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EVALUATION OF SITE EFFECTS AFTER THE 2009 ABRUZZO EARTHQUAKE USING NUMERICAL AND EXPERIMENTAL ANALYSES FOR THE RECONSTRUCTION PLANNING

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ABSTRACT

The earthquake of April 6th, 2009 in L'Aquila area is one of the largest seismic events of the last years in Italy. The events, that caused significant damage in a large area of Abruzzo regions (cental Italy) and site amplification phenomena, were recorded even at large distances from the epicentre. After the emergency period, a detailed study of the surface effects was necessary for the post-earthquake reconstruction, but in a way it should be carried out rapidly enough to give instructions to urban planners, codes to public administrators and information to engineers. A team of surveyors were trained to collect field information such as geologic and geomorphologic features and geotechnical or geophysical information. The expected seismic inputs were provided, and the collected information where analyzed with the aid of dynamic codes to calculate the possible local site effects. The results are presented as response spectra and amplification coefficients. In this paper the results for one of the most severely damaged area (up to IX-X MCS), the Paganica – Tempera – Onna - San Gregorio area, located 6 to 10 km east of the April 6th main shock, are presented.

Keywords: microzoning, amplification factors, earthquake spectra, urban planning, project design.

INTRODUCTION

The central Italy earthquake of April 6, 2009 (Mw 6.3) occurred very close to L'Aquila, a medieval town of approximate population of 73,000. The shock produced severe damages in the town and in many small villages in the surrounding region. Collapsed and damaged structures included both older masonry buildings and relatively modern reinforced concrete structures; 306 people died and about 60,000 were homeless (Istituto Nazionale di Geofisica e Vulcanologia, INGV at www.ingv.it for official reports).

The main shock nucleated at ~9.5 km depth, on a dip-slip normal fault striking N130-135° and dipping to the SW at 50-55° (Pondrelli et al. 2009). The earthquake reactivated a pre-existing normal fault cropping out near the village of Paganica, about 10 km NE of the epicentre: the Paganica normal fault (Boncio et al., 2010a, Falcucci et al., 2009).

After the earthquake, the Italian Department of Civil Protection decided that the amplification arising from the local effects had to be taken into account during reconstruction. A working group, formed by researchers from several Universities and Institutions has been charged to define a procedure able to give the needed information on villages destroyed by the earthquake in few months (www.protezionecivile.it

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under "*Microzonazione Sismica dell'area aquilana*"). Under these constraints the working group decided upon the following procedure:

1. Selection of the inhabited areas most severely damaged by the earthquake;
2. Collection of all the pre-existing basic geologic, geomorphologic, geotechnical and geophysical data;
3. Geologic and geomorphologic field surveys at a detailed scale (1:5,000 or 1:2,000);
4. New geotechnical and geophysical investigations and definition of the geologic and geophysical models;
5. Definition of the seismic input for the numerical analyses;
6. Computations of site amplifications through one-dimensional (1D) and two-dimensional (2D) soil modelling;
7. Experimental analyses using registrations of both earthquakes and noise;
8. Evaluation of the amplification through the definition of the amplification factors and acceleration response spectra for each analyzed situation useful for urban planning or project design.

We present the results, in the form of microzoning maps, amplification factors and acceleration response spectra, obtained for the Paganica-Tempera-Onna-San Gregorio area, located between the epicentre of the April 6 mainshock and the emergence of the seismogenic fault (Figure 1a). This was one of the most severely damaged area (macroseismic intensity between VIII and IX-X on the MCS scale; Galli et al., 2009).

GEOLOGIC AND GEOTECHNICAL MODEL

Geology

The Paganica-Tempera-Onna-San Gregorio area is characterized by extensive covers of lacustrine and alluvial deposits which accumulated during the Quaternary upon a Meso-Cenozoic carbonate bedrock within a NW-SE-trending extensional tectonic basin, the Middle Aterno River basin (Figure 1a) (APAT, 2005). The geometry of this basin is controlled by SW-dipping Quaternary normal faults and antithetic NE-dipping splays. The most important faults of the area are the SW-dipping Paganica and San Gregorio active normal faults, that were reactivated during the April 6, 2009 earthquake (Boncio et al., 2010a).

The stratigraphy of the continental Quaternary covers can be synthetically divided into (Boncio et al., 2010b, Geological and geophysical characterization of the Paganica-Tempera-Onna-San Gregorio area after the April 6, 2009 L'Aquila earthquake (Mw 6.3, central Italy): implications for site response. Bollettino di Geofisica Teorica ed Applicata, accepted for pubblication):

- a lower part, formed by Lower Pleistocene lacustrine carbonate silt (Lac-s in Figure 1b; "Poggio Picenze" cycle of Bertini & Bosi, 1993) capped by gravels and conglomerates in silty lacustrine matrix (Lac-g; "Vall'Orsa cycle" in Bertini & Bosi, 1993);
- a Middle-Upper Pleistocene sequence formed by alluvial fan, fluvial, fluvial-lacustrine and slope-derived deposits; the alluvial fan (Fan1, Fan2, Fan3) and fluvial (All2, All3) deposits are dominated by thick coarse-grained grain-supported sediments; the fluvial-lacustrine deposits (Flu-Lac) are characterized by abundant, or prevailing, fine-grained sediments (sand, silt and clay) with gravel interbeds, while the slope-derived deposits are characterized by coarse-grained highly heterometric breccia (Br);
- thin covers of Late Pleistocene-Holocene fine-grained alluvium (All4), coarse-grained slope-derived debris (Db), fine-grained eluvial-colluvial deposits (Coll) and, human backfill and waste material (Bf).

The basic geologic features of the area, meaningful for seismic microzoning purposes, are synthesized here through a litho-technical map (Figure 1a) and correlated stratigraphic columns (Figure 1b) and geologic sections (Figure 2). This map corresponds to the "Level 1" microzoning map (Working Group MS, 2008). A "Level 1" microzoning map classifies an area into a number of homogeneous microzones, including stable zones (bedrock outcrops), stable zones susceptible for local stratigraphic and/or morphologic amplifications and zones susceptible for instability (e.g., landslides, liquefaction, settlements, surface rupture hazard along active faults). The map also reports all the geomorphologic elements that might affect the site response (e.g., scarps, narrow valleys, alluvial fans, cavities, ridges).

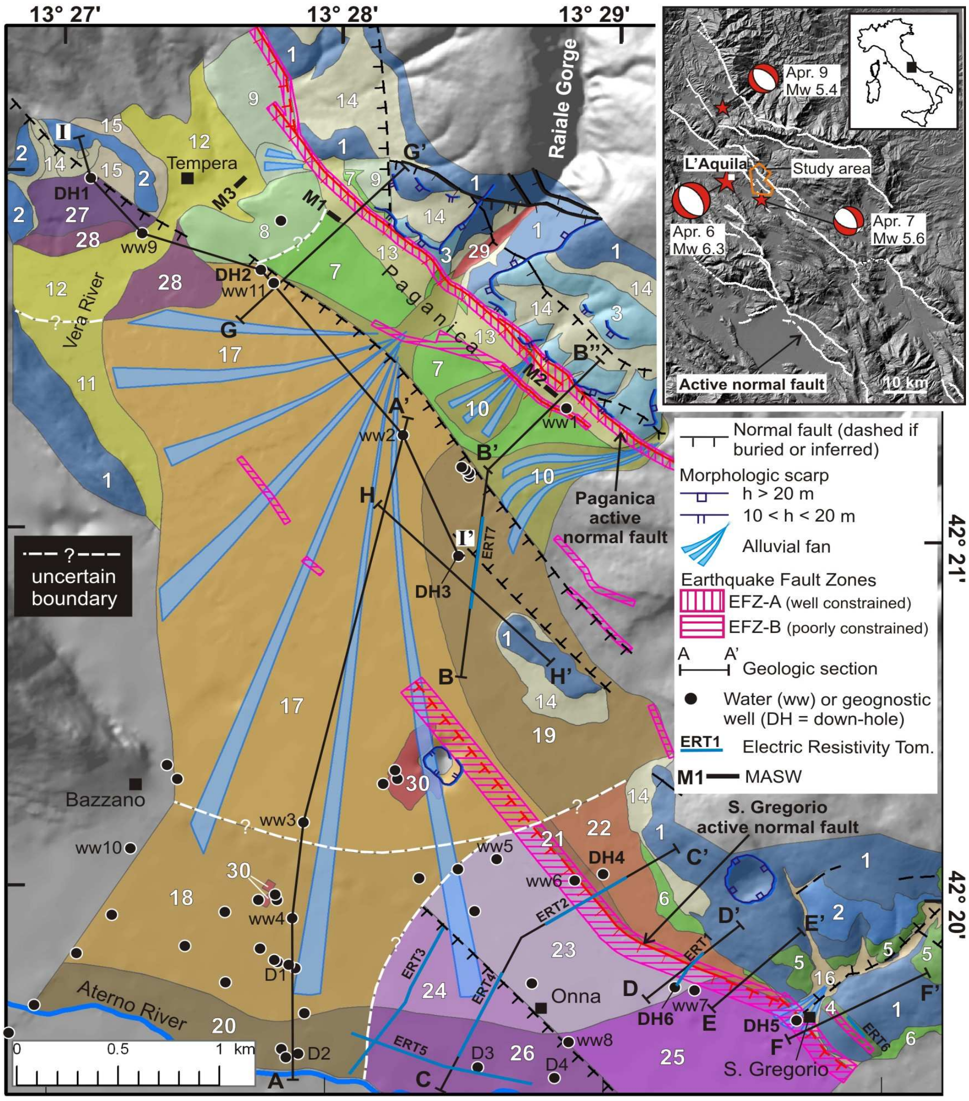


Figure 1a. Geology-based microzoning map of the Paganica–San Gregorio area; zones 1, 2, 3 are stable zones, zones 4 to 30 are stable zones susceptible for stratigraphic amplifications; EFZ-A, EFZ-B are zones affected by coseismic surface fracturing/faulting

The map of Figure 1a derives from a detailed field survey (1:5,000 scale) performed shortly after the April 6 earthquake and aimed to map the different lithologic units and to define their stratigraphic relations (details about the geology of the area may be found in Boncio et al., 2010b and Working Group MS-AQ, 2010, Microzonazione sismica per la ricostruzione dell'area aquilana. Regione Abruzzo - Gruppo di lavoro coordinato dal Dipartimento della protezione civile L'Aquila 3 vol. and Cd-rom, in press).

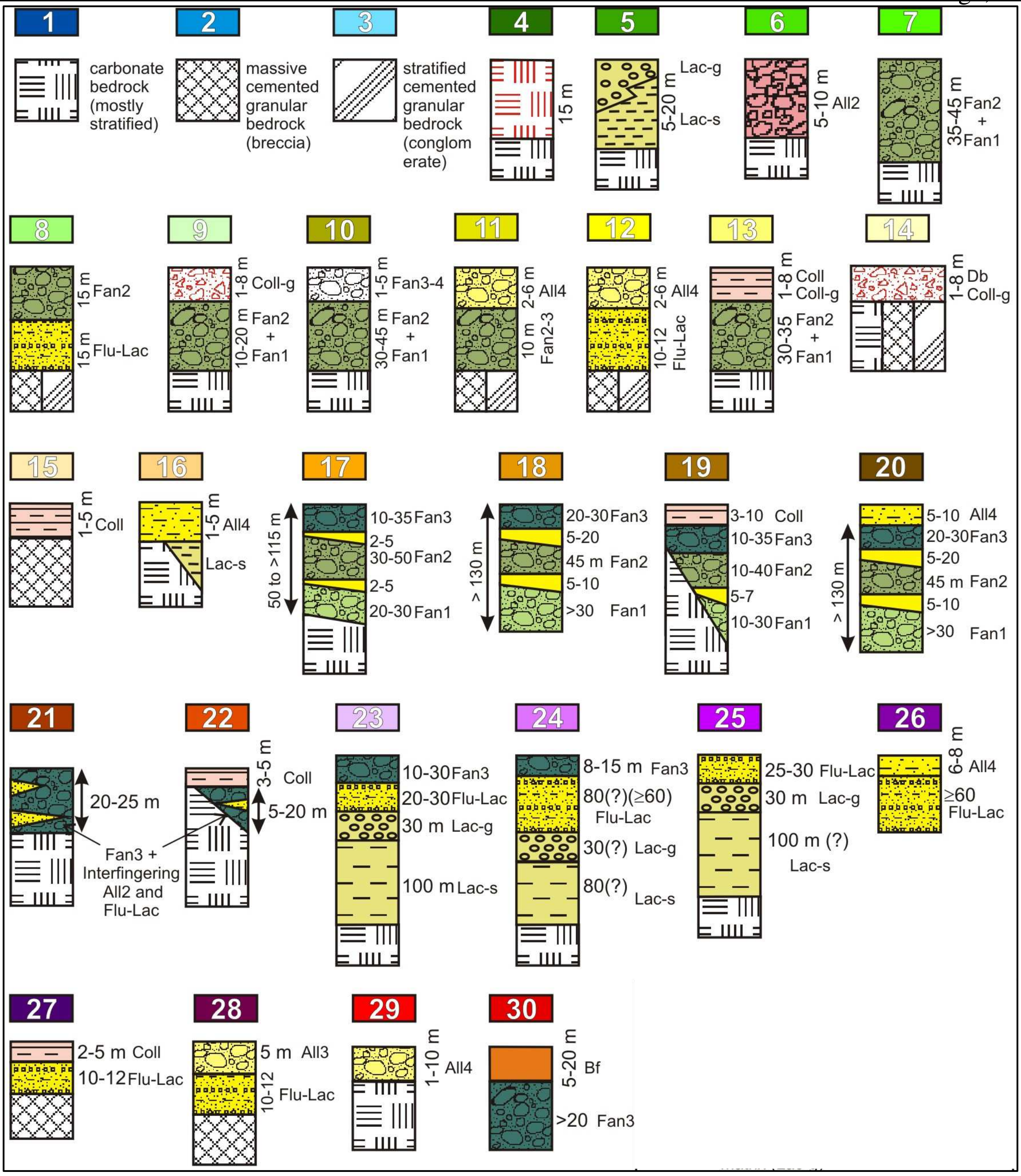


Figure 1b. Synthetic stratigraphic columns of the different zones; average thickness or thickness variations within the zones are indicated in meters. Sedimentary units: Lac-s) lacustrine deposits (Early Pleistocene); Lac-g) fluvial-lacustrine deposits (Early-Middle(?) Pleistocene); Br) slope-derived breccia, partially etheropic with Lac-g (Middle(?) Pleistocene); Fan1) alluvial fan deposits, containing paleosols and tephra horizons (Middle Pleistocene, lower part); Fan2) alluvial fan deposits, containing silty paleosols with volcaniclastic material (Middle Pleistocene, upper part – Late Pleistocene(?)); All2) Terraced fluvial deposits (Middle Pleistocene); Fan3) alluvial fan deposits (Late Pleistocene); All3) Terraced fluvial deposits (Late Pleistocene); Db) slope debris (Late Pleistocene – Holocene); Coll) eluvial-colluvial deposits (Latest Pleistocene – Holocene); Fan4) recent fan deposits (Holocene); All4) modern and recent fluvial deposits (Holocene); Bf) human backfill and waste material (present)

The surface geology was integrated with pre-existing subsurface data, mostly consisting of stratigraphic logs from water wells and geognostic drillings (ww and D in Figure 1a). Additional subsurface and geophysical data were acquired during the seismic microzoning; they include geognostic drillings with down-hole experiments (DH in Figure 1a), Electric Resistivity Tomographies (ERT), Multichannel Analyses of Surface Waves (MASW), Refraction Microtremor analyses (ReMi), and seismic recordings of both ambient noise and earthquakes (Boncio et al., 2010b and Working Group MS-AQ, 2010). The stable zones of Figure 1a (zones 1, 2 and 3) correspond to outcrops of pre-Quaternary bedrock (stratified or massive limestone and stratified marly limestone, marls and clayey marls) or to well-cemented Quaternary continental deposits that may be reasonably considered as a seismic bedrock (i.e., breccia, conglomerate). The stable zones susceptible for site amplifications are zones characterized by a subsurface stratigraphy that might significantly amplify the ground motion. Except zone 4, which corresponds to a zone of intensely fractured carbonate rocks, all the zones correspond to outcrops of Quaternary lacustrine, alluvial, slope-derived or eluvial-colluvial granular deposits of different grain size (gravel prevailing) and varying compactness/consistency. We distinguished 27 different zones susceptible for stratigraphic amplifications, each one characterized by relatively homogeneous stratigraphy; the representative stratigraphic columns are reported in Figure 1b. The geometry of the sedimentary bodies and the vertical and lateral relations among the different lithologic units were reconstructed along 9 geologic sections; the most representative sections are shown in Figure 2.

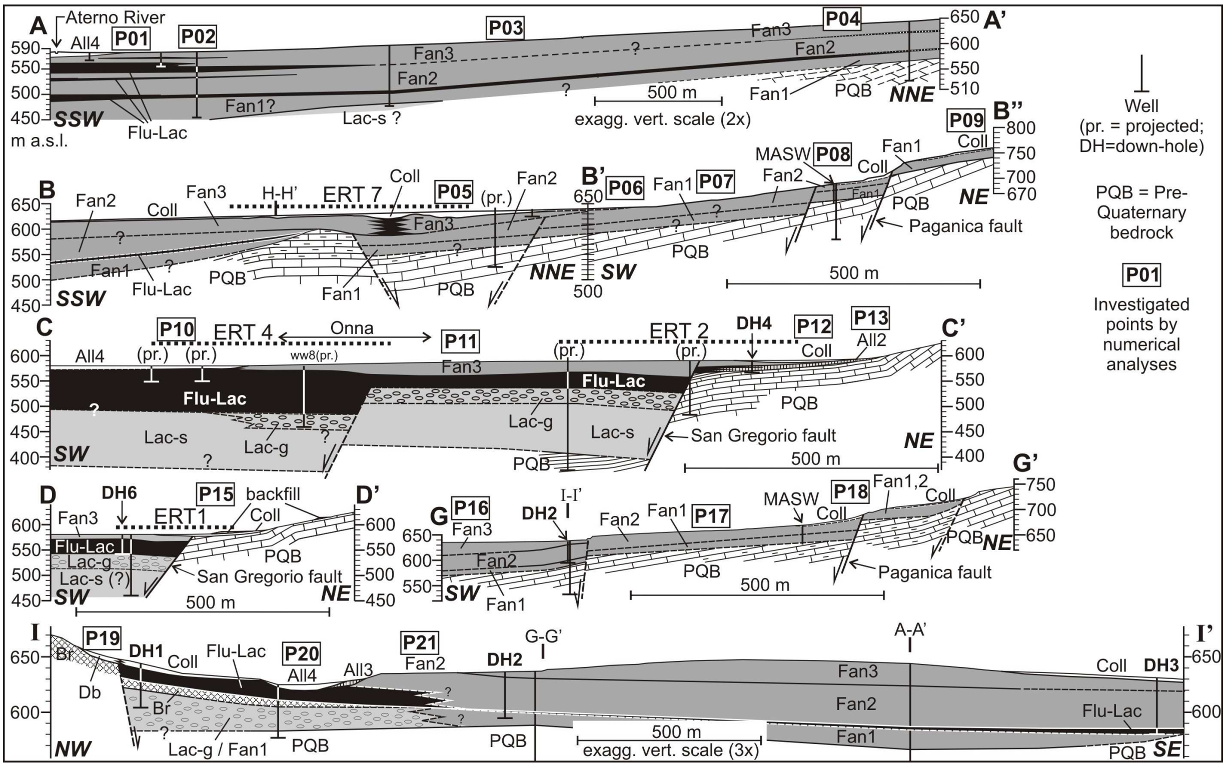


Figure 2. Most significant geologic sections with location of the points used for numerical analysis; location in Figure 1a; codes for sedimentary units as in Figure 1b

The boundaries between different zones correspond to lithologic or tectonic boundaries mapped at the surface. Dashed boundaries in Figure 1a represent lateral stratigrafic variation that were suggested by the available well but that cannot be firmly constrained due to the large distance among the wells and the absence of geophysical data for constrained lateral correlations. The Earthquake Fault Zones (EFZ) of

Figure 1a are zones susceptible for instabilities due to coseismic surface faulting. They envelope the system of normal faults, and associated coseismic ground ruptures, that were reactivated during the April 6, 2009 earthquake (Paganica and San Gregorio normal faults; Boncio et al., 2010a; Falcucci et al., 2009). The shape and width of these zones depend on a) the geometry of the fault, b) the width of the zone along the fault affected by coseismic ground ruptures and, c) the uncertainty in mapping these features (e.g., ≤ 15 m for the Paganica fault). We distinguished an EFZ-A from an EFZ-B. The EFZ-A was shaped around the well-constrained Paganica normal fault. The EFZ-B is affected by larger uncertainties and includes: a) the San Gregorio normal fault, less constrained in its surface and subsurface geometry compared to the Paganica fault, and b) the alignments of coseismic ground ruptures that cannot be certainly associated to a fault. The EFZ-B needs additional specific analyses in order to be better constrained, but the lack of this detail does not influence the results presented here. We did not find areas susceptible for other kinds of instability, such as landslides.

Geotechnical model

On the basis of the geologic model, we selected 27 points for numerical analyses and we characterized them in terms of geophysical parameters: 6 points correspond to the Down-Hole tests (DH1 to DH6 in Figures 1a and 2); 21 points (P1 to P21 in Figure 2) were selected along the geologic sections in order to adequately sample the most important geologic and geotechnical heterogeneities.

Along the geognostic drillings some samples were collected to perform laboratory tests to obtain the geotechnical static and dynamic parameters. Particularly, the non-linear behaviour of the soils was considered through 4 different sets of shear modulus reduction curves (G/G_0) and damping ratio curves (D); consequently, the soils were grouped as follows (Figure 3):

- Curve 1 (Sanò, 2009, personal communication) - Gravels (Fan1, Fan2, Fan3, All2, All3), gravels with silt and sand (Db), human backfill (Bf);
- Curve 2 (Working Group MS-AQ, 2010) - Sands and sands with silt (All4);
- Curve 3 (Working Group MS-AQ, 2010) - Silt, clay with gravel, silt with clay and sand (Coll);
- Curve 4 (Working Group MS-AQ, 2010) - Sands and silts with clay (Flu-Lac)

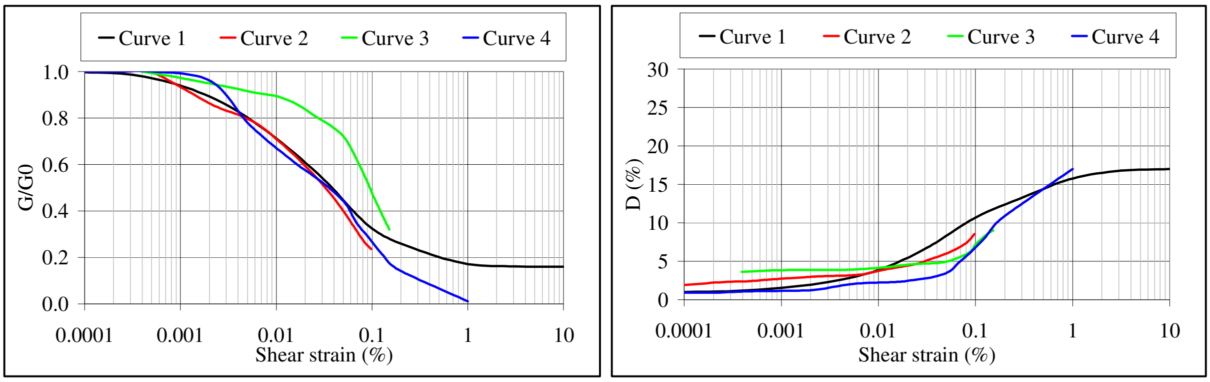


Figure 3. Normalized shear modulus reduction and damping ratio curves with shear strain: Curve 1-Gravels (Fan1, Fan2, Fan3, All2, All3), gravels with silt and sand (Db), human backfill (Bf); Curve 2-Sands and sands with silt (All4); Curve 3-Silt, clay with gravel, silt with clay and sand (Coll); Curve 4-Sands and silts with clay (Flu-Lac)

Figure 4 shows the 1D models of the analyzed sequences: Vs profiles vs Vs depth, the total unit weight is variable between the values of 17.00-22.00 (kN/m^3) and the initial damping ratio is variable between the values of 0.036-0.005.

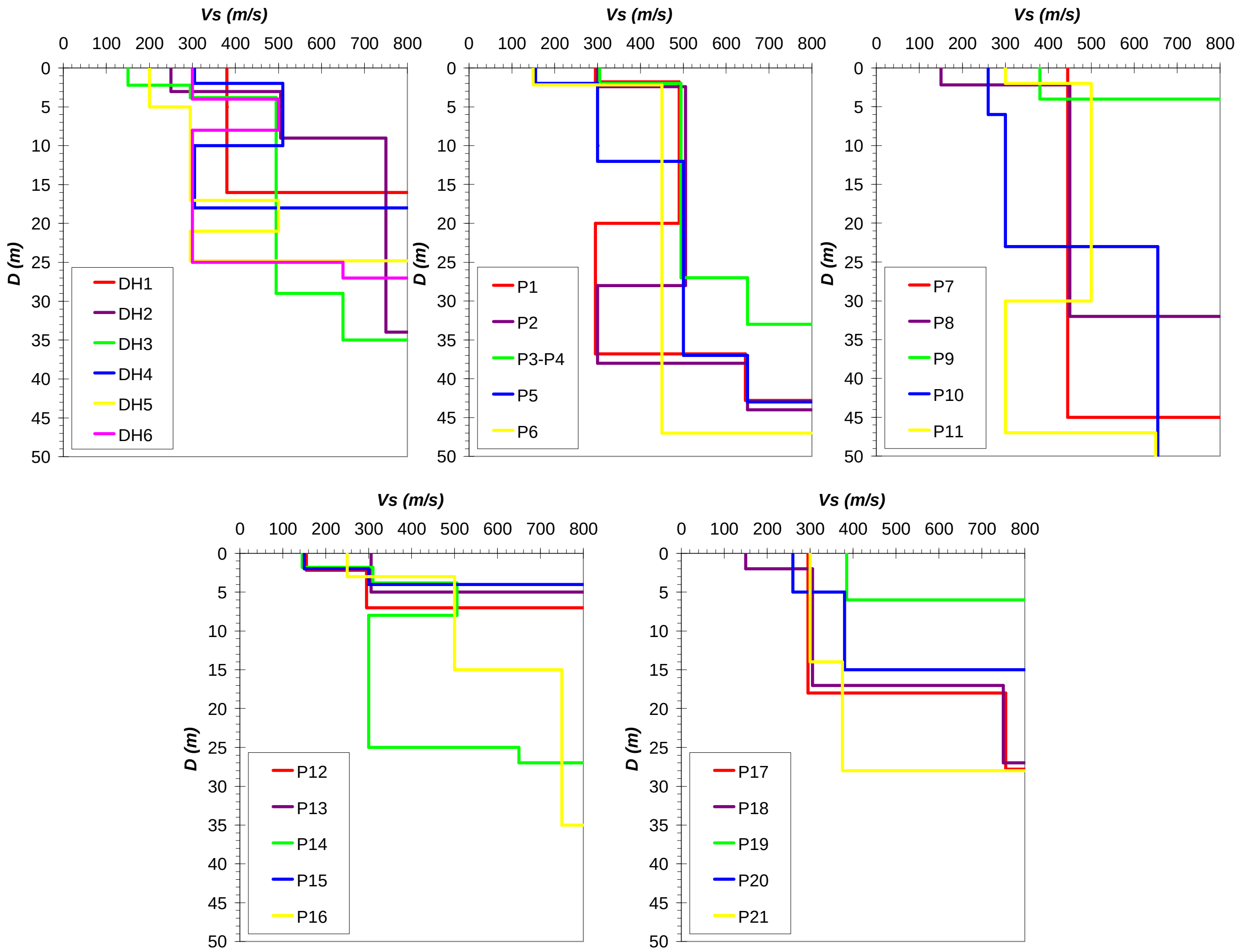


Figure 4. 1D models of the analyzed sequences: Vs profiles vs Vs depth (27 points: 6 points correspond to the Down-Hole tests and 21 points P1 to P21 in Figure 2)

NUMERICAL ANALYSIS

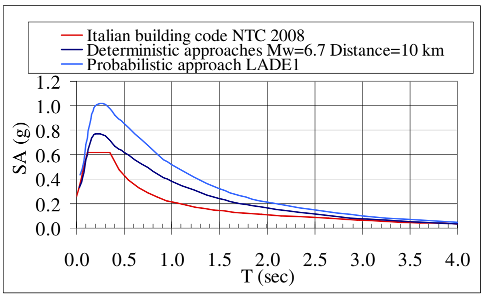
The used numerical code was a mono-dimensional program designed to analyze sites approximated as horizontal infinite layers with shear waves propagating vertically, useful to the studied areas. Each layer is homogeneous and isotropic with known thickness, mass, shear modulus and damping ratio; the program also incorporates non-linear soil behaviour, applying an equivalent linear model. For each sequence, we calculated the results in the free field by applying different seismic inputs. The seismic inputs after the L'Aquila earthquake, to be used for the numerical simulations during seismic microzonation, were analysed by Pace et al. (2010, Predicted ground motion after the L'Aquila 2009 earthquake (Italy, Mw 6.3): input spectra for seismic microzoning, submitted) The analysis followed two different approaches:

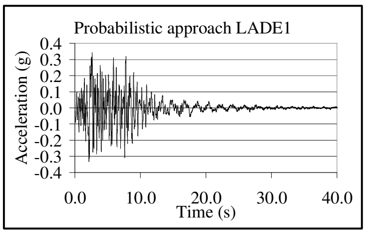
1. probabilistic approach based on a time-dependent seismic hazard assessment of the Abruzzo region, for the definition of uniform hazard spectra.

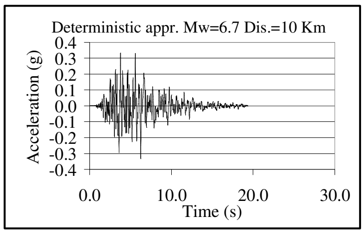
2. deterministic approach based on the selection of a reference earthquake derived from: a) the disaggregation of the probabilistic hazard and, b) magnitude/distance pairs extracted by probabilistic analysis of historical intensities.

For the probabilistic approach, Pace et al. (2010) applied the LAyered Seismogenic Source model in Central Italy (LASSCI, Pace et al. 2006), modified and implemented with the seismotectonic data acquired after the L'Aquila 2009 earthquake. In particular, the model used for the L'Aquila area (named LADE1) is a model characterized by individual seismogenic sources constrained by geological and seismotectonic data. The seismic hazard of each seismogenic source was evaluated on the basis of a time-dependent approach, namely renewal one, using the formulation of Brownian passage time distributions, starting from the time elapsed since the last maximum event and using the average slip rate. In this model, the elapsed time on the Paganica normal fault was set to zero, after the April 6 earthquake occurrence. Through the LADE1 model the uniform hazard spectra for a return period of 475 years were calculated, using different ground motion predictive equations and choosing the Sabetta and Pugliese equation (Sabetta and Pugliese 1996). Using the deterministic approaches, Pace et al (2010) obtained, for the entire mesoseismal area, a reference magnitude-distance pair with Mw = 6.7 and epicentral distance = 10 km. In according to these values and applying the Sabetta and Pugliese equation, the uniform hazard spectrum was performed. Finally, the uniform hazard spectrum of the Italian building code (NTC 2008) relative to the study area was considered. In Figure 5 the three different uniform hazard spectra are presented.

Starting from the uniform hazard spectra three non-stationary strong ground motion time-histories were generated through the procedure proposed by Sabetta and Pugliese (Sabetta & Pugliese, 1996); the procedure is based on the Arias value (Arias, 1970) and the duration of the significant phase of the strong ground motion time-histories: to obtain these parameters the values of magnitude-distance pairs, compatible with the expected maximum acceleration value, were chosen. Using the values of duration and Arias intensity, a power spectrum was generated, so from this, a series of harmonics with different and casual phases were calculated, at last the non-stationary strong ground motion time-histories so generated were modified to adapt the response spectrum of the generated accelerogram to the reference spectrum. In Figure 5 the three strong ground motion time-histories are shown.







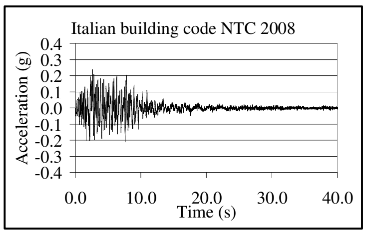


Figure 5. Uniform hazard spectra and accelerograms derived from a probabilistic approach (LADE1), deterministic approaches (Mw=6.7, Distance=10 Km) and Italian building code (NTC 2008)

The choice of the type of the results was due to the aims of the study; in fact, the results could be useful both for the urban planning and for the project design. So the results were expressed in terms of amplification factors (FA and FV) and in terms of acceleration response spectra at 5% of the critical damping. In the first case the results could be used for urban planning, whereas in the second case the results could be used for project design. The amplification factors were defined as:

$$FA = \frac{1}{Tao}\int_{0.5Tao}^{1.5Tao} SAo(T)dT \Big/ \frac{1}{Tai}\int_{0.5Tai}^{1.5Tai} SAi(T)dT \qquad FV = \frac{1}{0.4Tvo}\int_{0.8Tvo}^{1.2Tvo} SVo(T)dT \Big/ \frac{1}{Tvi}\int_{0.8Tvi}^{1.2Tvi} SVi(T)dT \quad (1)$$

where SA and SV are the acceleration and velocity spectral values, respectively, T is the period and, Ta and Tv are the periods where the acceleration and velocity spectra values are the highest, respectively (the subscripts “i” and “o” refer to input and output). Table 1 shows the average results in terms of FA and FV for each analyzed sequence, due to the application of the different accelerograms.

Table 1. Amplification factors (FA and FV) for each analyzed sequence (27 points: 6 points correspond to the Down-Hole tests and 21 points P1 to P21 in Figures 2, 7, 8)

	DH 1	DH 2	DH 3	DH 4	DH 5	DH 6	P1	P2	P3-P4	P5	P6	P7	P8
FA	1.70	1.36	1.46	1.50	1.30	1.30	0.51	0.46	1.50	1.59	1.26	1.26	1.44
FV	1.43	1.17	1.74	2.04	2.32	2.64	1.85	1.69	1.62	2.15	1.76	1.82	1.85

	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21
FA	1.29	1.46	0.41	2.47	1.28	1.32	1.66	1.59	1.79	1.88	1.20	2.13	1.73
FV	1.01	2.65	2.16	1.27	1.03	2.66	1.03	1.27	2.40	2.4	1.02	1.98	2.75

Figure 6 shows the acceleration response spectra at 5% of the critical damping, for each analyzed sequence, applying only the accelerogram derived by National Italian Code spectrum. To perform a comparison with the expected acceleration response spectra due to the National Italian Code, the spectra obtained by the analysis were smoothed, according to Working Group MS (2008), to reach a similar structure. Furthermore, the different calculated spectra were grouped according to the different soil types provided by the National Italian Code: Soil A – Vs30 > 800m/s; Soil B – Vs30 360-800m/s; NSPT30 > 50; cu30 >250kPa; Soil C – Vs30 180-360m/s; NSPT30 15-50; cu30 70-250kPa; Soil D – Vs30 < 360m/s; NSPT30 < 15; cu30 < 70kPa; Soil E – Soil C and Soil D characterized by thickness < 20 m, where the parameters are calculated considering a depth of 30m.

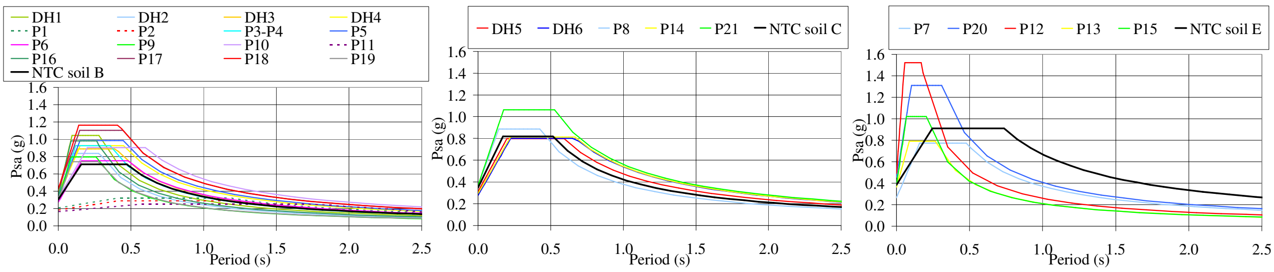


Figure 6. Acceleration response spectra for each analyzed sequence, applying only the accelerogram derived by National Italian code spectrum and National Italian code spectrum at 5% of the critical damping. The different calculated spectra are grouped according to the different soil types provided by the National Italian Code: Soil B; Soil C; Soil E

RESULTS

The values of the calculated amplification factors (FA, FV) were extrapolated in the areas characterized by similar geologic and geotechnical features of the analyzed sequences. In this way, we obtained two maps of amplification factors (Figures 7 and 8), useful to urban planning. The maps show a classification of the expected amplification, useful to define the priority in the reconstruction phase and to identify the areas affected by higher amplification values that should be excluded from new urbanization. Furthermore, the two amplification factors can be referred to different dominant periods: lower period for FA, associated to rigid structures characterized by less than 4 or 5 floors and, higher period for FV, associated to flexible structures characterized by more than 5 floors. So, the knowledge of the two different values can help to decide the best typology of construction during the repair or reconstruction phase. As shown in Figures 1a, 2 and 4, the SW sector of the investigate area is characterized by an inversion of the Vs; this behaviour is documented by the Down-Hole experiment of the DH6 geognostic drilling. This stratigraphy produces low values of FA (less than 1.3) and high values of FV (more than 1.7). Particularly the FA values of the points P01, P02 and P11 are less than 1.0, indicating a possible deamplification. In Figure 7, we assigned to these points and to the surrounding areas, amplification factors equal to 1.0, in order to obtain more precautionary results due to the stratigraphic uncertainties which characterize these points (synthetic stratigraphies of water wells, without firm constraints from continuous coring). The SE sector is characterized by low values of FA and FV (1.0), excluding a small area corresponding to DH4, P12 e P13, where the values of FA and FV are higher than 1.3. The central sector of the investigated area, is characterized by medium values of FA and FV (1.5-1.6); instead, the eastern area of this sector, presents medium values of FA (1.5-1.6) and high values of FV (more than 1.8). The N sector of the investigated area can be divided in two areas: north of the Paganica active normal fault: the values of FA and FV are negligible (less than 1.3); south of the fault: the values of FA and FV are high (up to 1.8 or more). In presence of the bedrock (carbonate rocks, conglomerates) there are not amplification phenomena, as expected. On the maps, the instability areas related to the presence of the active faults and of the seismic fractures are also reported.

The results in terms of acceleration response spectra (Figure 6), useful for the design project of the existing or new constructions (repair or reconstruction phase), show, for the soil type B, an overestimation for low periods (0.1-0.5 s) and in many cases an underestimation for high periods (0.5-2.5 s) of the calculated spectra in comparison with the spectra proposed by the National Italian Code; the points P1, P2, P11 that show low values at low period (0.1-1.0 s) are characterized by an inversion of the velocity in the stratigraphy. We performed the same calculations also for soil types C and E: for the soil type C, the calculated spectra are similar to the National Italian Code spectra; for the soil type E, in some cases (P12, P20) the overestimation for low periods (0.1-0.3 s) and the underestimation for high periods (0.3-2.5 s) of the calculated spectra in comparison with the spectra proposed by the National Italian Code are very high. The underestimation or overestimation, probably, are due to the fact that the National Italian Code uses a constant depth of 30 m and an equivalent value of Vs to discriminate the soil category and the relative response spectrum, whereas the response spectra derived by our analyses consider a depth as far as the seismic bedrock ($Vs \geq 800$m/s) and a more detailed geophysical sequence (Vs and thickness for each layer). So, the calculated acceleration response spectra seem to be more adequate, being derived from a more detailed analysis.

An experimental field analysis was performed in the area, measuring both earthquake weak motion (31) and ambient noise (60) (Boncio et al. 2010b and Working Group MS-AQ). These analyses were carried out using both the Horizontal/Vertical Spectral Ratio method (HVRS) and Reference Site Method (RSM). The weak motion HVRS data pointed out high amplifications (3-5) in the periods 0.2-0.5 s in the centres of Paganica and Tempera and in the southern area, between San Gregorio and Onna. The RSM analyses confirmed the previous amplifications. The HVRS data from noise measurements confirm the results obtained by weak motion, in terms of both dominant periods and amplification values. In conclusion, the results of the experimental analyses show a good fit with the results of the numerical analyses, particularly considering the FA map, and can be used as a test of validity of the study.

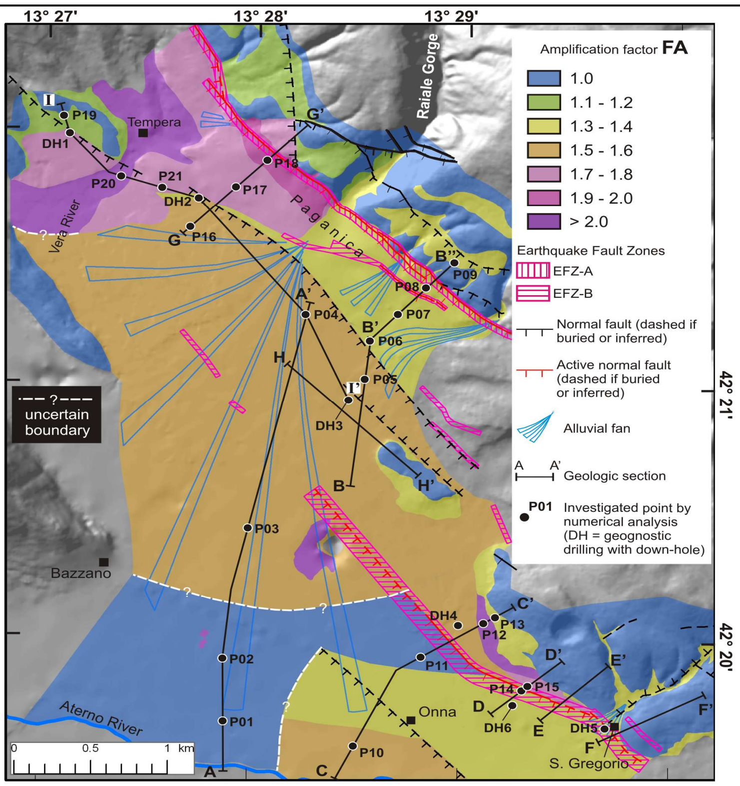


Figure 7. Map of FA factors associated to rigid structures characterized by less than 4 floors

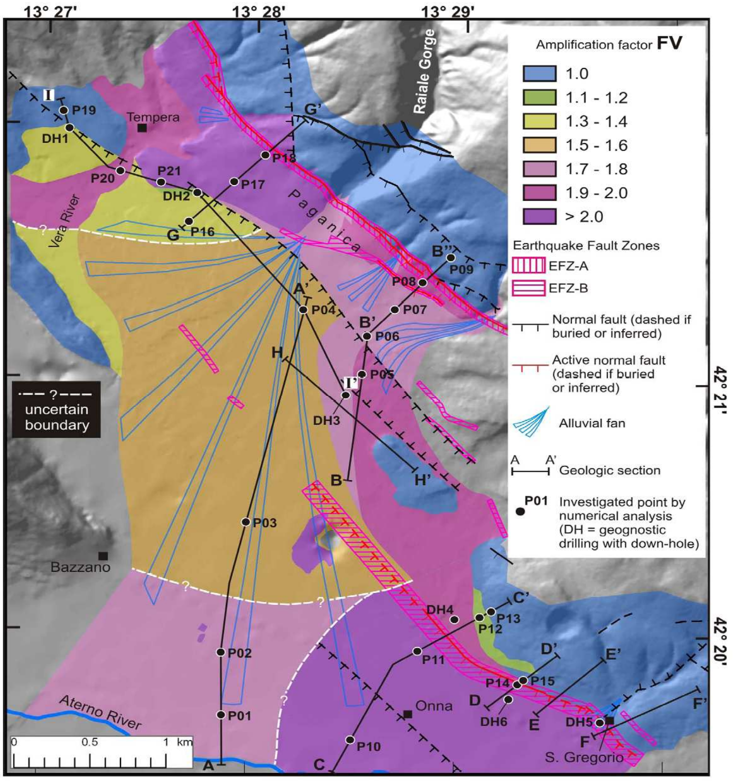


Figure 8. Map of FV factors associated to flexible structures characterized by more than 4 floors

CONCLUSIONS

After the L'Aquila earthquake of April 6, 2009 we carried out a detailed study to evaluate possible local amplifications, finalized for the urban planning and project design in the repair and reconstruction phases after the earthquake. We collected several new geologic, geomorphologic, geotechnical and geophysical data that collectively helped us to constrain a reasonable subsurface geological model. Starting form three different seismic inputs (probabilistic from the National Italian Code, newly determined probabilistic and deterministic), we analyzed the geological model with dynamic codes and we obtained the likely site amplifications. The results are presented as amplification factors (FA and FV) and acceleration response spectra at 5% of the critical damping depending to the aims of the study, and useful both for urban planning and project design. The amplification factors were extrapolated in the areas characterized by similar geologic and geotechnical features of the analyzed sequences; so we performed two maps showing a classification of the expected amplification useful to define the priority in the reconstruction phase and to identify the areas affected by higher amplification values that should be excluded from new urbanization. The calculated acceleration response spectra, useful in the project design phase, represent more detailed results than those proposed by the simplify procedure of the National Italian Code.

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