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L'Aquila Seismic Event on 6th April 2009: Site Effects and Critical Points in Microzonation Activity Within the Aterno Valley Municipalities

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L'AQUILA SEISMIC EVENT ON 6th APRIL 2009: SITE EFFECTS AND CRITICAL POINTS IN MICROZONATION ACTIVITY WITHIN THE ATERNO VALLEY MUNICIPALITIES

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ABSTRACT

L'Aquila earthquake was a complex seismic event characterized by its main shock on 6th April 2009 with magnitude Mw=6.3 and many foreshocks and aftershocks that stroke the whole Aterno River Valley from November 2008 up to September 2009. The huge amount of strong-motion records collected by permanent and temporary stations placed in the valley show a heterogeneous seismic hazard scenario related to different damage levels. With respect to the seismological features of the records within the "crater" (that is the portion of the Aterno Valley which suffered the strongest struck), they show "near field" and "near source" characters although the same records provide differentiated amplification effects among neighboring sites. Geological relieves and direct and indirect in field testing were performed for micro-zoning purposes soon after the main shock. The outcomes of these two year studies produced satisfactory results that have been collected as guidelines for identifying the areas showing homogeneous seismic response. Nonetheless, some questions have not been answered yet, that are (1) how much geo-lithological conditions affect the seismic response within "near field" areas and (2) which means can be used to predict the recorded amplifications. This paper focuses and discusses on some results carried out at a few sites, such as Onna and L'Aquila municipalities and proposes operating strategy to detect the local amplification effects within near field areas.

INTRODUCTION

6th April 2009 L'Aquila earthquake can be considered one of the most recent mournful event for many Italian citizens that lost their lives and their homes. Nonetheless, rationally speaking, it represents an opportunity for the whole Italian community of earthquake technicians and scientists for testing the theoretical studies carried on up today. As a matter of fact, among the Friuli earthquake in 1976 (Moment Magnitude Mw 6.4), the Irpinia earthquake in 1980 (Mw 6.9) and the Umbria-Marche in 1997 (Mw 6.0), L'Aquila earthquake is the third largest event recorded by strong-motion accelerometers in Italy. The Friuli earthquake, for the first time, boosted quantitative micro-zoning studies associated with the macro-seismic maps of damages: since then the differential local site effects in near field conditions were detected. Subsequently, after the Irpinia earthquake, the project "Geodinamica" was financed: it was the first research project, in Italy, that tried to introduce numerical one- and two-dimensional finite element simulations to assess site effects (Postpischl et al. 1985). In the last thirty years, developments in earthquake studies have been implemented in numerical codes and in scientific practices worldwide. L'Aquila earthquake 2009 occurred when the discussion on the best techniques for both measuring the seismic properties of the sites and representing seismic hazard scenarios at selected return periods was at its apex. Moreover, new technical guidelines for Italian building codes were published in 2003 by DPCM 3274, 20 marzo (2003) and from then on, many times they have been enriched by studies on seismic probability hazard over the national territory, on site effects due to topography and soil impedance contrasts. In addition, a great amount of new technical guidelines for designing new structures and retrofitting the old ones made up of masonry, steel and reinforced concrete buildings have been also published during the last years.

As seismic micro-zoning is concerned, the Italian Department of Civil Protection (DPC) published in 2008 the "national guidelines" for executing micro-zoning studies related to liquefaction, instability and amplification phenomena (Gruppo di Lavoro MS 2008). The working scales vary between 1:5000 and 1:10000 along with the municipal territory extension. Such activities can be performed at three detail levels: level 1, by mapping homogeneous geological units with respect to seismic behavior; level 2, by mapping numerical indexes for homogeneous susceptible areas; level 3, by mapping homogeneous seismic responses carried out by means of one-, two- and even three-dimensional numerical analyses. Soon after the terrible unpredicted earthquake on 6h April 2009, all the financial efforts of Italian government were devoted on one hand to face the emergency, and, on the other hand, to check the effectiveness of the technical guidelines already published. Such back-analysis studies were carried out by several scientists throughout the whole Aterno Valley and started just after the main shock event. At that time, many strong and weak motion records were available from main shock and aftershocks of the 6^{th} April seismic event; these records are now published on two public databases: ITACA (for strong motion events) at http://itaca.mi.ingv.it/ItacaNet/itaca10_links.htm and ISIDE (for weak motion and instrumental events) http://iside.rm.ingv.it/iside/standard/index.jsp managed by the Italian National Institute of Geophysics and Volcanology (INGV). Then, all the micro-seismic studies that have been undertaken, have been collected within a book published in 2010 (Working Group MS-AQ 2010). It aimed at providing amplification factors and input spectra for reconstruction purposes. Such information has been provided for twelve macroareas within the Aterno Valley chosen by the seismic intensity suffered higher than VI measured in Mercalli-Cancani-Sieberg (MCS) scale.

With the same purpose of the above mention guidelines, the present study focuses on the level three of micro-zoning study. This paper discusses the role played by geo-lithological conditions in the amplification effects occurred at different sectors of the Aterno Valley. Moreover, the authors provide suggestions to quantify surface geology contribution to the overall amplification effects in near field conditions. To this end, two out of twelve macroareas identified within the Aterno Valley are considered, that are the macroarea 1 (L'Aquila city center) and the macroarea 5 (Onna site) (Fig. 1).
Here, one-dimensional (1D) numerical simulations have been performed to overpass some inconsistencies between the strong-motion records and the proposed strategies for local seismic response prediction.

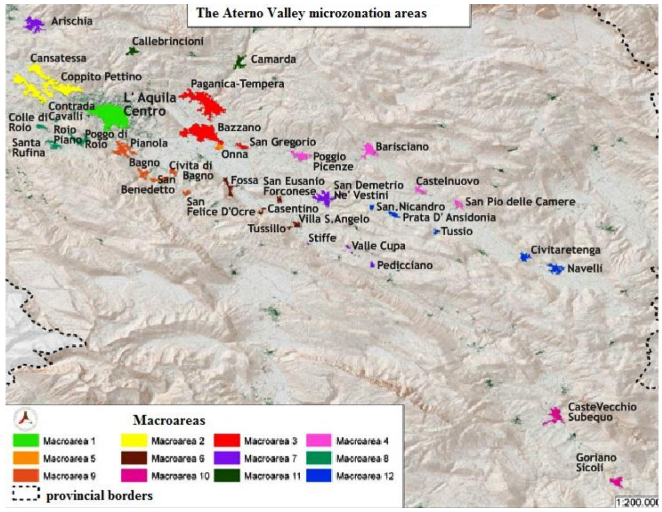


Fig. 1. Twelve macroareas map where micro-zoning activities have been performed.

MAIN FEATURES OF THE ATERNO VALLEY SEISMICITY

The Aterno Valley is an intermountain quaternary basin generated by the normal fault tectonic regime, dominating the seismic activity within the central sector of the Apennine chain. It is located between the Gran Sasso mountain and the Monti Ocre-Velino-Sirente structural units. It is elongated NW-SE and it can be subdivided into three areas: Northern, Southern and central area where L'Aquila city is located. Before the 2009 L'Aquila earthquake, no active faults had been identified within the Aterno Valley according to the Database of Individual Seismogenic Sources DISS3 (DISS Working group 2009), that is a georeferenced repository of seismogenic source models for Italy.
Nonetheless, Valensise *et al.* (2004) included the Paganica Fault (responsible for 2009 L'Aquila earthquake) within the inventory of the active faults belonging to the central sector of the Apennine chain, whose activity dated in the late Quaternary. On 6^{th} April 2009, at 01:32 UTC, a M_W 6.3 earthquake struck the Aterno Valley, especially L'Aquila city center and its surroundings causing 306 fatalities and more than 60,000 people displaced, due to the heavy damages to civil structures and buildings. Moreover, a large part of the historical buildings and churches were severely affected: the old town of L'Aquila was strongly damaged and Onna city (Fig. 2), south of L'Aquila, was fully destroyed: the MCS intensity reached IX-X at Onna site and L'Aquila city center.
The main shock followed a seismic sequence started in October 2008 and thousands of aftershocks followed the main shock showing NW-SE striking trends.
The aftershock distribution (Chiarabba *et al.* 2009), as well as DinSAR analyses (Atzori *et al.* 2009) in Fig. 3, showed the reactivation of Paganica fault, 15km long, NW-SE striking (about 150°) and SW dipping structure (about 50°). The fault plane was 28km and 17.5km wide and the hypocenter was

located at 9.5km (Ciriella *et al.* 2009). Furthermore, the joint inversion of SAR interferometric and GPS data performed by Atzori *et al.* (2009), Fig. 4, showed an asymmetric deformation field, with maximum displacements no greater than 10-12 cm, compared to a maximum slip of about 1 m recognized SE of L'Aquila town. Accordingly, Milana *et al.* (2011) recognized a decreasing trend in the amplification factors from South to North. Such behavior suggested a relevant role of the fault directivity effects (Atzori *et al.* 2009).

Fig. 2. Onna city after the 6th April 2009 seismic struck.

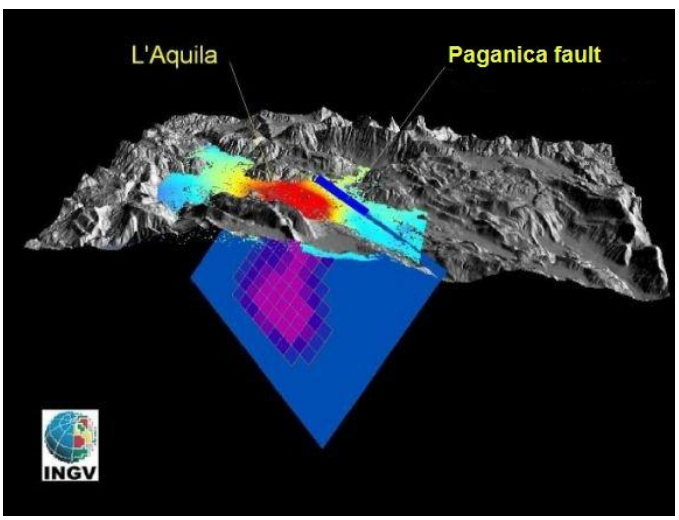


Fig. 3. Fault plane solution by InSAR data inversion, corresponding to the theory of a seismogenic and capable Paganica fault (Salvi et al., 2009).

Looking at Fig. 4, each concentric fringe quantifies 1.5 cm of co-seismic vertical deformation; in addition, Onna is placed where the settlement lines are denser while L'Aquila city shows lower vertical displacement. As can be seen, Onna city is less than 5km far from Paganica fault whereas L'Aquila city is 5.7km far from it: the two cities fall within the Paganica fault hanging wall.

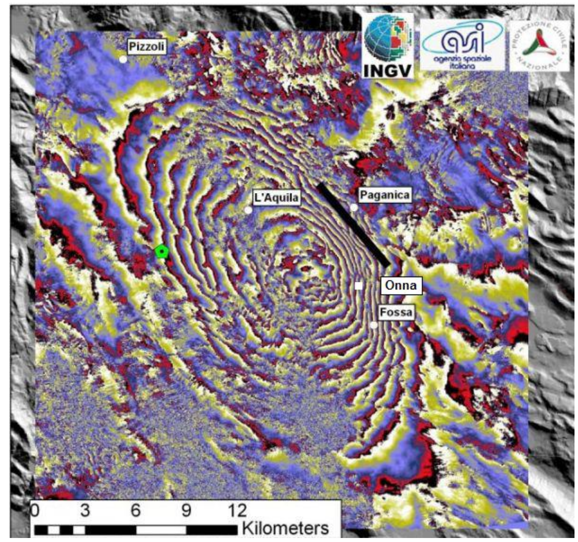


Fig. 4. COSMO-SkyMed ascending interferogram (post-event image April 13), normal baseline 430 m, look angle 36° from an ascending orbit. Green symbol indicates the Mw=6.3 main shock location (INGV 2009).

Unfortunately, main shock registrations are only available at L'Aquila city center and in the northern part of the Aterno Valley. Nonetheless, Onna seems to have experienced higher regime of vertical deformation than L'Aquila city. Does it depend on its vicinity to the Paganica fault or it could be due to the deformability of the sediments where Onna is settled? In the following, some clues will be collected to show the prominent role of sediments on the damages occurred at Onna and L'Aquila. Finally, it is worth noticing the epicentral projection of the hypocenter area (see Fig. 4, the green point) doesn't correspond to the most solicited area. Thus, hereafter, the epicentral distance of seismic stations will not be taken into consideration.

MAIN FEATURES OF SURFACE GEOLOGY OF THE ATERNO VALLEY

The Aterno Valley is a river tectonic depression hosting continental deposits since the Early Pleistocene, mainly lacustrine, alluvial and colluvial in origin, as well as landslide accumulations (Bosi and Bertini 1970).

As shown in Fig. 5, continental deposits were sedimented inside the Valley, mainly belonging to lacustrine, fluvial and slope environments. According to an essential description of the geological sequences observed within the Aterno Valley (Working Group MS-AQ 2010), the most ancient units of the basin-fill deposits are unexposed and only known from a borehole, recently drilled in L'Aquila downtown hill, nearby AQK seismic station. It evidenced a 250 m thick homogeneous sequence formed by clayey silts and sands laid upon carbonate bedrock (Amoroso *et al.* 2010). Middle Pleistocene variably-cemented calcareous breccias and dense calcareous gravels (the so called L'Aquila Breccias) outcrop in several areas of Aterno Valley and form L'Aquila downtown hill. They are superimposed to the clayey-sandy-lignitiferous upper unit and the clayey-sandy unit of L'Aquila

downtown hill. L'Aquila Breccias are composed by clasts, whose size may reach even several cubic meters, came northwards from the Gran Sasso chain. The Quaternary sequence continues with terraced fluvial deposits from the Aterno paleo-River (Vetoio Stream unit) which are laterally in contact with alluvial-debris fan deposits (Mt. Pettino unit) corresponding geomorphologically to the sediment surface of Mt. Pettino. Finally, the youngest sediments exposed along the whole Aterno river valley are dated to the Holocene- upper Pliocene. Such deposits (unit 1, Fig. 5) are alluvial deposits consisting on alternations of more or less coarse gravels, sands and silty clays of fluvial and alluvial-fan environments organized in lenticular bodies associated with the hydrographical system of the Aterno river.
The lithological and geophysical characters of the recent continental deposits of the area have been investigated in the framework of projects funded by the Italian Department of Civil Protection, over the last 5 years, as well as additional geotechnical and geophysical investigations for the microzonation study of the areas struck by the 2009 earthquake (Working Group MS-AQ 2010).

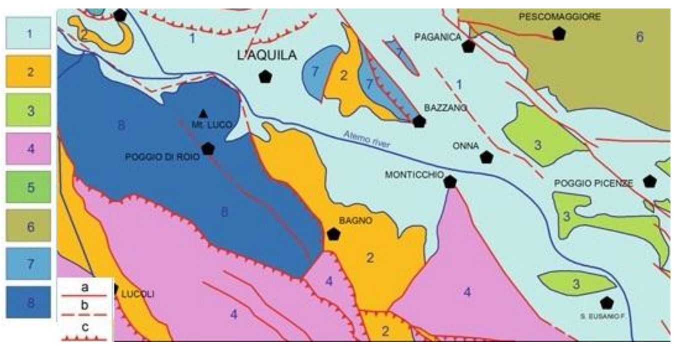


Fig. 5. Essential geologic outlines (After Working group MS-AQ 2010, modified): 1 Continental deposits (Holocene—upper Pliocene?), 2 soil units (upper Miocene), 3 Mesozoic platform and miocenic limestones (area of Aterno River), 4 Cretaceous platform and miocenic limestones (Ocre Mts.) and cherty-calcareous-marly-detrital lithologies; Liassic and Triassic platform limestone and dolomite:5 Mt. Ruzza area, 6 Filetto-Pescomaggiore area, 7 Mt. Pettino area, 8 Roio-Tornimparte area; a normal fault, b presumed normal fault, c overthrust or transgressive fault.

Figures 7-10 display the shear wave velocity profiles derived from cross-hole and down-hole tests performed at those 5 seismic stations that recorded the main shock on 6th April 2009, that are: AQA, AQV and AQG in the upper Aterno valley and AQK at L'Aquila city center (Fig. 6). The results of lithological and seismic tests are available on the website http://itaca.mi.ingv.it/ItacaNet/itaca10_links.htm. AQA (Fig. 8) and AQV (Fig. 10) stations are founded on Holocene deposits of alluvial origin, whose variable thickness is due to the basin shaped carbonate bedrock. At AQV station, at the central sector of the valley (Fig. 6), the carbonate bedrock is intercepted at a depth of 50m; at AQA (Fig. 8) the breccias show since 9m depth typical rocky shear wave velocity value, that is 800m/s.

Fig. 6. Location of epicenter of the main shock and some strong aftershock of 2009 L'Aquila earthquake; location of the seismic stations that recorded the main shock.

AQK (Fig. 7) station is placed on the Aielli-Pescina Supersynthem, in particular the landslide carbonate breccias exposed in L'Aquila city center. Here, the breccias reach 40m depth overlying stiff silts that show constant shear wave velocity value equal to 650m/s up to the end of the sounding. This drilling doesn't intercept the bedrock, that is the Mesozoic carbonate bedrock. Nonetheless, as mentioned before, a further deeper drilling has been recently performed nearby AQK (Amoroso *et al.* 2010): it found this formation at 250m depth.

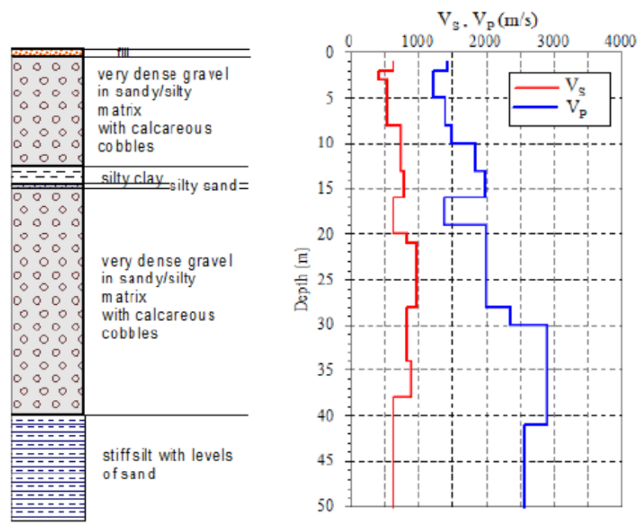


Fig. 7. AQK seismic station characterization: on the left, lithology; on the right, seismic wave velocity profile.

Finally, AQG station (Fig. 9) is placed on the edge of the valley which AQV and AQA belong to: AQV is placed at the center, AQA in the middle between AQV and AQG. Accordingly, the lithological characters of the sequence under AQG shows fractured carbonate rock where shear wave velocity is 700m/s as a mean value over the first 25m depth.

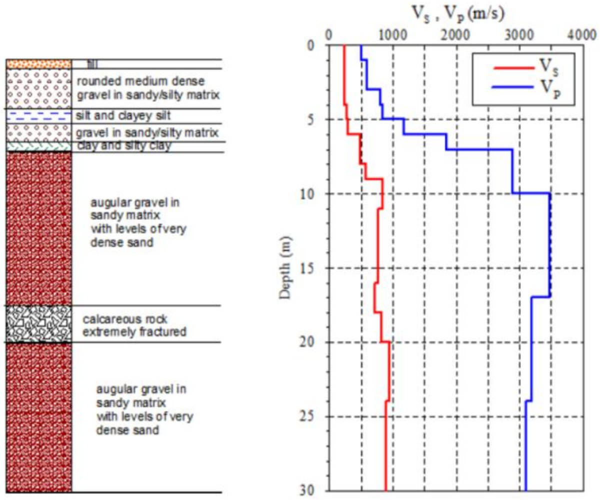


Fig. 8 AQA seismic station characterization: on the left, lithology; on the right, seismic wave velocity profile.

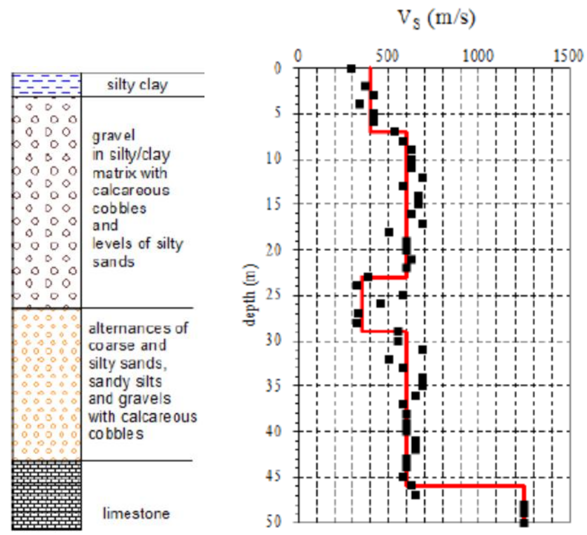


Fig. 10. AQV seismic station characterization: on the left, lithology; on the right, seismic wave velocity profile.

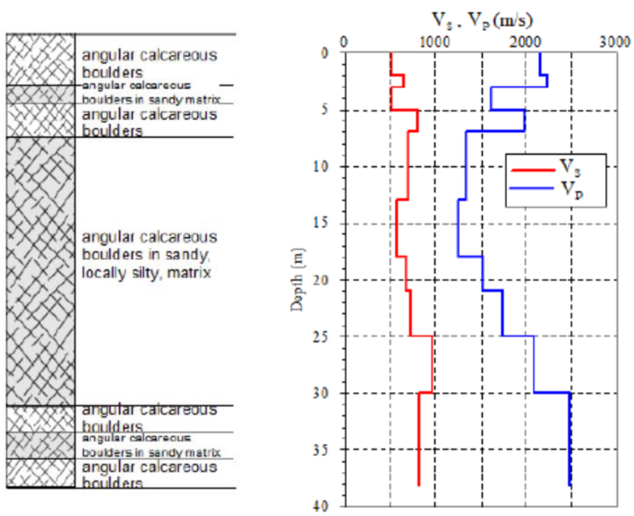


Fig. 9. AQG seismic station characterization: on the left, lithology; on the right, seismic wave velocity profile.

Such lithological description with seismic wave velocity measure is useful, although preliminary, in local site response description. As the next section shows, the characters of the seismic records of the main shock at those stations cannot be fully understood whether "near field" conditions are not taken as predominant. On the contrary, whether local seismic behavior due to the complex surface geology is taken into account, the observed amplifications can be explained and even predicted by means of 1D numerical simulations, at a preliminary stage.

SOME EVIDENCES FROM THE MAIN SHOCK RECORDS

Five seismic stations recorded the main shock event on 6th April 2009 at 1:32 UTC within the Aterno Valley: they are shown in Fig. 6. Three out of five (AQA, AQG and AQV) are placed in the northern part of the Aterno Valley, along a basin shaped seismic bedrock; whereas the others (AQU and AQK) are placed at L'Aquila city center.

The two groups of seismic stations show similar distances from the epicenter, as shown in Fig. 6 (varying between 4.4 to 6.0km), although the first group (AQA, AQV and AQG) is placed more than 10km far from Paganica fault. Four out of five stations have been seismically characterized by means of wave velocity profiles (Fig. 7-9): only AQU station, placed in the castle of L'Aquila city, is not characterized. Nonetheless, in the present study the acceleration spectrum registered at AQU has been plotted with the others in Fig. 11.

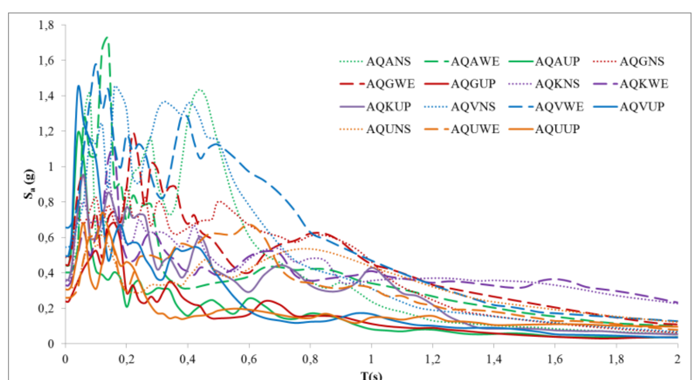


Fig. 11. Acceleration spectra of the three components of the main shock registrations at the five seismic stations considered.

The all five acceleration spectra for the three components have been plotted in Fig. 11: the color identifies the station, the line type the component: solid line for UP component, dotted line for NS and broken line for WE components.

Despite the distance from the fault, Fig. 11 shows that:

(1) with respect to the vertical component, the maximum peak in the acceleration spectra is shown at AQV, then at AQA, AQK and AQU. These three sites show Holocene sediments with decreasing thickness. This is true also for the horizontal components, as can be easily noticed from Table 1;

(2) the vertical peaks are all aligned on 19-20Hz except for AQG (Table 2). Whether "near field" or "directivity" effects shall be relevant, the responses at AQG, AQV and AQA shall be quite the same. On the contrary, the lowest peak and the lowest frequency is shown at the seismic station where fractured rock outcrops;

(3) the horizontal peaks seem to occur at lower frequencies than the vertical ones: it could be due to the seismic properties of the lithological sequences of soil layers and geometric effects. Accordingly, from Table 2, along the valley that is oriented SW-NE, AQG, AQA and AQV stations show their peaks at different frequencies. Moreover, the peaks are comparable between AQA and AQV whereas at AQG, they are far lower. Such behavior recalls the basin effect (among others Vessia *et al.* 2011) although the investigation of this phenomenon is beyond the scope of this paper.

Table 1. Peak of the Acceleration Spectra (g) for each main shock component at seismic stations within the Aterno Valley.

Station code	WE	NS	UP
AQK	1.1	0.94	0.99
AQA	1.74	1.65	1.55
AQV	1.79	1.52	2.36
AQG	1.20	0.89	0.79
AQU	0.85	0.70	1.29

Table 2. Amplified frequencies (Hz) in the acceleration spectra related to the three components of the main shock at five seismic stations.

Station code	WE	NS	UP
AQK	6.2	25	20.8
AQA	7.2	17.8	18.9
AQV	9.0	5.4	20.8
AQG	4.5	5.0	6.6
AQU	7.8	7.6	19.6

As already mentioned, every stations but AQU, have been characterized by means of a sounding and a Down Hole test, published on the website: hhttp://itaca.mi.ingv.it/ItacaNet/itaca10_links.htm). Here, main features of this characterization has been summarized in Table 3. The seismic bedrock has not been detected under all the station, although at different depths as well as for different shear wave velocity seismic profiles, V_S mean values have been calculated. Moreover, the shear velocity contrasts have been calculated (that is the ratio between the shear wave velocities of the bedrock and the overlying sediments) and reported in Table 3.

Considering the weighted mean value for shear wave velocity over the bedrock depth, it can be seen that AQV and AQA show the first and the second highest velocity contrasts C_v respectively. Such parameter plays a relevant role in surficial amplifications.

Table 3. Seismic properties of the soil under the seismic stations that recorded the main shock.

Seismic station	V_{S30} [m/s]	Bedrock depth [m]	Mean V_s over the bedrock depth [m/s]	Shear velocity contrast C_V
AQK	717	13	622	1.25
AQA	552	9	342	2.36
AQV	474	47	523	2.42
AQG	685	25	651	1.5
AQU	-	-		-

Comparing Tables 1 and 3 it can be noted that the highest horizontal peaks are registered at those stations that are further away from Paganica Fault but are characterized by higher velocity contrast than AQK and AQU, placed at L'Aquila city center (nearer to Paganica fault).

AQK shows a first seismic bedrock at 20m, made up of L'Aquila "megabrecce" formation, that is very dense gravel in sandy matrix with calcareous cobbles: the mean value of shear wave velocity V_S within the first 20m depth is 900m/s. The megabrecce overlies the stiff silts that probably reach 250m depth and shows V_S=622m/s as a mean value over the bedrock (Table 3).

Comparing the peaks at AQK and AQG in WE direction, it can be noted that the second station is more amplified, although the shear wave mean value over the bedrock is similar (Table 3). On the contrary, the velocity contrast at AQG is higher than at AQK. The seismic bedrock, at AQG is 25m depth whereas at AQK there are two seismic bedrock: one at 20m and the other at about 250m.

From the response characters highlighted, the role of surface geology seems to be significant although difficult to identify and quantify. For instance, the high amplified frequencies can be related to the high frequency content of the seismic signals in "near field" conditions but further studies are needed for shedding lights on the influence of the local seismic response of heterogeneous surface geological conditions at high frequency contents. However, the amplified high frequencies seem to be also affected by seismic properties of soils and structures or buildings, that can be estimated by measuring the resonance frequencies of both soil and structure (Rainone *et al.* 2010; Vessia *et al.* 2012).

Finally, some evidences from Lanzo *et al.* (2010) study highlighted the relevance of local amplifications in 2009

L'Aquila earthquake. Accordingly, Fig. 12 shows 5% damped pseudo-acceleration response spectra for four stations on the hanging wall of the fault. Such spectra are related to the motions rotated into fault normal and fault parallel directions, based on the 147 degree strike reported in the Earthquake setting and source characteristics section. According to Lanzo *et al.* (2010), the plot shows:

(1) no evidences of significant polarization of ground motion in the fault normal direction, that is related to the rupture directivity;

(2) a significant energy content at high frequencies, 10-20Hz. Focusing on the period range 0.3-1.0 sec, the spectral ordinates at AQA and AQV stations, overlying soft sediments, are larger and relatively more energetic than AQG and AQK stations, founded on firmer soils.

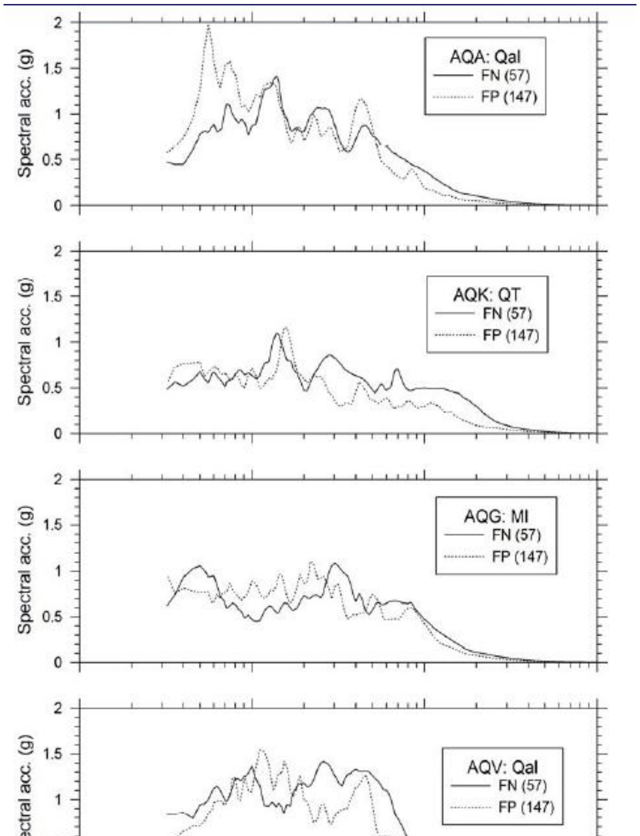


Fig. 12. Acceleration Spectra from main shock records on the hanging wall of the Paganica fault (after Lanzo et al. 2010).

This study strengthens the role played by local and surface geology on amplification phenomena in near field conditions.
In the next section, some 1D simulations have been performed for the cases of Onna and L'Aquila city center, at the seismic station called MI03 and AQK. Unfortunately, MI03 didn't register the main shock on 6th April 2009. The present numerical simulations have two main objectives: (1) to stress the influence of the litho-technical description of surficial geological sequences for predicting amplification effects and (2) to suggest an operating tool for characterizing the amplification at the site in micro-zoning studies.

PREDICTING LOCAL SEISMIC RESPONSE AT ONNA AND L'AQUILA CITY CENTERS

When the first macro-seismic map was deployed (Fig.13), it was evident the spot-like damage pattern. It confirmed the paramount role of local seismic effects played within near fault and near field areas. The first seismological studies clearly pointed out: (1) the impulsive character of the recorded signals, (2) their high frequency content, (3) the south-east direction of the peak ground accelerations and velocities increasing according to the directivity effects of the rupture propagation along the Paganica fault, (4) the recorded vertical components higher than the horizontal ones according to near field conditions. Despite the common agreement on the abovementioned phenomena, some relevant exceptions have been observed at some seismic stations: AQV registered anomalous high amplified horizontal components with respect to AQK or AQU. Moreover, some anomalous heterogeneous damages occurred at neighboring sites, suggested to investigate the role of local geo-lithological conditions on the heterogeneous damaging. For instance, the main shock provoked severe damages and many fatalities throughout Onna city (Fig. 2) MCS IX-X whereas at Monticchio site, that is less than 2km far from Onna, a few damages caused MCS VI. Figure 14 shows the great differences in amplifications registered for a minor aftershock (M_w 2.6 and hypocenter depth at 9.1km) occurred on 21st April 2009 at 23:35 UTC, at the two sites.

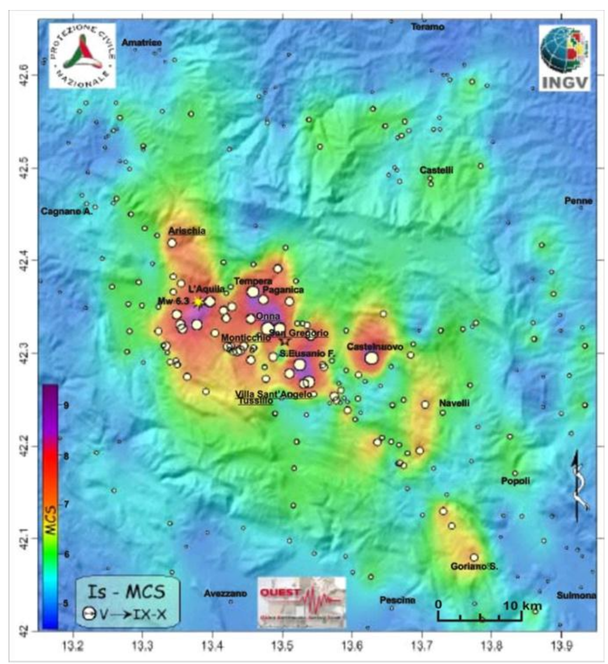


Fig. 13. Macro-seismic map of the main shock on 6th April 2009 (Galli and Camassi 2009).

Thus, for those areas where the MCS intensity was higher than

VI, micro-zonation maps have been drawn during 2009 and 2010 years (Working group MS-AQ 2010).

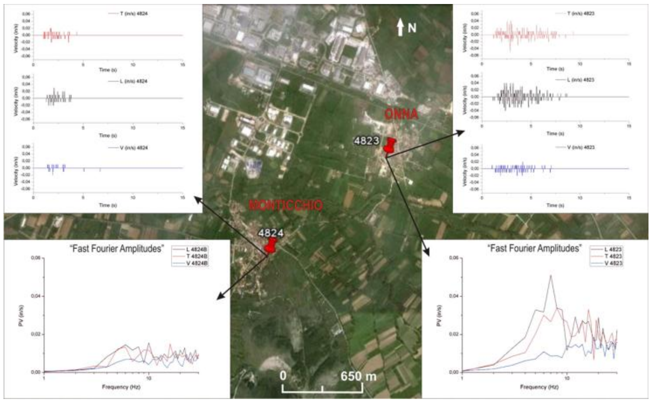


Fig. 14. Accelerograms and Fourier spectra recorded at Onna and Monticchio sites on 21st April 2009 at 23:35 UTC.

At this end, the Aterno Valley has been divided into 12 areas where field investigations and numerical analyses have been carried out according to the microzonation guidelines (Gruppo di Lavoro MS 2008). In this paper, only two macroareas have been considered:

- macroarea 1 where AQK station is placed. It is L'Aquila city center and Fig. 15 shows level three micro-zoning map;
- macroarea 5 where MI03 station is placed. It covers Onna city and Fig. 16 shows level three micro-zoning map.

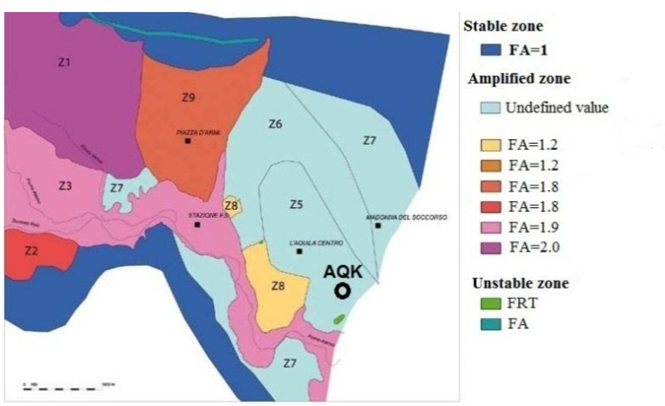


Fig. 15. Macroarea 1: seismic micro-zonation of level three at L'Aquila center (after Working Group MS-AQ 2010 modified).

At level three, micro-zoning maps derived from the calculated amplification factor F_a. It is defined as the ratio between the acceleration spectra according to the modified Housner definition (Gruppo di Lavoro MS 2008):

$$Fa = \frac{SA_{output}}{SA_{input}} = \frac{\frac{1}{T_a}\int_{0.5Ta}^{1.5Ta} SA_{output}(T)dT}{\frac{1}{T_a}\int_{0.5Ta}^{1.5Ta} SA_{input}(T)dT} \qquad (1)$$

where SA is the acceleration spectrum: the output is related to the results of 1D and 2D numerical simulations, and the input is the strong motion signal used as input motion in the same simulations. Ta is the amplified period within the acceleration spectra. Although quantitative micro-zoning procedures have been carefully defined and explained, many critical points arise. Among others, the undefined value within the blue area in macroarea 1(Fig. 15) where the AQK station is placed. At the same time, Onna city is classified with F_a=1.8 but differentiate damages and amplifications have been recognized by the authors through seismic investigations and personal inspections.

In the last year, many studies on local seismic effects within the Aterno Valley have been published (among others Di Giulio *et al.* 2011, Bergamaschi *et al* 2011, Lanzo *et al.* 2011). However, no answer has been given to the need of an operating tool by which quantifying the influence of surface geology on a strong motion seismic signal.

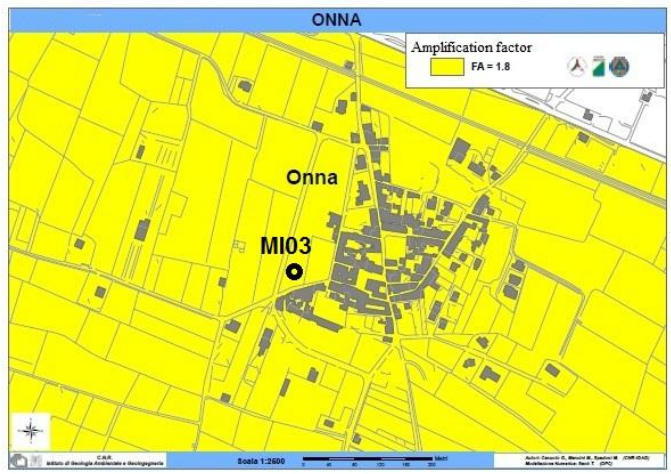


Fig. 16. Macroarea 5: seismic micro-zonation of level three at Onna city.

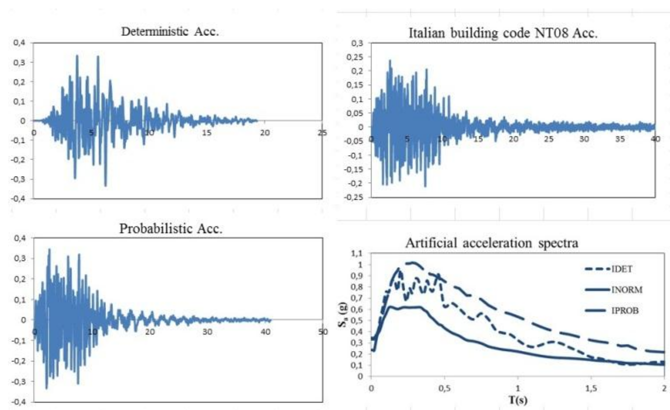


Fig. 17. Artificial input motions simulating 6th April 2009 main shock for numerical analyses to be performed within Macroareas 1 and 5.

Thus, the authors, hereafter try to suggest a simple method for relating the litho-technical properties of a sequence of surface sediments to the amplified seismic response. To this end, 1D simulations have been carried out on a few possible sedimentary sequences at AQK and MI03. The code used is

EERA (Bardet *et al.* 2000) which simulates a non linear seismic response of soils by means of an equivalent linear constitutive law. For implementing such a seismic behavior, $G(\gamma)/G_{max}$ and $D(\gamma)$ curves measured by laboratory tests, e.g. resonant column are needed for each lithotype. For the present analyses, the curves measured by Working Group MS-AQ (2010) for the soils belonging to macroareas 1 and 5 have been used. Moreover, the input motions considered are the ones illustrated in Fig. 17, provided by Pace *et al.* (2011) for micro-zonation studies carried out in the mentioned macroareas:

(1) the uniform hazard spectrum of the Italian Building code (NTC08). It is a lower bound spectrum of 2009 L'Aquila earthquake;

(2) a probabilistic uniform hazard spectrum with a return period of 475 years has been obtained by two source models named LADE1 and SP96 GMPE (Pace *et al.* 2011). This spectrum gives an upper bound spectrum to L'Aquila earthquake, reaching a maximum spectral value of about 1g at 0.25s;

(3) a deterministic spectrum obtained from SP96 GMPE for a magnitude-distance pair (M_w 6.7, R_{epi}=10km). The deterministic spectrum gives intermediate spectral values ranging from 0.35g at 0s, to 0.8g at 0.25s and 0.4g at 1s.

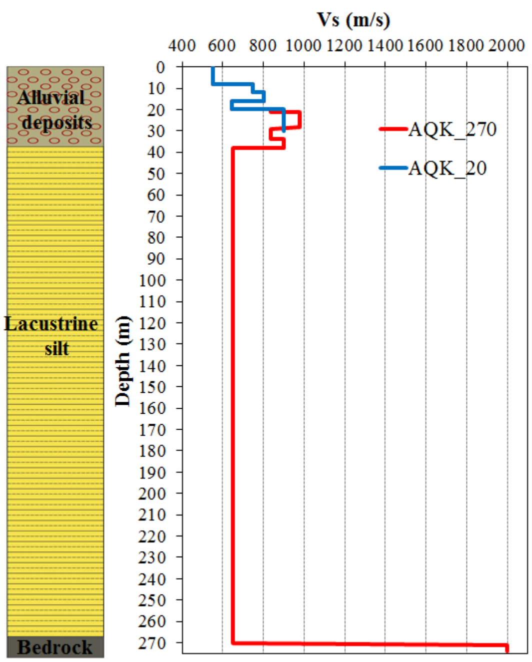


Fig. 18. Litho-seismic model of AQK station for 1D numerical analyses. Model 1: in red, 20m depth. Model 2: in blue, 270m depth.

The 1D numerical study presented here considered two models for the sediment sequence under AQK station (Fig. 18) and two other models under MI03 station (Fig. 19). The two models at AQK concern different points of view about the role of the velocity contrasts within the Holocene sequences, here named "alluvial deposits". As mentioned before, the heterogeneity of the most recent and surficial sediments result in wave velocity inversions within the first 20m depth.

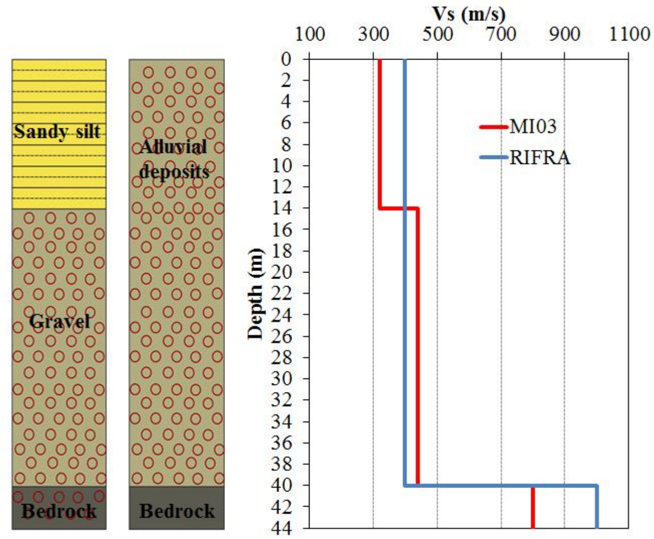


Fig. 19. Litho-seismic model of MI03 station for 1D numerical analyses. Model 1: in red, 40m depth. Model 2: in blue, 40m depth.

Such fast strata, according to the present authors, can be considered as preferential paths for seismic waves, playing the role of "hanging bedrocks". This idea is alternative to the common standpoint that poses the seismic bedrock at about 250m depth that is the geologic bedrock. Here, at AQK, such a bedrock has been found at 270m (Amoroso *et al.* 2010).

Similarly, under MIO3 station at Onna city center (Fig. 16), the seismic bedrock has been reached at 40m without any velocity inversions. The sedimentary sequence published by Working Group MS-AQ (2010) shows a downwards graded increase in shear wave velocity values. The authors performed a refraction test, in 2009, from which the sequences of sands and gravels show a mean value of 400m/s up to the bedrock depth where a 1000m/s has been found: the bedrock shear wave velocity value is higher than the one suggested by the Working group MS-AQ (2010). Thus, the second model suggested by the present authors put in evidence the presence of a velocity contrast C_v=2.5 instead of 1.8. Such condition, from the author standpoint, can influence the local response of the sediments by increasing surficial amplification.

The results of the abovementioned 1D numerical analyses are presented in Figs. 20-21 concerning AQK and Fig. 22 concerning MI03. Fig. 20a shows, in blue, the output acceleration spectra calculated for the 20m bedrock model, whereas in black, the input acceleration spectra deconvoluted at the seismic bedrock depth. In the same plot the acceleration spectra of the main shock horizontal components recorded at AQK station have been reported. Model 1 amplifies the same periods keeping the shape of the input acceleration spectra Thus, such model does not change the input frequency content. Looking at Fig. 20b, from the shape of the amplification function A_f can be seen that the model amplifies the period range 0.05-0.2s (5-20Hz), that is the amplified range of periods in the NS and WE components of the main shock at AQK station.

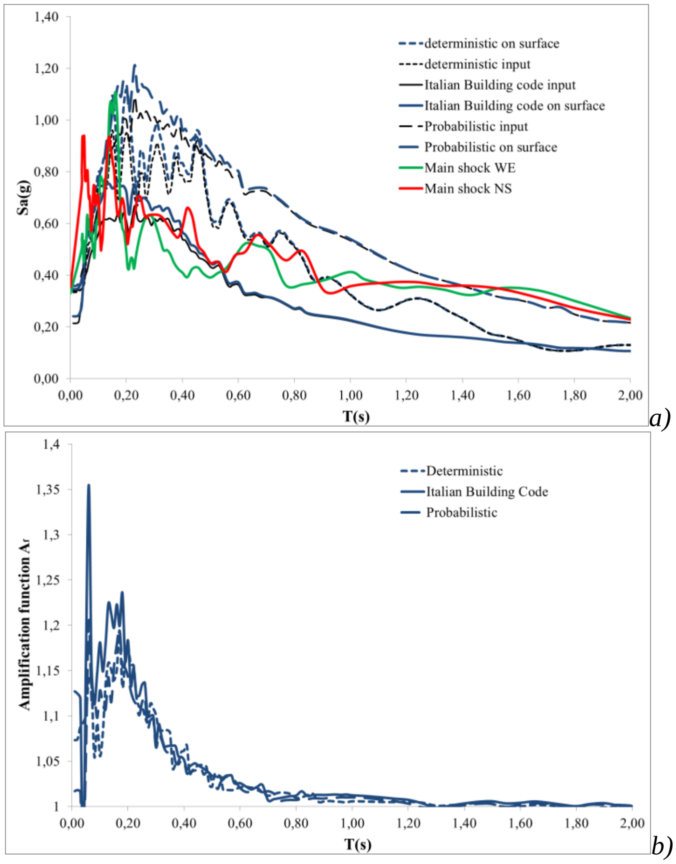


Fig. 20. 1D numerical analyses results at AQK, for Model 1: a) Acceleration Spectra; (b)Amplification function A_f.

Hence, Model 1 response is influenced by the input motion but it amplifies those high frequencies as shown in the strong motion registrations. The amplification extent varies from 1.2 to 1.35. Thus, according to Model 1, AQK site is strongly influenced by the input frequency content that is moderately amplified. Figure 21a shows the output acceleration spectra of Model 2, where the seismic bedrock is set at 270m depth. In this case, the frequency content of the output spectra is changed and the amplified periods are the longer ones. As can be better understood by Fig. 21b, the recorded strong motion NS and WE components show amplified periods lower than the ones amplified by Model 2. As a matter of fact, the periods amplified are higher than 0.20s. This is true for the three inputs. Finally, although the site response is conditioned by the input motion, the two analyzed models show how relevant can be the contribution of the litho-technical model in modifying the amplified ranges of periods/frequencies. In the case of AQK, the model of the "hanging seismic bedrock" fits better the measured records.

For the case of MI03 station at Onna city, Fig. 22a shows the site responses of two models: one suggested in this paper (RIFRA, in blue) and the other commonly accepted (MI03, in red). The three input motions have been deconvoluted at 40m: both models show higher amplifications with respect to AQK station but Model RIFRA amplifies a broader range of periods, from 0.2 to 0.7s. It is true for the three input and the amount of this amplification can be read in Fig. 22b: up to 1.5 at 0.2s (5Hz) and up to 2.4 at 0.5-0.7s (2-1.43Hz). The other model (MI03) produces lower amplifications (up to 2) in a narrower period range (0.2-0.55s). Unfortunately, at MI03 no main shock records are available. Nonetheless, Di Giulio *et al.* (2011) analyzed three strong aftershocks registered at MI03, that occurred on 9th April with Ml 5.4, 5.1 and 5. They show a large spectral content in horizontal components for T<0.3s, and a spectral peak at 0.4s with relative amplification level of 5, on average. Moreover, the shapes of spectral ratios between MI03 registrations and a reference bedrock site indicates amplifications in a large frequency band, up to 10Hz (0.1s). At MI03, the resonance frequency derived from the spectral ratio between the recorded horizontal and vertical components, for the case of Ml 5.4 aftershock, shows a spectral peak at 1.8Hz (0.6s). Thus, in the case of MI03 seismic station, the Model RIFRA proposed by the present authors better explains the main characters of the strong motion registrations.

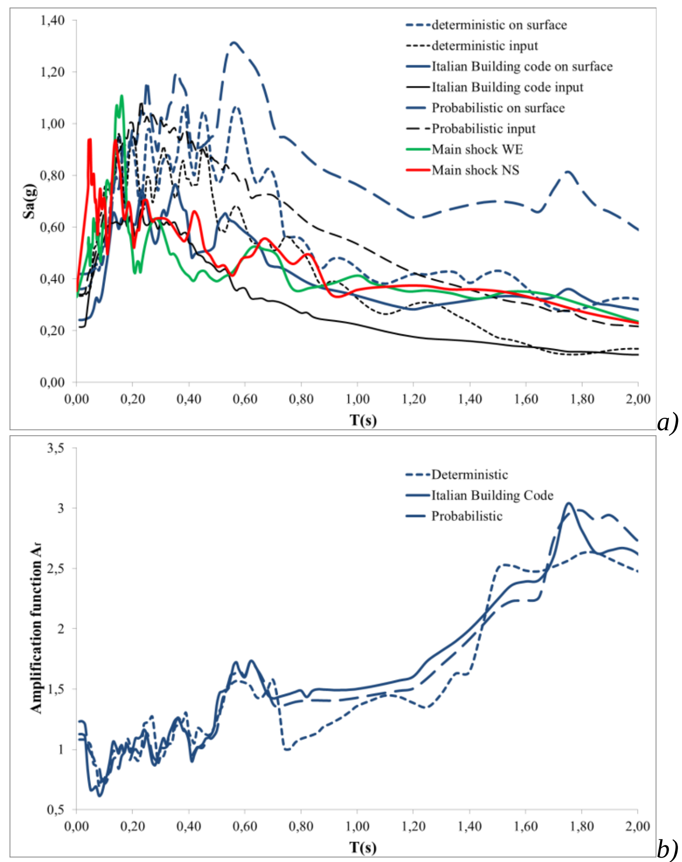
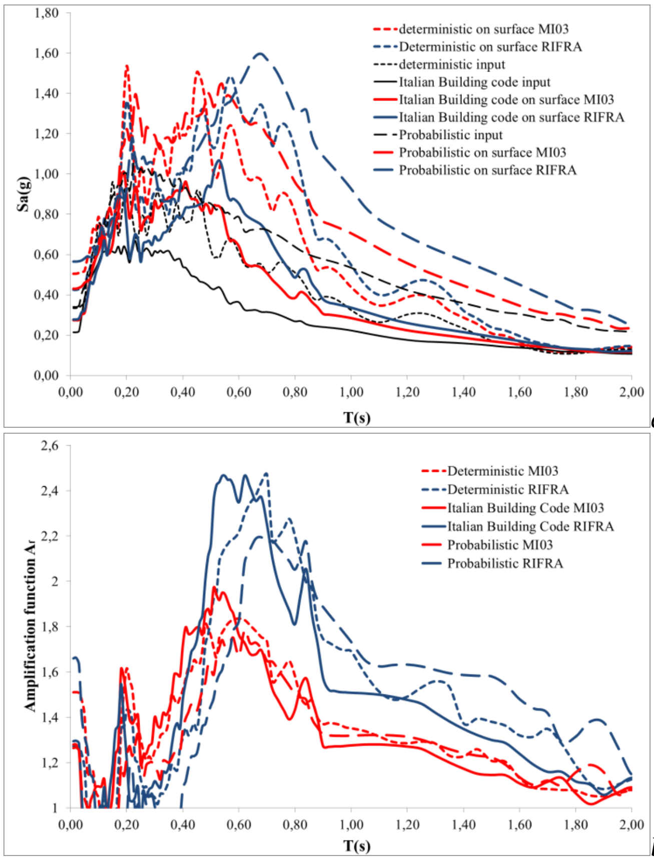


Fig. 21. 1D numerical analyses results at AQK, for Model 2: a) Acceleration spectra; (b)Amplification function A_f.

Accordingly, the role of the velocity contrasts seems to be relevant at both sites. Finally, in order to suggest a practical method for measuring the possible amplifications at site, the amplification function A_f can be employed joined to the litho-technical models that correctly interpret, according to 1D simulations, the role of the velocity contrasts and the velocity inversions in the sediment sequences. Moreover, AQK model here proposed, can be used at L'Aquila site where deep geologic bedrock is associated with surficial velocity inversion. Finally, an accurate seismic characterization of the surface sediment behavior is needed for reproducing the relevant features of the local seismic response.



a)

b)

Fig. 22. 1D numerical analyses results at MI03, for Model 1(in red) and Model 2(in blue): (a)Acceleration spectra; (b)Amplification function A_f.

CONCLUDING REMARKS

The present paper discusses some critical points raised from the great work undertaken from the Working Group MS-AQ (2010) aiming at micro-zoning macroareas 1 and 5 in the Aterno Valley. Results from 1D simulations at two seismic stations at L'Aquila city center and at Onna city, highlight the relevance of the local seismic effects in the amplifications shown by strong motion registrations of the main shock on 6th April and some strong aftershocks occurred soon after.
According to the objective of the paper, the amplification function A_f between the input motion and the surficial output response in terms of acceleration spectra is suggested for operating purposes. Such function, shall be provided associated with proper seismic litho-technical models of the sediment sequences.

REFERENCES

AAVV [2011a]. "*Contributi per l'aggiornamento degli Indirizzi e Criteri per la Microzonazione sismica 2008*". Special Issue of Ingegneria Sismica, No. 2.

AAVV [2011b]. "L'Aquila Earthquake: Seismic Sequence of 6th April 2009, Abruzzo, Italy". Special Issue of Bulletin of Earthquake Engineering, Vol. 9, No. 1.

Amoroso, S., F. Del Monaco, F. Di Eusebio, P. Monaco, B. Taddei, M. Tallini, F. Totani and G. Totani [2010]. "Campagna di indagini geologiche, geotecniche e geofisiche per lo studio della risposta sismica locale della città dell'Aquila: la stratigrafia dei sondaggi (giugno–agosto 2010)". Report CERFIS n. 1. (in Italian).

Atzori, S., I. Hunstad, M. Chini, S. Salvi, C. Tolomei, C. Bignami, S. Stramondo, E. Trasatti, A. Antonioli and E. Boschi [2009]. "Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy)", Geophys Res Lett, No. 36, L15305. doi:10.1029/2009GL039293.

Bardet J.P., K. Ichii and C.H. Lin [2000]. "*EERA A computer program for Equivalent-linear earthquake site Response Analyses of layered soil deposits".* University of Southern California, Department of Civil Engineering.

Bergamaschi, F., G. Cultrera, L. Luzi, R. M. Azzara, G. Ameri P. Augliera, P. Bordoni, F. Cara, R. Cogliano, E. D'Alema, D. Di Giacomo, G. Di Giulio, A. Fodarella, G. Franceschina, F. Galadini, M.R. Gallipoli, S. Gori, P. Harabaglia, C. Ladina, S. Lovati, S. Marzorati, M. Massa, G. Milana, M. Mucciarelli, F. Pacor, S. Parolai, M. Picozzi, M. Pilz, S. Pucillo, R. Puglia, G. Riccio and M. Sobiesiak [2011]. "Evaluation of site effects in the Aterno river valley (Central Italy) from aftershocks of the 2009 L'Aquila earthquake", Bull Earthquake Eng, No. 9, pp. 697–715.

Bosi, C. and T. Bertini [1970]. "Geologia della Media Valle dell'Aterno", Memorie della Società Geologica Italiana, Volume IX, pp.719-777 (in Italian).

Chiarabba, C., A. Amato, M. Anselmi, P. Baccheschi, I. Bianchi, M. Cattaneo, G. Cecere, L. Chiaraluce, M.G. Ciaccio, P. De Gori, G. De Luca, M . Di Bona, R. Di Stefano, L. Faenza, A. Govoni, L. Improta, F.P. Lucente, A. Marchetti, L. Margheriti, F. Mele, A. Michelini, G. Monachesi, M. Moretti, M. Pastori, N. Piana Agostinetti, D. Piccinini, P. Roselli, D. Seccia and L. Valoroso [2009]. "The 2009 L'Aquila (central Italy) Mw 6.3 earthquake: main shock and aftershocks", Geophys Res Lett, No. 36, L18308. doi:10.1029/2009GL039627.

Cirella, A., A. Piatanesi, M. Cocco, E. Tinti, L. Scognamiglio, A. Michelini, A. Lomax and E. Boschi [2009]. "Rupture history of the 2009 L'Aquila (Italy) earthquake from non-linear joint inversion of strong motion and GPS data", Geophys Res Lett, Vol. 36, L19304. doi:10.1029/2009GL039795.

Di Giulio, G., S. Marzorati, F. Bergamaschi, P. Bordoni, F. Cara, E. D'Alema, C. Ladina, M. Massa and The L'Aquila experiment Team [2011]. "Local variability of the ground shaking during the 2009 L'Aquila earthquake (April 6, 2009 Mw 6.3): the case study of Onna and Monticchio villages", Bull Earthquake Eng, No. 9, pp. 783–807.

DISS Working group [2009]. "*Database of Individual Seismogenic sources (DISS), Version 3.1.0: A compilation of potential sources for earthquakes larger than M 5.5. in Italy and surrounding areas*". Technical report, Istituto Nazionale di Geofisica e Vulcanologia (INGV).

Faccioli, E. (a cura di) [1986]. "*Elementi per una guida alle indagini di Microzonazione Sismica*". Progetto Finalizzato Geodinamica, monografie finali, vol. 7, C.N.R.

Galli P. and Camassi R. [2009]. "*Rapporto sugli effetti del terremoto aquilano del 6 aprile 2009*". Dipartimento della Protezione Civile Istituto Nazionale di Geofisica e Vulcanologia QUEST Team. http://emidius.mi.ingv.it/DBMI08/aquilano/query_eq/ quest.pdf.

Gruppo di Lavoro MS [2008]."*Indirizzi e criteri per la Microzonazione sismica*". Conferenza delle Regioni e delle Province autonome – Dipartimento della protezione civile, Roma.

INGV [2009]. *"Measurement and modeling of co-seismic deformation during the L'Aquila earthquake. Preliminary results"*, Synthetic report of the activities of ASI-SIGRIS personnel and Earthquake Remote Sensing Group of the Remote Sensing Laboratory, National Earthquake Center, INGV, Rome.

Lanzo, G., G. Di Capua, R.E. Kayen, D.S. Kieffer, E. Button, G. Biscontin, G. Scasserra, P. Tommasi, A. Pagliaroli, F. Silvestri, A. D'Onofrio, C. Violante, A.L. Simonelli, R. Lanzo, G., M. Tallini, G. Milana, G. Di Capua, F. Del Monaco, A. Pagliaroli and S. Peppoloni [2011]. "The Aterno valley strong-motion array: seismic characterization and determination of subsoil model", Bull Earthquake Eng, No. 9, pp. 1855–1875.

Lanzo, G., G. Di Capua, R.E. Kayen, D.S. Kieffer, E. Button, G. Biscontin, G. Scasserra, P. Tommasi, A. Pagliaroli, F. Silvestri, A. D'Onofrio, C. Violante, A.L. Simonelli, R. Puglia, G. Mylonakis, G. Athanasopoulos, V. Vlahakis and J.P. Stewart [2010]. "Seismological and geotechnical aspects of the M_w=6.3 l'Aquila earthquake in central Italy on 6 April 2009", International Journal of Geoengineering Case histories, Vol.1, No. 4, pp. 206-339.

Milana, G., R. Azzara, E. Bertrand, P. Bordoni, F. Cara, R. Cogliano, G. Cultrera, G. Di Giulio, A. Duval, A. Fodarella, S. Marcucci, S. Pucillo, J. Régnier and G. Riccio [2011]. "The contribution of seismic data in microzonation studies for downtown L'Aquila", Bull Earthquake Eng., Vol. 9, No. 3, pp. 741-759.

Ordinanza del presidente del Consiglio dei Ministri 20 marzo 2003, n. 3274 [2003] "*Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica*".

Pace, B., D. Albarello, P. Boncio, M. Dolce, P. Galli, P. Messina, L. Peruzza, F. Sabetta, T. Sanò and F. Visini [2011]. "Predicted ground motion after the L'Aquila 2009 earthquake (Italy, M_w 6.3): input spectra for seismic microzoning", Bull Earthquake Eng., DOI 10.1007/s10518-010-9238-y.

Postpischl, D., E. Faccioli and F. Barberi [1985]. "*Progetto Finalizzato 'Geodinamica': Monografie Finali*". Quaderni de "La ricerca scientifica", Consiglio Nazionale delle Ricerche, Editore Consiglio Nazionale delle Ricerche.

Puglia, G. Mylonakis, G. Athanasopoulos, V. Vlahakis and J.P. Stewart [2010], "Seismological and geotechnical aspects of the Mw=6.3 l'Aquila earthquake in central Italy on 6 April 2009*", International Journal of Geoengineering Case histories*, Vol.1, No. 4, pp. 206-339.

Rainone, M.L., P. Torrese, F. Pizzica, P. Greco and P. Signanini [2010]. "Measurement of seismic local effects and 1d numerical modeling at selected sites affected by the 2009 seismic sequence of L'Aquila", *SAGEEP*, Keystone, Colorado.

Salvi, S., and Working Group [2009]. "*Risultati Preliminari SAR*". INGV Report (in Italian).

Valensise, G. [2009]. "Faglie attive e terremoti: tempo di cambiare strategie", Geoitalia, No. 28.

Vessia G., S. Russo and D. Lo Presti [2011]. "A new proposal for the evaluation of the amplification coefficient due to valley effects in the simplified local seismic response analyses", Italian Geotechnical Journal, No. 4, pp. 51-77.

Vessia, G., M.L. Rainone, P. Signanini, P. Greco, S. Di Benedetto and P. Torrese [2012]. "Integrated Geophysical and Geotechnical seismic techniques for dynamic site characterization at urbanized centers", *8th Alexander von Humboldt International Conference, Natural Disasters, Global Change, and the Preservation of World Heritage Sites*, Cusco, Peru, 12–16 November.

Working Group MS–AQ [2010]. "*Microzonazione sismica per la ricostruzione dell'area aquilana*", Regione Abruzzo - Dipartimento della Protezione Civile, L'Aquila 3 vol. and Cd-rom (in Italian).