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In situ measurements of site effects and building dynamic behaviour related to damage observed during the 9/9/1998 earthquake in Southern Italy

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Abstract

After the event that struck the border between Calabria and Basilicata regions in Italy, a series of in-situ measurements were undertaken. Applying the methodology already used in the aftermath of Marche-Umbria, 1997 and Slovenia, 1998 earthquakes, HVSR were measured using aftershocks, microtremors and man-made excitations. The measurements were performed both on free-field and inside damaged buildings. It was possible to see how the enhancement of damage can be attributed to a double resonance effect observed when a building fundamental mode approaches soil resonance frequency.
With respect to previous case studies, some more interesting effects were observed, namely:

1) differential damages in buildings that appear to be exactly similar but that show different fundamental frequency;
2) the coupling of frequency of adjacent building with different characteristics (RC and stone masonry);
3) the increase of amplification effect close to fault gauge zones not activated by the event.

1 Introduction

On September 09 1998 a 5.5 Ml earthquake occurred North of Mt. Pollino area (Italy), at the border between Calabria and Basilicata. The focal parameters of main shock given by National Geophysics Institute are:

Date	Epicentre Co-ordinates	Epicentre Area	Magnitude	Estimated Int. max	Observed Int. max
1998 0909	39.99N-16.01E	Castelluccio-Rotonda-Laino	4.8 Md-5.5 Ml	VIII	VI-VII

The pattern of intensity distribution (by P. Galli and D. Molin [1], fig.1) shows values greater than VI E.M.S. in the areas of Rivello, where important site effects are observed, and Perricchio, while values equal to VI E.M.S. are in the area near Castelluccio and Lauria. To supply as soon as possible a quick evaluation of ground amplification, which could be useful to understand the small-scale pattern of damage distribution, it was decided to take some microtremor measurements, and to process them according to the Nakamura technique (Nakamura [2]). Thus, what was actually performed is an analysis of the H/V ratio for weak-motion recordings and microtremors. As discussed in Mucciarelli and Monachesi (Mucciarelli and Monachesi [3]) it is then possible to evaluate amplification avoiding the criticisms most commonly addressed to the Nakamura method. Finally, it must be considered that the measurements were taken in sites within short distance of one another and showing different levels of damage; therefore, source effects can be neglected and a relative comparison is always possible.

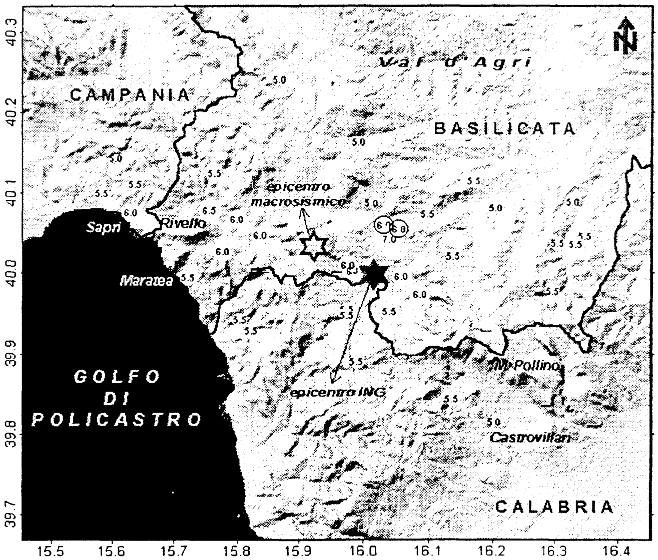

Figure 1: Pattern of intensity distribution of 5.5 Ml earthquake occurred in Pollino area at the border between Basilicata and Calabria (form P. Galli and D. Molin [1]).

2 Data collection and H/V ratios

The microtremor approach to seismic zonation has been widely debated (Atakan [4]). In particular, the Nakamura's technique has recently drawn much attention: a discussion of the aspects relevant to the measurements like those here presented can be found in Mucciarelli and Monachesi [3] and Mucciarelli [5] and for sake of brevity will not be reported here. The data collection and processing is described in the following. The signals used have been recorded with a tridirectional sensor Lennartz 3D-Lite (1 Hz period), connected with a 24 bit digital acquisition unit PRAXS-10 and a 486 100 MHz personal computer, all installed in a single metal case. The sensor has the same characteristics on all the three axes. The site transfer functions have been computed in the following way. First a set of at least 5 time series of 60 s each, sampled at 125 Hz, have been recorded. Time series have been corrected for the base-line and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal and bandpass filtered from 0.1 to 20 Hz, with cut off frequencies at 0.05 and 25 Hz. Fast Fourier transforms have been applied in order to compute spectra for 25 predefined values of frequency, equally spaced in a logarithmic scale between 0.1 and 20 Hz, selected in order to preserve energy (Castro et al. [6]). The arithmetical average of all horizontal to vertical component ratios have been taken to be the site amplification function. All mentioned procedures are automatically performed by the recording system short after acquiring noise data series. Back in the lab one can re-process the data, increasing the frequency resolution and separating orthogonal directions in the vertical plane.

3 In situ measurements of site effects and building dynamic behaviour

The most affected sites that were sampled are located in the area between Rivello and Castelluccio Inferiore along the NW-SE direction. A series of measurements were performed both on free field (to study soil amplification) as well as inside buildings (to determine fundamental frequencies of oscillation). The use of horizontal-to-vertical spectral ratio (HVSR) to determine dynamic behaviour of buildings has been recently proposed both using weak motion (e.g. Castro et al. [7]) as well as microtremors (Nakamura [8]; Mucciarelli and Monachesi [3]).

➢ **Lauria Superiore.** Many buildings in Lauria Superiore are situated in landslide areas: the large landslides involve not only the historical centre (where it is possible to see old houses which present tilted external walls), but also the new part of Lauria Superiore. Two reinforced concrete buildings were investigated. The first measurement was taken on the ground and fourth floor of building n°77 (stair D). This building presents heavy damages at the ground-floor outer walls fillings; some of them are 'exploded', but cracks do not pass through columns (this building is not considered unfit for use). Later, measurements were performed in building n°59, in particular on the first and fourth floor; this building is located at a distance of 50m from building n°77; also this one is affected by a landslide and has passing cracks only through first floor outer walls. We must remember that all buildings of this area had suffered

great damage during the 1980 Irpinia earthquake which had worsened the pre-existent instability. Following the 1980 earthquake, the building n°77 had not structural re-arrangements; on the contrary the building n°59 had structural reinforcements such as internal stiffening with steel beams. In fig.2a it is possible to see a dynamic joint inserted in the stairwell. Only the ground-floor was stiffened with steel 'double T' beams, fig.2b.
The foundation plinths had caged into steel beams. These two buildings have different dynamic behaviours due to different structural retrofitting.

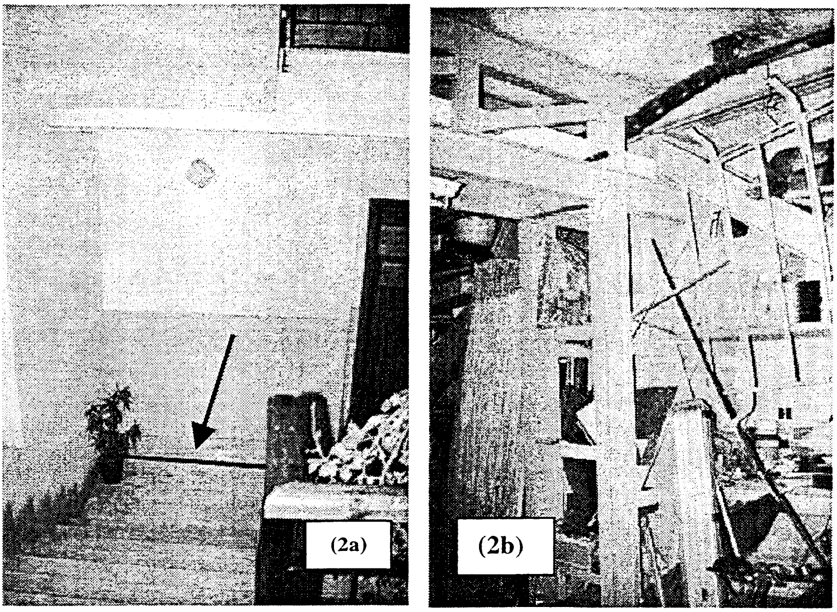

Figure 2: Photograph (2a) showing a dynamic joint inserted in n°59 building's stairwell (Lauria) following the 1980 earthquake. In the same building the ground-floor had stiffened with steel 'double T' beams (2b).

Fig.3a shows the amplification functions of building n°77, while Fig.3b shows the ones made at n°59. Because building n°77 had not structural adjustments following 1980 earthquake, displacement rate between floors is larger than the one of building n°59, which had important rearrangements. Ground-floor of building n°59 was stiffened with steel beam, then the part free to swing is shorter than the one of building n°77: for this reason the building n°59 presents its main peak at higher frequencies. Building n°59 has a sharp peak at about 4 Hz while building n°77 at 2.5 Hz. Building n°77 shows cracks at ground-floor while building n°59 has slight damage at first floor, where there are points with different stiffening: Fig.4 clearly shows the different amplification rate between building n°77 and n°59 at first and fourth floors.

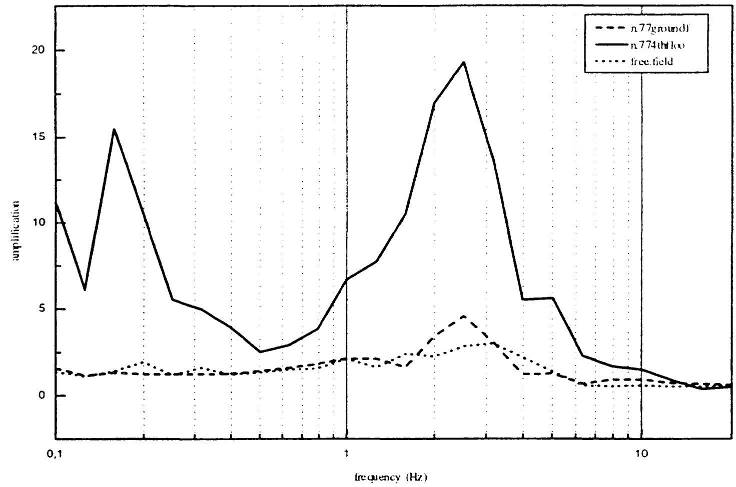

Figure 3a: Amplification functions measured in n°77 building (Lauria Sup.) on ground floor, on fourth floor and free-field. The sharp peak at 2.5 Hz for the building is close to the maximum amplification frequency range observed for free-field. The peak at 0.2 Hz is probably due to the less of resolving power at low frequencies. As shown by Mucciarelli 1998, below 1 Hz very low values of vertical component, in low noise area, may be due to instruments limitations and may give rise to spurious high ratio value.

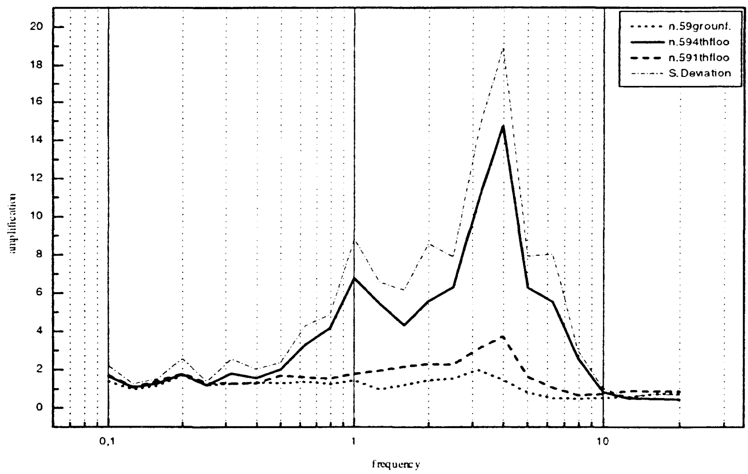

Figure 3b: Amplification function measured in n°59 building (Lauria Sup.) on ground floor, on fourth floor and free-field. Also 1 standard deviation is reported to show how dispersion is very low when HVSR is applied to buildings.

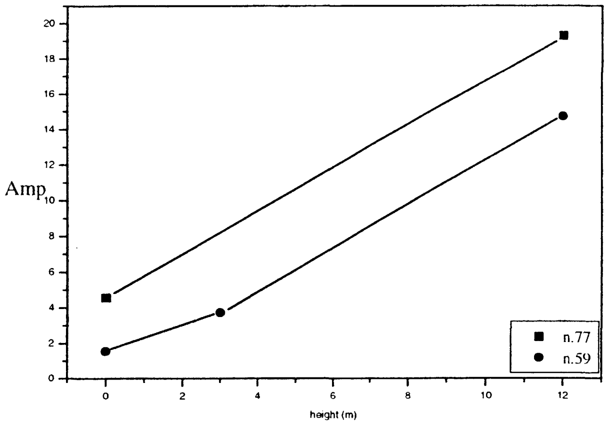

Figure 4: Diagram showing in abscissa the height at which the measurements were performed in buildings (at ground, first and fourth floor) and in ordinate the different amplification rate between building n°77 and n°59 in Lauria. Building n°77 shows a bi-linear behaviour due to the larger stiffness of ground-floor caused by reinforcements made after the 1980 earthquake.

➢ **Perricchio–Latronico.** In Perricchio heavy damages are present in an old stone house, with passing cracks through two parallel walls. The house is adjacent to another house built with a reinforced concrete frame, showing only slight damages. Fig.5 shows a schematic plan of this interconnected system composed by two different building typologies.

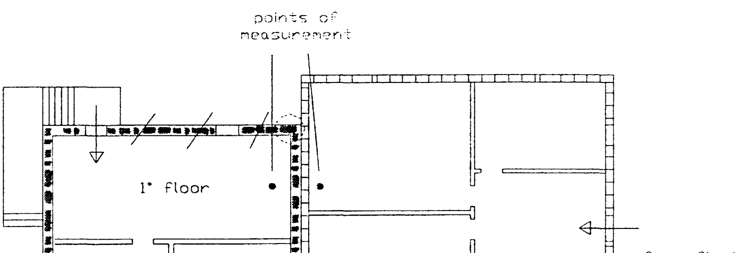

Figure 5: A schematic plan showing interconnected system composed by two different typology houses in Perricchio (Latronico), the points of measurements and location of damage.

The measurements were performed at two houses' first floor. Fig.6 shows amplification functions of stone masonry and reinforced concrete house: both measurements had been processed separating N-S amplification functions from E-W one, where N-S is identifying the most elongated direction of the building. E-W amplification function of damaged stone house shows a peak at about 2.5 Hz, very close to the maximum amplification frequency range observed for free field. On the contrary the N-S amplification function has another sharp peak at about 7 Hz. The amplification function of reinforced concrete house has in both components a sharp peak at 2.5 Hz, close to the free-field frequency. This house has a peak at the same frequency in N-S and W-E direction as expected from a square house with equal stiffening distribution in all the directions. The stone masonry house is on its turn showing an almost square floor map. The reason for the noticeable difference of frequency in two orthogonal directions (7 and 2.5 Hz) may be due to the interaction with the reinforced concrete house, which is having as expected a lower fundamental frequency. The presence of damage only in two parallel walls could be explained invoking a forcing mechanism caused by the motion of the reinforced concrete building which is discharging on the less resistant element of the system the energy transmitted by the amplified ground motion. In other words: the free-field measurement shows an amplification at about 2.5 Hz; The reinforced concrete house has both fundamental frequency near this value, but the damage is all transferred on the less resistant member (the stone masonry house) whose fundamental frequency (7 Hz) is altered in the direction subjected to the interaction with the reinforced concrete house.

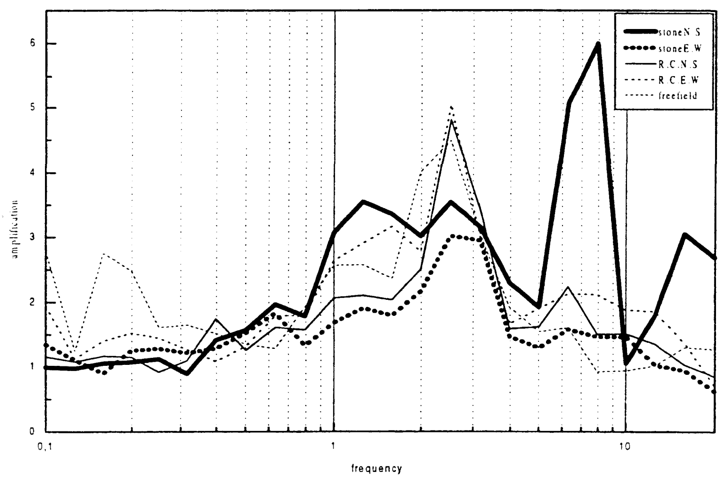

Figure 6: Amplification functions of stone and reinforced concrete house separated in orthogonal components. See text for details.

➢ **Castelluccio Inferiore.** In spite of slight damages present in the most part of the buildings in the ENEL neighbourhood (Fig.7a) some of them show higher damages, together with a recent building on the other site of the same street. The damaged ENEL building is a complex built in the late 1950s. It is composed by two identical part separated between them by technical joint, 4 storeys high with reinforced concrete frame and brick fillings. Only one part of this complex is now unfit for use: in fact, it has not only heavy damages at the infills but also it presents cracks at the first floor beams.

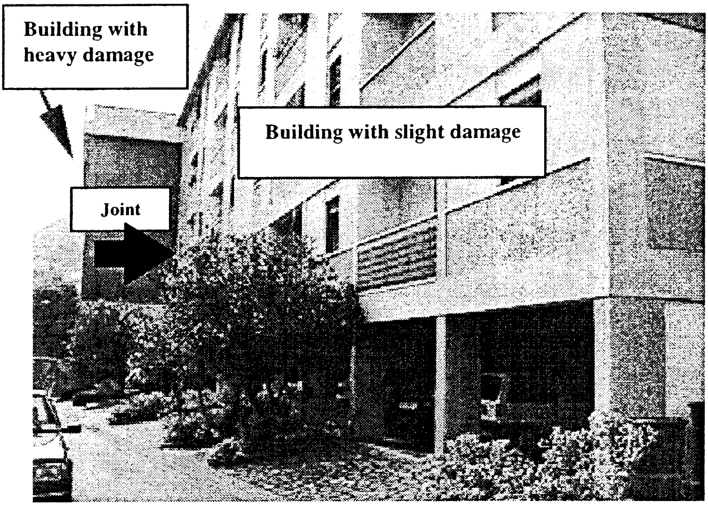

Figure 7a: Photograph showing two part of a damaged building (Castelluccio Inferiore), one of these is unfit for use, the other has only slight damages. The two parts are jointed.

The damages to the ENEL building and to the house in front of it probably are due to an impluvium that can be clearly seen in the aerial photograph (Fig.7b). The measurements undertaken, are reported in the same photo (Fig.7b):

1. at fifth floor of building which is considered unfit for use;
2. free-field measurement behind the heavy damaged building;
3. at fifth floor of building with lesser damages;
4. free-field measurement behind the less damaged building.

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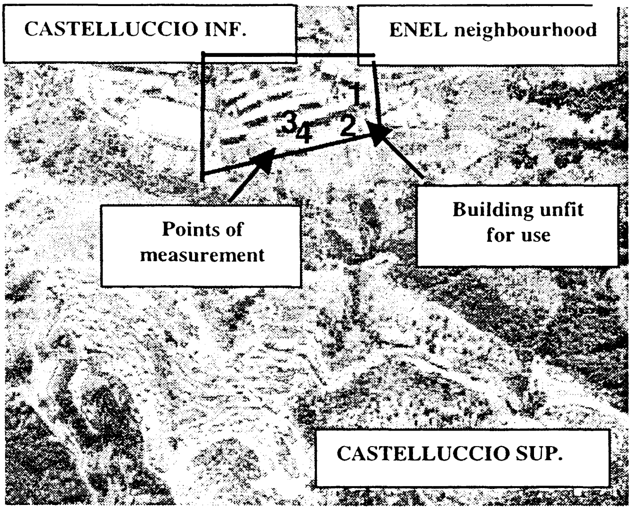

Figure 7b: An aerial photograph reporting points of measurements in Castelluccio Inferiore.

Fig.8 shows the amplification functions at the fifth floor of the two buildings together with the free-field. It is possible to see how inside the buildings there is a common peak at about 5 Hz. Another frequency peak is different in the two buildings. It will be interesting to see with ongoing studies if this difference is due to the damage observed in only one of the buildings or if different frequency reflects a different construction technique that might have led to a differential damage.

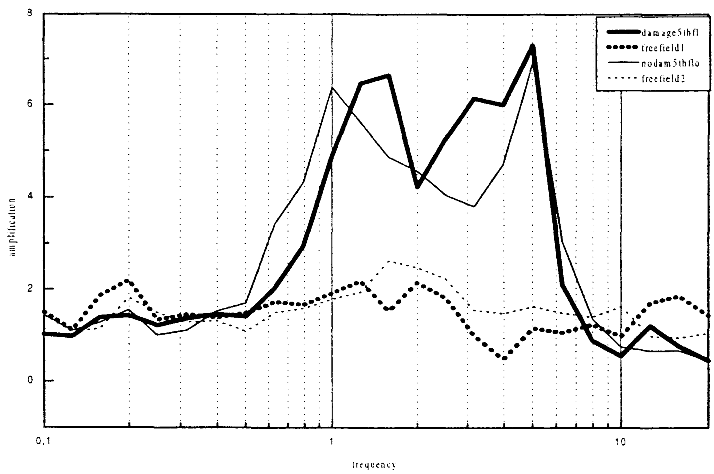

Figure 8: Diagram showing amplification function for free-field and fifth floor for the two part of the building showing different damage.

➢ **Castelluccio Superiore.** The geologic map points out a normal fault in Castelluccio Superiore that separates limestone from conglomerates. Fig.9a shows the fault plane at the entrance of town. The heaviest damaged buildings are Our Lady's church and the historical centre's church. Our Lady's church lies on conglomerates while most of the town of Castelluccio Superiore lies on limestone. In fig.9b three points of measurement are located on the geologic map:

1. on conglomerate;
2. on the fault plane;
3. on limestone.

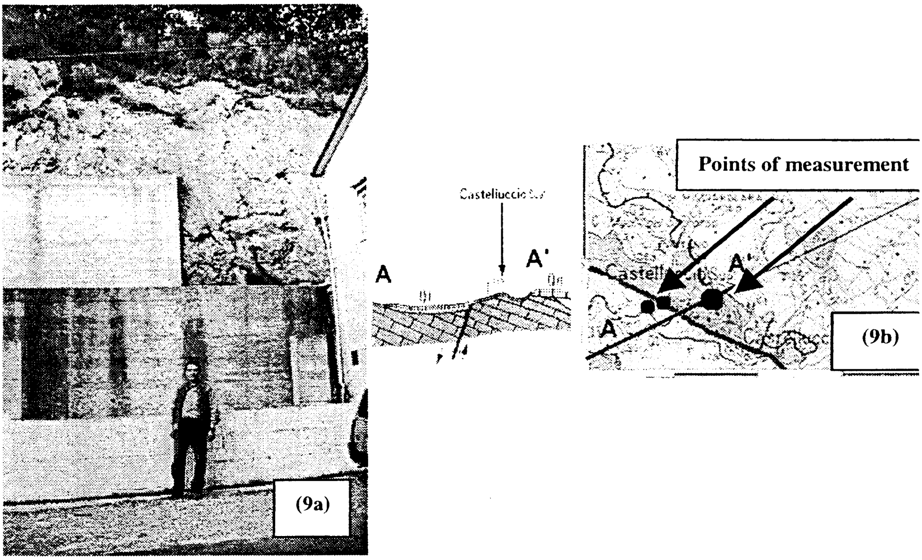

Figure 9: Picture of the fault plane at the entrance of Castelluccio Superiore, which separates limestone from conglomerate (9a). Geologic map showing the three points of measurement across the fault (9b).

Fig.10 shows the three amplification functions: the free-field amplification function measured on bedrock is substantially flat, the amplification function measured on conglomerates has an evident peak at 3.5 Hz and the fault plane one has a peak at 1 Hz. It is interesting to note how the limestone close to the fault, in the fault gauge zone, shows an amplification peak which is not present on the undisturbed limestone, few hundreds meters away.

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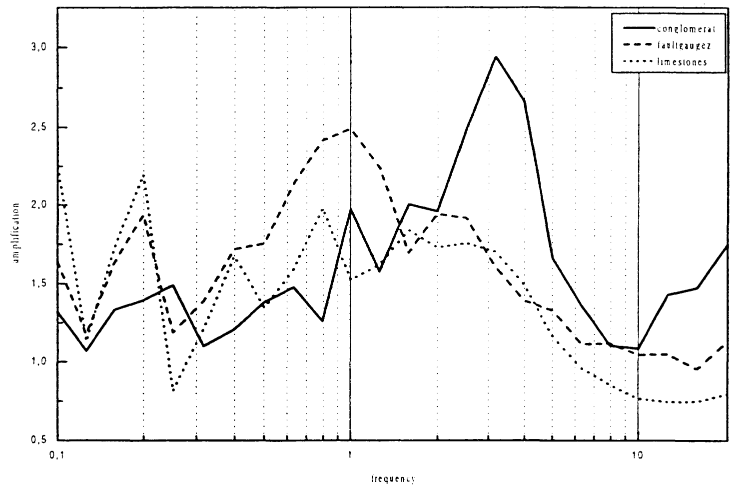

Figure 10: Three amplification functions in Castelluccio Superiore: on conglomerate, on limestone and on fault plane.

➢ **Rivello**. This town is composed by three parts: Serra, Motta and Poggio. Fig.11 points out Serra quarter, which was the mostly damaged. This affected area is located upon a crest parting from the principal ridge and so the cause of damages could be possibly attributed to topographic effects. The typology of damaged Serra houses is similar, with two floors, brick/limestone block bearing walls and almost identical dimension. The worst damages consist in falling of the tiles, collapse of the roof-tops and partial collapse of stone masonry in old buildings.

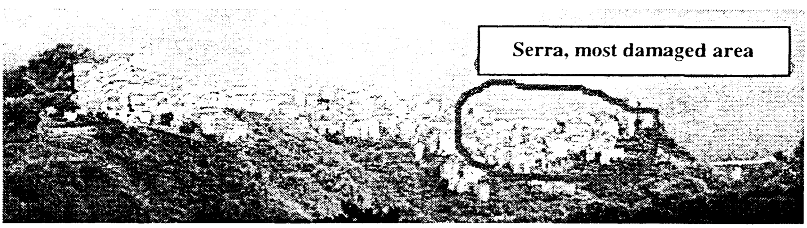

Figure 11: Picture of the ridge Rivello lies on, with Serra neighbourhood that had important localised damage.

The first free field measurement was undertaken in Serra Square near the most damaged buildings. The North of instrument was perpendicular to the most elongated direction of the crest. The second measurement was made in Motta's Belvedere where there no damage occurred. The two free-field amplification (fig.12) functions, possibly due to a morphological amplification are similar for both sites: Belvedere's free-field has a sharp peak at 3 Hz and Serra free-field at 4 Hz,. The cause of heavy damages in Serra square buildings could not be easily attributed to ground amplification or building vulnerability. Probably the localised damage is caused by geotechnical reasons, such as conglomerate constipation or slope instability, which cannot be detected by the microtremor technique.

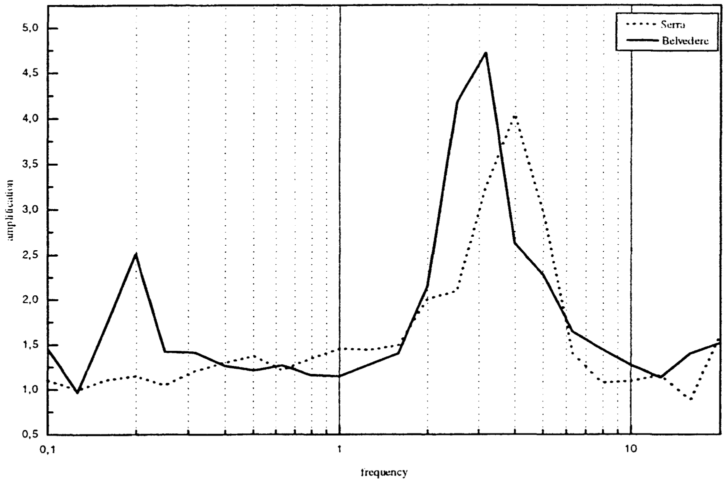

Figure 12: Free-field measurement taken near the house at n°42 in Serra Square, in front of damaged buildings, compared with the measurement made in Motta's Belvedere where there are no damages. The two free-field amplification functions are similar for both sites, thus leading to invoke other geotechnical problems.

4 Conclusion

The microtremor measurements, performed both in free-field and inside buildings after the Southern Italy earthquake 9/9/1998, allow for an explanation of some of the damage enhancement observed (Lauria, Castelluccio Sup., Perricchio). The higher damage degrees observed can be attributed mainly to double resonance between buildings and soil frequency. In one other case (Rivello) there is no instrumental evidence supporting the soil amplification as the primary cause of damage enhancement, thus leading to invoke other geotechnical non-linear phenomena. Finally, the measurements performed inside very similar buildings, showing a different damage degree and different fundamental frequency (Castelluccio Inferiore), will allow to establish if there are constructive difference inside the buildings or if it is possible to monitor the fundamental frequency shift due to ongoing damage.

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