been able to analyse have an average value of about 0.14 g with a maximum value of 0.18 g. It seems that the highest value of the soil acceleration are attained at the top of the hill, where the values of the local amplification factor are lower.
As a further analysis, a vulnerability assessment has been executed for 33 buildings aggregates, 16 in San Pio and 7 in Castelnuovo, with the aim to appreciate both the uniformity of the building quality and the base acceleration value which induces the collapse.
In particular, vulnerability estimation has been performed after processing the data collected through a second level assessment form proposed by Benedetti & Petrini (1984), developed by GNDT (1993) and more recently updated by Tuscany District, (Regione Toscana, 2003): starting from 11 parameters about the structural geometry and the mechanical features of the materials, a combination of the scores assigned to the structure according to the entries in the form allows to obtain a vulnerability index that is included in the range [0,1].
From the vulnerability index, the peak soil acceleration capable to lead the structure to collapse (the PGA - capacity) has been calculated

$$PGAc = 1/ (\alpha_c + \beta_c \cdot V^{\gamma}), \quad (5)$$

where V is the vulnerability index and

$$\alpha_c = 1.5371$$
$$\beta_c = 0.000974 \qquad (6)$$
$$\gamma = 1.8087.$$

as proposed by Bernardini (2000) and Zonno et al. (1999). In Tabel 2 are reported PGAc values.

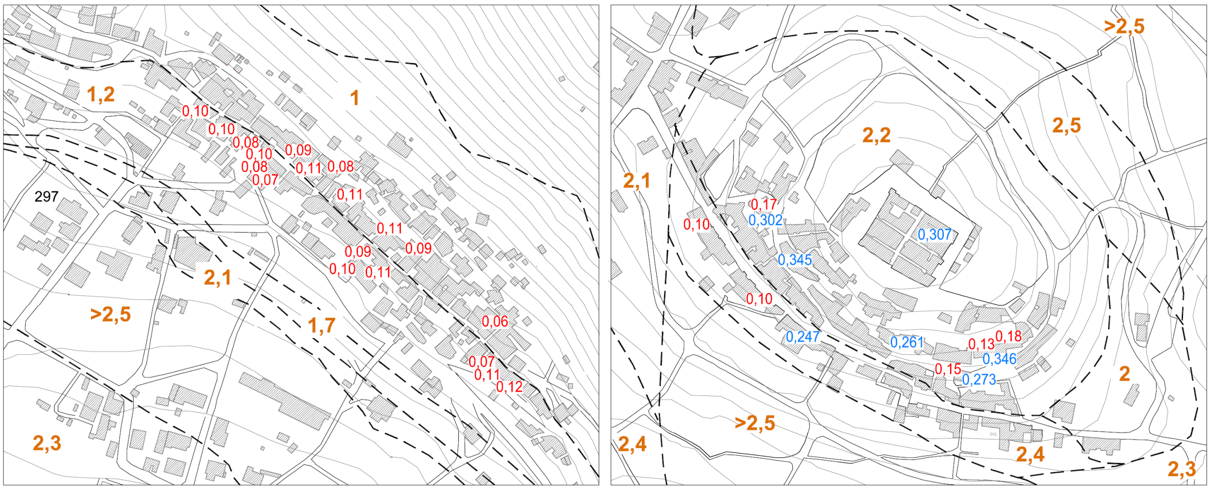

Figure 7. Map of the base accelerations in the historic centres of San Pio and Castelnuovo (on the left and the right side, respectively) - in red activation acceleration from the mechanisms, in blue the PGAc values.

Table 1. Data for the activation acceleration of the analysed mechanisms.

SITE	aggregate n°	a_0^* [m/s^2]	failure mechanism	a_0^* [g]
San Pio delle Camere	038	1.27	out of plane rotation of a portion of the façade	0.13
	271	1.47	out of plane rotation of the façade	0.15
	383	0.98	out of plane rotation of the corner	0.10
	128	0.98	out of plane rotation of the façade	0.10
	378	0.69	out of plane rotation of the façade	0.07
		1.08	out of plane rotation of the corner	0.11
		1.18	out of plane rotation of the façade	0.12
	363	0.78	out of plane rotation of the façade	0.08
	114	0.98	out of plane rotation of the corner	0.10
	589	0.69	out of plane rotation of the façade	0.07
		0.78	out of plane rotation of the façade	0.08
	134	0.59	out of plane rotation of the façade	0.06
	257	0.78	out of plane rotation of the façade	0.08
	351	1.08	out of plane rotation of the corner	0.11
	352	0.88	out of plane rotation of the corner	0.09
	361	0.88	out of plane rotation of the corner	0.09
		1.08	out of plane rotation of the corner (north wall)	0.11
	382	1.08	out of plane rotation of the corner	0.11
	434	0.98	out of plane rotation of the façade (street side)	0.10
		0.88	out of plane rotation of double corner (stairs side)	0.09
		1.08	out of plane rotation of the corner (stairs side)	0.11
Castelnuovo	088	0.98	vertical overturning	0.10
	158	0.98	vertical overturning	0.10
	234	1.667	corner failure	0.17
	521	1.47	vertical overturning	0.15
	239	1.27	vertical overturning	0.13
		1.77	vertical overturning	0.18

From this conventional analysis, one can deduce that the average soil acceleration that induces the collapse in San Pio is about 0.318 g, with a minimum value of 0.262 g, and the average soil

acceleration that induces the collapse in Castelnuovo is about 0.297 g, with a minimum value of 0.247 g. The reason of this low difference could lie in the different shape of the aggregates: in Castelnuovo they are generally lengthened, instead in San Pio they are more compact, with a shape ratio more favourable to withstand the earthquake.
This study allows us to estimate the upper limit of the peak soil acceleration in Castelnuovo: as a matter of fact, from Table 2 one can note that the totally collapsed buildings exhibit PGAc values about 0.27 g.
From these results it can be concluded that in the historic centre of San Pio the value of the soil peak acceleration attained during the main shock of 2009 have been higher than 0.12 g, instead in Castelnuovo have reached values between 0.18 g e 0.27 g.

Table 2. Data for the PGAc of buildings aggregates deduced from the vulnerability analysis.

SAN PIO DELLE CAMERE				
aggregate n°	PGAc [g]		aggregate n°	PGAc [g]
038	0.373		286	0.379
271	0.434		297	0.370
383	0.327		257	0.302
128	0.288		351	0.282
378	0.305		352	0.267
363	0.265		361	0.262
114	0.282		362	0.343
433	0.313		126	0.295

CASTELNUOVO		
aggregate n°	damage state	PGAc [g]
515	totally collapsed	0.247
159	totally collapsed	0.261
242	totally collapsed	0.273
239	partially collapsed	0.346
233	partially collapsed	0.345
234	mechanisms activated	0.247
176	partially collapsed	0.261

4. A CONTRIBUTION TO THE SEISMIC MICROZONATION

In order to estimate the extent of local effects in both villages, the PGA value attained during the main shock has been deduced as well from the anchor accelerations of the response spectrums calculated from accelerometric records in some near stations of the RAN. In Tabel 3 the main site parameters of the stations are listed.
For every registration, the anchor acceleration of the response spectrum has been referred to the bedrock, dividing its value by the local amplification coefficient S, deduced from the Italian regulation on the base of the typology of the subsoil and the topography of the site.
The site acceleration has thus been estimated trough the signal-distance law of Sabetta & Pugliese (1987) which furnishes the soil acceleration a_{gi}, as a function of magnitudo M (5,8 for the main shock 2009) and of the epicentral distance de_i (in km), according to the expression for the Italian area

$$\log(a_{g_i}) = -1.845 + 0.363 \cdot M - \log\sqrt{de_i^2 + 25} + 0.195 . \tag{7}$$

The anchorage acceleration for San Pio Se_{SP} has been thus obtained through a weighted average of the values Se_i from every station

$$Se_{SP} = \sum_{i=1}^{6} Se_i \cdot q_i , \tag{8}$$

with

$$q_i = \frac{a_{g\,SP}}{a_{g_i}} \quad \frac{1}{\delta_{SP\,i} \cdot \sum_1^6 1/\delta_{SP\,i}} , \tag{9}$$

where a_{gi} is the local acceleration for every station estimated by (7), a_{gSP} is the same for San Pio, whereas δ_{SPi} is the distance of every site from San Pio: so, nearer is the station, higher is the relative contribution.

Table 3. Site parameters for some accelerometric stations near San Pio delle Camere.

Station Code	*Latitude* N	*Longitude* E	*Site*	*Soil Class [from EC8]*	*Topography category*	*Local horizontal amplification S*	*Epicentral Distance* [km]	*Distance from San Pio* [km]	*PGA NS* [cm/s^2]	*PGA EW* [cm/s^2]	*PGA UP* [cm/s^2]
CLN	42.085	13.521	Celano	A*	T2	1.1	31.6	24	89.38	81.19	45.02
AVZ	42.027	13.426	Avezzano	C*	T1	1.5	34.9	34	67.69	54.80	26.12
ORC	41.954	13.642	Ortucchio	A*	T1	1	49.4	36.4	40.44	64.40	30.51
SUL	42.089	13.934	Sulmona	C*	T2	1.55	56.5	33.5	27.15	33.66	23.57
GSA	42.421	13.519	Gran Sasso (Assergi)	B*	T1	1.2	18.05	18.7	142.43	148.86	107.11
MTR	42.524	13.245	Montereale	A*	T3	1.2	22.4	43	62.23	43.00	22.68

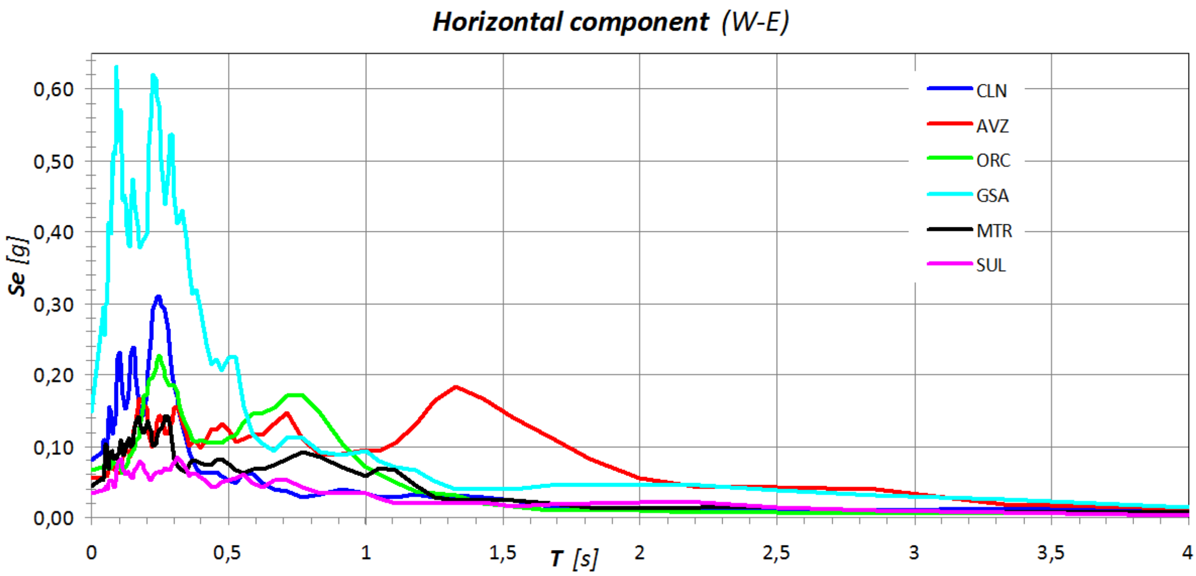

Figure 8. Response spectrums from the selected recording stations near San Pio and Castelnuovo.

The value of the anchorage acceleration referred to the bedrock is then 0.078 g in San Pio, whereas 0.087 g in Castelnuovo. Comparing this results with the estimation of the PGA from the damages, it can be deduced that, for the historic centre of San Pio, the minimum local amplification coefficient in the horizontal direction is about 1.5, in view of 1.2 obtained from the seismic microzonation, whereas, for the lower part of the village, the local amplification attains 2, in view of 2.1-2.3 from the microzonation. For the case of Castelnuovo, the minimum local amplification coefficient at the top of the hill should vary from 2.1 to 3.1, in view of 2.1 - 2.4 from the microzonation.
As a result, in San Pio the local amplification deduced from the analysis of the damage is similar to that obtained from microzonation studies, whereas in Castelnuovo is higher and the progressive growth of the seismic intensity toward the top of the hill is confirmed.

5. CONCLUSIONS

This work represents a first attempt to deduce information about the local seismic shaking, starting from the damages observed in structural systems, with the support of simple calculation tools. Even if the uncertainty margin of this rough simplification is high, the study of the damage may constitute an

useful tool for the validation of the results from microzonation studies.
Indeed, the microzonation performs a forecast of the dynamic behaviour of the soil, starting from the underground and using often conventional seismic input. The observation of the damages distribution may validate this forecast, starting from "above", i.e. from the building heritage, on the basis of seismic events effectively occurred.

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