# In-depth third level Seismic Microzonation studies in pilot areas of L'Aquila Municipality (Central Italy)

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## Introduction

The proposed study is part of the third level Seismic Microzonation (SM) project activities carried out on a 7 km$^2$ wide pilot areas (Preturo-Sassa and Bazzano-Monticchio) of L'Aquila Municipality financed by the Abruzzo Region (Department of Government of the Territory and Environmental Policies - Risk Prevention Service of Civil Protection).

L'Aquila Municipality pertains geologically to the middle Aterno River intermontane basin which was filled up by Plio-Quaternary coarse- and fine-grained detrital deposits related mainly to lacustrine, slope and alluvial environments and is characterised furthermore by a considerable seismic hazard as evidenced by the recent April 6, 2009 Mw 6.29 near source earthquake (Nocentini et al., 2017).

According to the DPC guidelines (Gruppo di lavoro MS, 2008), numerical maps and database were produced at the end of the third level SM project. The project was realized through the following activities, carried out in sequence and, partly, in parallel way: (i) update of database concerning boreholes, geotechnical and geophysical in-situ investigations; (ii) seismic input selection; (iii) computer code selection; (iv) geophysical and geotechnical soil characterization; (v) elaboration of the geological sections; (vi) 1D and 2D modelling; (vii) evaluation of the site liquefaction potential; (viii) mapping the third level SM microzones based on the calculated Amplification Factors and the estimated soil liquefaction potential; (ix) third level SM numerical maps elaboration.

## Database, seismic input, and computer code selection

Within the third level SM project, the previous elaborated first level SM database was updated with new ad hoc investigations that were placed in remarkable sites of the pilot areas.

Given the complex seismostratigraphy of middle Aterno River basin, characterized by a thick and complex sedimentary sequence, four 2D seismic arrays were performed which permitted to obtain the Vs profile up to great depths reaching the Meso-Cenozoic calcareous-terrigenous substratum.

For the estimation of the soil liquefaction potential, specific in-situ investigations (CPTU and SDMT tests) were also carried out in pivotal sites. In this case, particular attention was paid to the selection of sites which were considered potentially liquefiable based on geological and hydrogeological observations.

Following the Italian technical standards for construction NTC18 (CS.LL.PP., 2018), seven natural accelerograms were selected as seismic inputs and were used in the numerical simulations for the estimation of the Amplification Factors (AF). The online database used for the selection of the septuple is REXELite which is available at the link: DYNA-stage - REXELite [Cadmo v3.1690 page=REX_rexel_homepage] (ingv.it). REXELite is the simplified version of the Rexel database (Iervolino et al., 2009).

To have a rational balance between the analysis accuracy and the computational burden, able to consider the non-linear behaviour of soil, the local seismic effects, and the geological complexity of middle Aterno River basin, it was decided to resort to the 2D equivalent linear modelling. Based on these considerations, for the AFs evaluation, LSR2D code by software house Stacec s.r.l. (https://www.stacec.com/lsr-2d_pp92.aspx) was used. LSR2D performs the 2D equivalent linear modelling by using the finite element approach, in the time domain and in total stresses, and the Kelvin-Voigt model.

**Geological sections and geophysical & geotechnical soil characterization**

Many geological sections (n. 15) were elaborated and 2D simulations were carried out. The sections were traced to cross most of the SM microzones of the pilot areas and the most significant geological boundaries (fault contacts, alluvial terrace scarps, landslides, anthropic deposits, etc.). Moreover, the sections were located close to the geophysical investigations (microtremor measurements and down-hole tests) and boreholes to better constrain the subsoil model (Fig. 1). They start and end at least 400 m outside the extremes of the section almost always located in the seismic bedrock, so to minimize in the simulations the edge phenomena due to the lateral dispersion of the seismic energy (Fig. 2). Orthogonal sections have also been elaborated for checking with the simulations possible 2D phenomena due to seismic directionality. The seismolayers were characterized considering the geophysical (Vs, Poisson's ratio) and geotechnical (density, $G/G_0$-γ decay and D-γ damping curves) parameters starting from many studies on seismic site characterization and seismic ground response of L’Aquila area (Macerola et al., 2019 and references therein).

**Numerical modelling**

The Amplification Factors (AF) were calculated with LSR2D code along the sections every 30-50 m and with 3 calculated points located in a zone of 70 m, as a minimum, and 120 m, as a maximum. After the calculation of AFs, a 3-data filtering was performed to make the trend of the AF values homogeneous along the progressives of the section (Fig. 2). Since 2D simulations have been performed for each microzone, more points are available in which the AFs have been calculated. Therefore, based on an evaluation in favour of safety and subject to expert judgment, the AF of the microzone is the highest of those calculated within the microzones for the period interval 0.1-0.5 s and the accelerograms and response spectra representative of the microzone refer to those of the AF attributed to it.

To evaluate the reliability of the calculated AFs, a quality control was performed by comparing the AFs with the geological and the first level SM maps. Indeed, it has been noted that the distribution of the calculated AFs is congruent with the geological background. In fact, along the sections a rough correspondence between the boundaries of the AF classes with the geological units is observed. Further, for the outcropping geological units, the AF values vary within a narrow range. It has been also observed that the AF values are conditioned by the more superficial seismic impedance contrast. However, these observations agree with the theory (Kramer, 1996; Lanzo and Silvestri, 1999) and, therefore, lead us to believe that the AFs obtained with the simulations are to be considered reliable. Moreover, considering the good correlation between the AFs and the geological background, the boundaries of the third level SM microzones were areally extended, based on the geological unit boundaries, and via expert judgment (Pergalani et al., 2020).

Furthermore, to verify the quality control of the simulations and to refine the local seismic behaviour, any 2D effects were analyzed by comparing the AFs obtained with the 1D simulation with those calculated with the 2D ones in the same site. In several cases, the 2D basin effects were detected, as the AFs calculated in the basin center with 1D modelling was lower than the AFs estimated with 2D one (Fig. 2).

Furthermore, near the slope break between the reliefs and the Aterno R. plain, the AF values calculated with 2D simulation are higher with respect to those 2D-estimated in the surrounding areas and are lower than those estimated with 1D modelling. This behaviour would probably be attributable to 2D basin edge effect (Lanzo and Silvestri, 1999) (Fig. 2).

For almost all the sections of the Bazzano-Monticchio area crossing the Aterno R. plain, the AF values increase for the intervals of the higher periods, i.e., a shift of the seismic energy towards higher periods is noted (lower frequencies). This behaviour seems to be linked to 2D effect because the FAs calculated in points located on the Aterno R. plain with a 1D modelling are generally lower than the FAs estimated with the 2D one (Kramer, 1996).

Finally, for some microzones not covered by 2D simulations, 1D ones were performed with LSR2D and Strata code (Kottke and Rathje, 2009).

**Soil liquefaction potential evaluation**

In this study, 36 sites were examined in the Preturo-Sassa area and 5 in the Bazzano-Monticchio area for assessing the soil liquefaction potential. Most of the sites (where shear wave velocity data were available) were classified in subsoil category C, with an equivalent shear wave velocity, Vs,eq, between 180 m/s and 360 m/s. The results of the simplified analysis based on empirical charts lead to zero or low level of Liquefaction Potential Index, LPI (Iwasaki et al., 1984), except for the Pagliare di Sassa site (moderate level) (Fig. 1). In the examinated pilot areas, this result is due to the absence of factors predisposing to liquefaction, such as conditions of complete saturation and loose granular soils, while a secondary role is probably played by the triggering action (i.e., the seismic action). Therefore, the uncertainties related to the determination of the seismic demand, such as the simplifying assumption about the magnitude and the adoption of a single seismic scenario, do not affect the results of the study for the above-mentioned reasons. The zero/low liquefaction potential obtained from the simplified approaches did not make it necessary to use more sophisticated methods of analysis, such as simplified and advanced dynamic analyses (Chiaradonna, 2020).

**The third level SM deliverables**

The following documents have been produced for the Preturo-Sassa and Bazzano-Monticchio areas (L'Aquila Municipality): (i) third level SM maps of the AFs for the three period intervals (0.1-0.5 s, 0.4-0.8 s, 0.7-1.1 s) at 1:5000 scale; (ii) database organized by using the CNR-IGAG plugin "MzS Tools" operating on QGIS ver. 3.22 (Cosentino and Pennica, 2022).

For each microzone, the following data were also produced: (i) n. 3 AFs, one for each period interval; (ii) n. 7 natural accelerograms used as seismic input for the 2D modelling; (iii) n. 7 elastic acceleration response spectra at 5% damping (output spectra) at the surface, one for each input accelerogram; (iv) the representative output spectrum of the microzone, i.e., the average spectrum of the 7 above mentioned spectra; (v) the Vs,eq value and the related subsoil category according to NTC 2018. The Vs,eq value was calculated, for each microzone, using the average thickness of the seismolayers and the relative values of Vs used for the modelling.

**Conclusion**

Considering the complex seismostratigraphy of L'Aquila territory, 2D modeling was carried out on a very large number of sections (n. 15) to calculate in-depth the AFs and analyze their areal variation. The validity of 2D modelling was confirmed by the congruence between the geological background and the AFs value distribution. Finally, 2D modelling allowed to verify the existence of basin and basin edge effects via the comparison with 1D simulations.

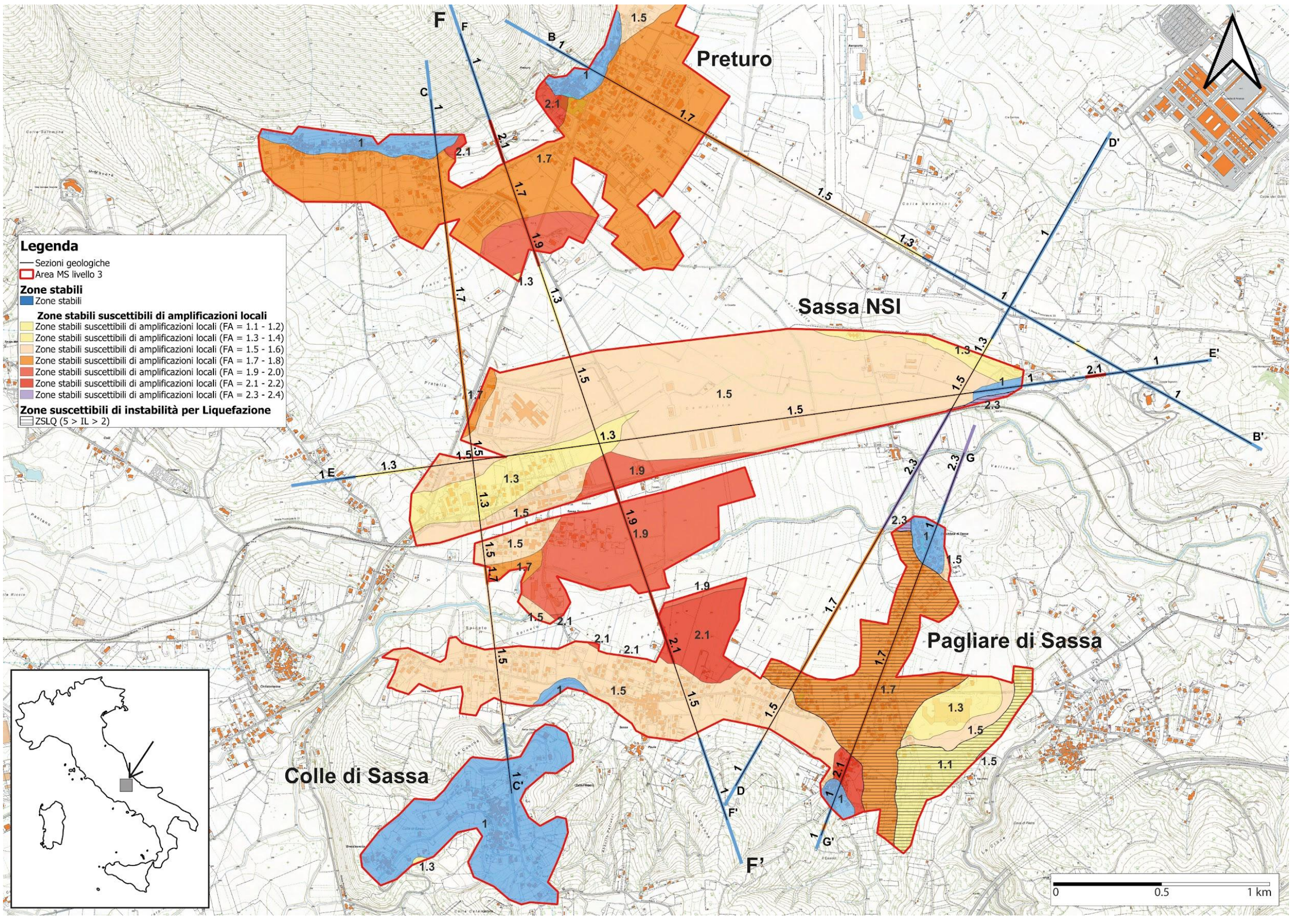


Figure 1 – Third level SM map for the period interval 0.1-0.5 s of Preturo-Sassa area. The sections with the AFs calculated with the 2D simulations are also reported. Section F-F’ is reported in Fig. 2. AF intervals: Class 1.0: AF<1.05; Class 1.1: 1.05≤AF>1.25; Class 1.3: 1.25≤AF>1.45; Class 1.5: 1.45≤AF>1.65; Class 1.7: 1.65≤AF>1.85; Class 1.9: 1.85≤AF>2.05; Class 2.1: 2.05≤AF>2.25; Class 2.3: 2.25≤AF>2.45.

| site | A | B | C | D | E |
|---|---|---|---|---|---|
| AF 1D (0.1-0-5 s) | 2.12 | 1.85 | 1.96 | 2.0 | 1.74 |
| AF 2D (0.1-0-5 s) | 2.25 | 2.23 | 2.02 | 2.07 | 2.47 |

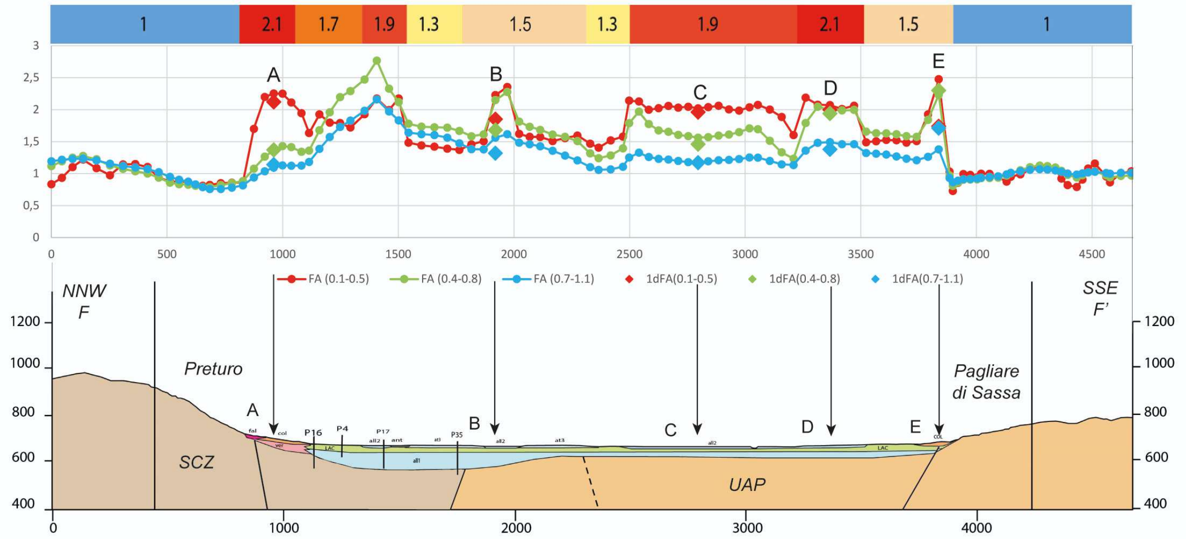


Figure 2 – In the Preturo - Pagliare di Sassa basin represented in section F-F', a partial 2D basin effect is hypothesized because, in site B located within it, the one-dimensional AF1D (1.85) is lower than the two-dimensional AF2D (2.23). Furthermore, a basin edge effect, as defined in Lanzo and Silvestri (1999), is hypothesized because at site E the AF1D (1.74) is smaller than the AF2D (2.47). The diamond symbol refers to AF calculated with 1D simulation. P: boreholes; SCZ and UAP: calcareous and terrigenous units belonging to the seismic bedrock; the other units refer to the Plio-Quaternary basin-filling detrital units. The location of section F-F’ is reported in Fig. 1. AF intervals: Class 1.0: AF<1.05; Class 1.1: 1.05≤AF>1.25 (not present); Class 1.3: 1.25≤AF>1.45; Class 1.5: 1.45≤AF>1.65; Class 1.7: 1.65≤AF>1.85; Class 1.9: 1.85≤AF>2.05; Class 2.1: 2.05≤AF>2.25; Class 2.3: 2.25≤AF>2.45 (not present).

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