THE ROLE OF SITE EFFECTS AND NEAR-SOURCE SEISMIC ACTIONS ON GROUND AND BUILDINGS RESPONSE ACROSS THE ATERNO RIVER VALLEY (ITALY)

Marco CHIARINI¹, Anna d’ONOFRIO², Lorenza EVANGELISTA³, Augusto PENNA⁴, Francesco SILVESTRI⁵

ABSTRACT

The L’Aquila earthquake (Mₚ 6.3) occurred on April 6, 2009, was the first case, in Italy, of a well-recorded seismic event in a near-source region, with a dense population of engineering structures. Both the variability of the strong motion recorded by the accelerometric stations, and the macroseismic intensity distribution showed that site amplification significantly affected even the near-fault seismic actions across the Aterno river valley. This paper investigates the role of near-source site effects on both free-field seismic response and structural damage, using seismic records, geotechnical data and numerical simulations.

The influence of stratigraphic and morphological site effects was preliminarily evaluated through a 2D site response analysis along a transversal section of the upper Aterno valley, where a linear array of seismic stations recorded the main shock.

The acceleration time histories at a reference station (AQG), properly scaled to account for the topographic effects, were then used as input motion in seismic response analyses carried out at a site where a different degree of damage was recognized on similar r.c. buildings.

Keywords: Site effects, seismic response analysis, near source, building damage.

INTRODUCTION

The Abruzzo earthquake of April 6, 2009 (Mₚ 6.3) caused considerable damage to structures over an area of approximately 600 square kilometres, including the urban center of L’Aquila and several villages of the Aterno river valley (Lanzo et al., 2010). Figure 1 reports the results of the macro-seismic survey carried out after the event on the inhabited areas of the valley are reported in (Galli and Camassi, 2009). The map shows an asymmetric distribution of damage with respect to the mainshock epicenter (black star). Damage is limited north and west of the epicenter, with macroseismic intensity never higher than VI MCS. Conversely, southeast of L’Aquila the intensity reaches IX-X MCS in an elongated area. The local

¹ Master student, Department of Hydraulic, Geotechnical and Environmental Engineering, Università degli Studi di Napoli Federico II (ITALY), parodra@hotmail.com
² Professor, Department of Hydraulic, Geotechnical and Environmental Engineering, Università degli Studi di Napoli Federico II (ITALY); donofrio@unina.it
³,⁴ PhD doctors, Department of Hydraulic, Geotechnical and Environmental Engineering, Università degli Studi di Napoli Federico II (ITALY); lorenza.evangelista@unina.it; aupenna@unina.it
⁵ Professor, Department of Hydraulic, Geotechnical and Environmental Engineering, Università degli Studi di Napoli Federico II (ITALY); francesco.silvestri@unina.it
distribution of damage was often irregular even for similar buildings (Verderame et al., 2009), due to both rupture directivity effects (Chioccarelli & Iervolino, 2010) and site amplification (Lanzo et al., 2010).

A research team (AQ-FII) has been set up at the University of Naples Federico II, with the aim of applying an integrated approach to reconcile earthquake engineering evidences from the event, trying to simulate source, path, site effects and engineering systems’ response. For an ideally correct evaluation of the seismic response in a near-fault region, in principle an integration between accurate source and low- to high-frequency propagation models is needed, possibly by two or three-dimensional analyses (Calcaterra et al., 2009). This paper shows the first analyses carried out by the geotechnical working group of the AQ-FII research team, addressed to evaluate the influence of site amplification on both the overall seismic response of the valley, and the behaviour of the structures significantly damaged by near-source seismic actions.

Numerical 2D analyses were first carried out to reproduce the variability of the mainshock, as recorded by an accelerometric strong motion array installed along a section crossing the upper Aterno valley (Figure 2). Being very few buildings located across the valley, there was no evidence of site effects from damage distribution. The reconstruction of the bedrock morphology and the geotechnical characterization of the subsoil were based on the synthesis of data collected from geological, geophysical and geotechnical investigations carried out throughout the whole area.

Thereafter, the possible occurrence of site effects was examined in the nearby intensely damaged area of Pettino (cross-hatched area in Figure 2), where seismic records were not available. 1D site response analyses were carried out at a specific site, where similar reinforced concrete buildings showed very different seismic performance, from light non-structural damage to complete structural collapse. The subsoil data available in the selected area were analysed in detail, to define site-specific geotechnical models relevant to the building scale.

The results of the above analyses, relevant to the valley and building scales, will be reported and discussed in detail in the following sections.
The mainshock, characterised by a 6.3 moment magnitude, occurred at 03:32:39 local time and was recorded by more than 50 strong motion stations of the national seismic network (RAN) distributed along the Apennines, mostly NW and SE of the source area. The focal mechanism shows that the event took place along a normal fault trending NW-SE (strike 147°) with dip SW ~ 50° (Cirella et al., 2009). Four RAN stations are located on the hanging wall side of the fault, within 5 km from the epicenter (AQG, AQA, AQV, AQM) forming an array transversal to the upper Aterno valley, as shown by Figure 2.

Figure 3 shows the acceleration time histories and 5% damped acceleration elastic spectra of the main shock recorded at AQG, AQA and AQV, projected along the longitudinal (L-V) and transversal (T-V) directions of the valley. The data were processed according to the standard procedure used in the Italian Accelerometric Archive ITACA (http://itaca.mi.ingv.it/ItacaNet/); the records at AQM were not available, due to clipping. PGA and spectral acceleration values for AQA and AQV stations are generally higher that those recorded at AQG, located on outcropping rock, clearly highlighting site effects. The combined effects of directivity and alluvial basin amplification are also evidenced by the variability of dominant periods, with an increase of low-frequency content moving from AQG to AQA and AQV, i.e. towards the center of the valley.

**Geological setting and geotechnical characterisation**

The area hit by the earthquake is located in a vast intra-Apennine tectonic basin, elongated in NW-SE direction, crossed by the Aterno river, and surrounded by the high peaks of the Gran Sasso and the Velino-Sirente mountains. The bedrock consists of Meso-Cenozoic carbonate rocks, generally outcropping along the sides of the valley and on ridges located within the Aterno River basin. The bottom of the valley was filled during the Quaternary with continental deposits, resulting from lacustrine to subsequent fluvial sedimentations. The maximum thickness of the Quaternary deposits is estimated as high as about 400-500 m. The older Pleistocene lacustrine deposits, placed on the calcareous bedrock, form a complex depositional sequence of silt, sand and conglomerate units (Bosi and Bertini, 1970). The most recent alluvial Holocene soils, placed on the top of the Meso-Cenozoic and Pleistocene deposits, mainly consist of sands and cobbles, while sands and silts are sometimes found. The foot of the flanks and of the ridges bordering the valley are covered by talus debris and locally by large debris fans.
Figure 3. Acceleration time histories and response spectra of the main shock.

A geological map of the area is shown in Figure 4a, together with a cross-section through the array of stations (Figure 4b). The geometry of the geo-lithological section was developed by the geology group of AQ-FII, based on the results of geological and geophysical surveys. It was also calibrated on the basis of the boreholes executed to characterize the seismic stations (http://itaca.mi.ingv.it/ItacaNet/), as well as on noise and weak-motion instrumental records (Chiarini, 2010).

The seismic station AQG is located on the ridge of an outcropping limestone hill; AQV and AQA on the recent alluvial deposits of the Aterno river. Figure 5a shows the stratigraphies and shear wave velocity profiles of these latter stations, as reported by ITACA database (http://itaca.mi.ingv.it/ItacaNet/). The limestone formation was encountered at a depth of 46 m in the borehole at AQV, but it was not reached at AQA. In this site, the bedrock depth was back-figured by varying the alluvial soil thickness, and comparing the fundamental frequency computed from the 1D linear amplification function with that individuated on the H/V spectral ratio of aftershocks recorded at the same site (Chiarini, 2010).

The shear wave velocity in the Holocene alluvial deposit slightly increases with depth and does not exceed 400 m/s. The underlying Pleistocene alluvia are characterized by alternances of gravelly, sandy and silty soils, with velocity increasing with depth, although showing a clear inversion at AQV (Figure 5a). The debris fan formation laying on the eastern flank of the valley was characterized on the basis of the results of the down-hole tests carried out in the Pettino area, shown in the next section.

The non-linear properties adopted for the numerical analyses are plotted in Figure 5b, in terms of variation of normalised shear modulus, $G(\gamma)/G_0$, and damping ratio, $D(\gamma)$, with shear strain, $\gamma$. The significant variability of the curves relevant to the different materials highlights their wide variety of grain size and degree of cementation. The curves for the terraced alluvia and for the Holocene deposits were taken from cyclic/dynamic laboratory tests carried out on borehole samples of similar sandy soils in
the Aterno valley (d’Onofrio et al. 2010); the non-linear properties of the debris were assigned as literature curves relevant to comparable gravelly soils (Rollins et al. 1998; Anh Dan et al. 2001).

Numerical analysis
The numerical 2D simulations of the seismic response of the valley were carried out using the FLAC 5.0 (Itasca, 2005) code, operating in the time domain with the finite difference method (FDM).

The transversal component of the acceleration time history of the main shock recorded at AQG was assumed as reference input motion. The T-V component shown in Figure 3 was preliminarily scaled to account for the topographic effects, adopting a frequency-independent factor equal to 1.2, compatible with literature relationships (Pagliaroli et al., 2007) and with the specifications given by the National Technical Code (NTC, 2008).

Due to the large extension of the section used for the 2D analyses, in order to limit the mesh element size, the frequency of 15 Hz was selected as the maximum value to be transmitted. As a consequence, the input motion was pre-processed with a Butterworth low-pass filter of order 4 and a cut-off frequency of 15 Hz. Such filtering induced a reduction of more than 50% in the PGA value, which resulted about 0.23g.
The soil behavior was assumed as linear equivalent visco-elastic, with non-linear stiffness and hysteretic damping controlled by sigmoidal functions, calibrated on the curves $G/G_0$-$\gamma$ and $D$-$\gamma$ reported in Figure 5b. The small strain parameters used in the numerical analysis are summarised in Figure 5c. The small strain damping ratio, $D_0$, was included in the FDM algorithm according to the well-known Rayleigh formulation (e.g. Hashash and Park, 2002), with the coefficients $\alpha$ and $\beta$ chosen following a ‘double frequency’ approach yielding the same damping-frequency function as the ‘single frequency’ method used by the program.

The mesh grid used to model the geological section was characterized by thickness of the elements set equal to 3 m, in order to reproduce the maximum input frequency of 15 Hz, according to the rule suggested by Kuhlemeyer and Lysmer (1973). To avoid undesired wave reflections, a ‘quiet boundary’ condition was adopted for the bedrock (Lysmer and Kuhlemeyer 1969), consisting of viscous dampers acting along normal and tangential directions, whereas ‘free-field boundary’ conditions were used for the lateral contours. These latter consist of one-dimensional columns simulating the behaviour of a lateral semi-infinite medium, linked to the mesh grid through viscous dashpots.

The lines plotted in Figure 6 show the results of the analysis in terms of surface distribution of PGA (left axis) and amplification factors (right axis) referred to the input motion. These factors were computed for peak ground acceleration, $A_p$ (blue solid line), and Housner Intensity in the period range 0.1-0.5 s, $FH$ (red dashed line). The amplification factors plot with similar trends and comparable values; approaching the outcropping bedrock at the valley borders, both factors show a significant jump, which can be ascribed to the interference between direct upcoming body waves and surface waves generated at the edges. Wave focusing in the centre of the river valley amplifies more than two times the reference
motion; the maximum amplification is reached where the recent alluvium layer is thicker, i.e. between AQA and AQV.

The amplification tends to gradually decrease towards NE, along the debris fan, until its thickness decreases; thereafter, another significant amplification peak occurs uphill, approximately at the same position of Pettino site. Topographic amplification effects can be noted on the carbonate rock slopes at both SW and NE sides of the valley.

In Figure 6, the values of PGA (read as $A_F$ on the right axis) and FH recorded at the seismic stations, and subsequently filtered with the same procedure as the input motion, are plotted with different symbols. The PGA predicted by the seismic response analysis results in a very good agreement with that measured at AQA station, while it significantly underestimates the value recorded at AQV. Such partial inconsistency, relevant to the high frequency range, may be only partially due to the low-pass filtering of the signal. On the other hand, the numerical predictions of FH are fairly close to the experimental values at both stations, demonstrating that the subsoil model can reliably reproduce the ground motion in the range of frequency most significant for the building response.

**AMPLIFICATION IN THE PETTINO SITE**

The high variability in the PGA distribution observed in the N-E side of the Aterno section (Figure 6) is further confirmed by the irregular damage pattern recorded in the Pettino area. Structure-by-structure damage surveys were preliminarily performed by GEER (Geoengineering Extreme Events Reconnaissance) working group (Lanzo et al., 2010) and subsequently carried out more in detail by the structural working group of AQ-FII research team (Verderame et al., 2009).

The area of Pettino is a recently developed suburban district of L’Aquila; therefore most buildings are relatively modern r.c. frame structures with masonry infills on exterior walls. Most residential buildings
are two to five-storey high; the collapses were mainly observed in the case of five-storey reinforced concrete buildings, typically at the ground floor level. Figure 7 reports the variable structural performance of a cluster of seven similar r.c. buildings, showing uneven damage, the level of which was assigned and marked with different colours according to the categories reported in Table 2. Two collapsed buildings (D5 level) suffered a soft floor mechanism, while the remaining five showed only minor, non-structural damages (D1). Although buildings were not exactly identical, such irregular damage distribution suggested that site effects may have played an important role. The influence of soil amplification was therefore evaluated through 1D site response analyses at the building scale, on the basis of the subsoil investigations carried out after the earthquake.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>No damage</td>
</tr>
<tr>
<td>D1</td>
<td>Cracking of non-structural elements, such as</td>
</tr>
<tr>
<td>D2</td>
<td>Major damage to the non-structural elements, such as collapse of a whole masonry infill wall; minor damage to load bearing elements</td>
</tr>
<tr>
<td>D3</td>
<td>Significant damage to load-bearing elements, but no collapse</td>
</tr>
<tr>
<td>D4</td>
<td>Partial structural collapse (individual floor or portion of building)</td>
</tr>
<tr>
<td>D5</td>
<td>Full collapse</td>
</tr>
</tbody>
</table>

Figure 7. Map of the studied area with the details of the non uniform damage.

Geotechnical characterization
The cluster of buildings is entirely settled on the alluvial fan that covers the toe of Mt. Pettino (Figure 4). After the earthquake, subsoil investigations were addressed both to the seismic micro-zoning and to the reconstruction of the collapsed buildings. Figure 7 shows the location of two down-hole tests (P1, P2) and
a borehole (P3); in the same area microtremor measurements were taken and large-scale seismic surface surveys were also carried out (Working group, 2010).

Weathered and fine debris fan are present in the first 10 m, as shown by the boreholes logs drawn in Figure 8a. They overlie a gravelly debris layer of about 10 m, covering a finer alluvial silt on the top the calcareous bedrock. No borehole reached the top of the bedrock, the depth of which was assumed at 54 m, on the basis of the seismic surface surveys. Such hypothesis was validated by a comparison between the fundamental frequency obtained by a linear 1D analysis with the assumed bedrock depth, and the experimental frequency measured by H/V spectral ratio of microtremors. In Figure 8a the results of downhole test are also reported; the S wave velocity value assigned to each soil layer was obtained by averaging the $V_S$ resulting from the dromochrones. The weathered debris fan is characterised by a shear wave velocity of 330 m/s, significantly lower than that measured on the underlying gravel debris; a significant velocity inversion is identified on both profiles, as the alluvial silt alternances topping the calcareous bedrock have an average shear wave velocity considerably lower than that of the gravelly soil.

![Figure 8a: Stratigraphies and $V_S$ profiles](image1)

**Figure 8. a) Stratigraphies and $V_S$ profiles; b) linear equivalent parameters used in the numerical analyses**

**Numerical analysis**

At the building scale, the site response analyses were carried out adopting a 1D linear equivalent model, by the EERA code (Bardet et al., 2000), working in the frequency domain. The two shear wave velocity profiles in Figure 8a were considered, while the curves of variation of stiffness and damping with shear strain (Figure 8b) were taken from laboratory tests carried out on similar soil samples retrieved in the Aterno valley (D’Onofrio et al, 2010). Once again, the acceleration time history recorded during the mainshock at the reference station (AQG), preliminarily scaled for the topographic effect, was used as input motion in the site response analyses; in this case, however, N-S and E-W components were considered separately, in order to predict the surface motions acting along the principal axes of the buildings.

The results of the analyses are reported in Figure 9a in terms of PGA profiles obtained with the two reference input motions. The acceleration profiles are quite similar for the two verticals, being the main contribution to the amplification given by the shallow deformable layer of silty sand. Table 3 contains the...
values of PGA of the input motions, those predicted at surface, and the corresponding amplification coefficients. The table also reports the amplification coefficient, $S$, specified by the National Technical Code (NTC, 2008) for a class B soil ($V_{S30} = 360-800$ m/s), with reference to the life safety (SLV) and collapse (SLC) limit states. The amplification coefficients computed are comparable to those suggested by the NTC, pointing out that site amplification is not unusually high in terms of peak ground acceleration. Figure 9b shows the non-linear transfer functions obtained for both profiles, plotted along with the Fourier spectra of the two different input motion components. A clear resonance effect appears on the N-S component: the computed fundamental frequency of the subsoil is 2 Hz, while the dominant frequency of the input motion is 1.9 Hz. This is not the case for the E-W amplification reported in Figure 9b: here the dominant frequency of the input motion is lower than the fundamental frequency of the non-linear transfer function.

In Figure 9c the 5% damped response spectra at surface for the two components are plotted together with those of the input motions and those suggested by the NTC for a class B soil, with reference to SLV and SLC limit states. It is apparent that the code spectra underpredict the computed response spectra for both components, at least for periods lower than 1 s. The overall spectral amplification computed at this site is consistent with the results of the 2D numerical analysis, which showed an average amplification factor of 1.6, in terms of FH, for periods between 0.1 and 0.5 s.

The subsoil resonance at about 2 Hz, i.e. at the dominant frequency of the N-S input motion, is evidenced by the high peak spectral acceleration at 0.5 s. Using the simple rule of thumb that allows to estimate the resonance period of a r.c. building from the number of floors, a fundamental period of 0.5 s corresponds to a 5 storeys building, i.e. the same size of the collapsed buildings in this area.

The response spectra of the E-W component show a flatter shape through the range of periods 0.1-0.5 s, which corresponds approximately to the interval between the first (2 Hz) and second (6 Hz) natural frequencies of the transfer function. In fact, this time the peak spectral acceleration at surface is attained around 0.16 s, i.e. the second natural subsoil frequency.

**CONCLUSIONS**

A joint research group (AQ-FII) has been set up at the University of Naples Federico II, with the purpose of applying an interdisciplinary approach for a rational interpretation of the evidences of damage induced by L’Aquila earthquake. In this paper, the first studies of the geotechnical working group of the AQ-FII team are shown, and proved that the role of site effects on the near-source seismic motion was significant. The influence of site effects was first investigated at a larger scale, reproducing by numerical 2D analyses the variability of the main shock, as recorded by the accelerometric strong motion array installed along a section crossing the upper Aterno valley, where buildings were very few and scattered. The numerical results highlighted the influence of both morphological and stratigraphic effects on the variability along the section of the surface motion, expressed in terms of PGA and Housner intensity amplification factors. In the future, a non-synchronous seismic input motion along the valley will be considered, to take into account the proximity of the fault; this and other upgrades of the seismic response model are expected to reduce the differences observed insofar between the recorded and predicted PGA values.

The possible occurrence of local effects was also examined at a smaller scale, in a particular site located in the residential area of Pettino, where similar r.c. buildings showed very different performance, from light non-structural damage to complete structural collapse. 1D seismic response analyses showed that double resonance phenomena may have occurred along the N-S direction, due to the coincidence between the fundamental frequency of 2 Hz of the subsoil and the dominant frequency of the reference input motion. This could in turn justify the collapse of two five storeys buildings, as a peak spectral acceleration higher than 1 g was predicted at a period of 0.5 s. However, other comparable buildings in
the same area did not collapse, although apparently subjected to the same surface motion; therefore, an accurate investigation on the role of structural details and ductility is currently in progress by AQ-FII.

**Figure 9.** (a) PGA profiles (b) non-linear transfer functions and (c) acceleration response spectra obtained for the two verticals P1 and P2 along the N-S (left) and E-W (right) directions.

**Table 3. Results of the 1D numerical analyses**

<table>
<thead>
<tr>
<th>Input</th>
<th>borehole</th>
<th>$a_{\text{max input}}$ (g)</th>
<th>$a_{\text{max surface}}$ (g)</th>
<th>$A$ (analysis)</th>
<th>$S_\delta$ (SLV)</th>
<th>$S_\delta$ (SLC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQG NS</td>
<td>P1</td>
<td>0.43</td>
<td>0.49</td>
<td>1.13</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>0.43</td>
<td>0.51</td>
<td>1.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AQG EW</td>
<td>P1</td>
<td>0.40</td>
<td>0.44</td>
<td>1.11</td>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>0.40</td>
<td>0.45</td>
<td>1.14</td>
<td></td>
<td>1.08</td>
</tr>
</tbody>
</table>
REFERENCES


