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1D and 2D seismic site response to the microzoning of pilot areas in L'Aquila Municipality

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Introduction

We report the preliminary results of the 1D and 2D numerical modeling, preparatory for the 3rd level microzoning (*sensu* Gruppo di Lavoro, 2008) in Coppito and Preturo villages selected as pilot areas in L'Aquila Municipality. The analysis was performed on the Preturo-Coppito section representative of the geology of the pilot areas (Figs. 1 and 2) (AA.VV., 2014) by using the methodologies reported in Gruppo di Lavoro MS (2008) and Gruppo di Lavoro MS–AQ (2010). The preliminary results of the seismic response have revealed the likely valley edge effect found on the edges of the section (double values in pseudo-acceleration between 1D and 2D modeling) and lack of 2D effect in the middle of the section.

Seismic input

The seismic input used in the numerical modeling includes four free field accelerograms at the bedrock as reported in the seismic microzoning studies of L'Aquila Municipality (Gruppo di Lavoro MS–AQ, 2010) (Fig. 1). We used an accelerogram compatible with the Uniform Hazard Spectrum (UHS) of NTC-08 regulations and three accelerograms compatible with the spectrum obtained from deterministic attenuation relationship for specific magnitude and distance parameters ($Mw = 6.7$, $R_{epi} = 10$ km) (Sabetta and Pugliese, 1996) obtained from disaggregation analysis (DET_1, DET_2 and DET_3). We decided to compare the average of the output (pseudo-acceleration, pseudo-velocity and displacement) based on accelerograms DET_1, DET_2 and DET_3 with output calculated with the NTC accelerogram. Both 1D and 2D analysis, the response spectra derived from NTC input understate those derived from disaggregation analysis input.

1D and 2D calculation codes

The calculation codes can be divided mainly depending on the subsoil model geometry and the analysis approaches as the equivalent linear or non-linear ones and in total stress or effective stress soil behavior. The equivalent linear analysis was carried out in total stresses soil behavior. It allows a simplified treatment of the problem and, at the same time, to take into account complex aspects such as the deposit heterogeneity and the non-linearity of the stress-strain relationship. Conversely, the equivalent linear analysis does not allow (i) to evaluate the seismic induced pore pressure increase; (ii) to consider the soil stiffness falling due to the seismic induced pore pressure increase; (iii) to calculate permanent soil deformation.
The non-linear analysis may be conducted in total and effective stresses. The use of non-linear effective stress approach takes into account the soil behavior submitted to cyclic seismic loadings which can cause (i) a considerable surplus of pore pressure effecting liquefaction phenomena; (ii) pore pressure redistribution and dissipation during and after the earthquake; (iii) progressive declining of soil stiffness; (iv) permanent deformation.
As a rule, nonlinear analysis therefore allows a more accurate and reality consistent modeling of soil stress-strain behavior, with respect to the equivalent linear analysis. The choice between the two mentioned approaches must be properly weighted according also to the cost-effectiveness analysis to determine the representative parameters (seismic input and the geophysical subsoil model). The calculation codes, most frequently used for the 1D and 2D modeling are respectively SHAKE (Idriss and Sun, 1992) and QUAD4 / QUAD4M (Idriss et al., 1973; Hudson et al., 1993), both characterised by the equivalent linear approach. The calculation codes provide (i) time histories of shear stress, shear strain, acceleration and the corresponding response Fourier spectra at free field condition and at intermediate depths from the ground; (ii) maximum values of acceleration, tension and shear strain vs. depth.
The calculation codes used in this study were for the 1D and 2D modeling, EERA (Idriss and Sun, 1992) and LSR 2D from Stacec srl (http://www.stacec.com/).

1D analysis: code EERA

The code EERA considers a half-space that refers to a continuous model formed by horizontal soil layers of infinite extent. The linear viscoelastic model refers to the Kelvin-Voigt rheological model (spring and viscous damper in parallel) in which it is assumed that the shear waves propagate vertically. The equivalent linear model treats the shear modulus G and the damping ratio D as a function of the shear strain γ. In the software, G and D are calculated by iterations that are leaded by the level of deformation of the subsoil layers induced by the earthquake shaking. In general, the results of the seismic site response are: (i) the response spectra in pseudo-acceleration, pseudo-velocity and displacement that are basic parameters for structural design; (ii) the time history of free field acceleration, which is necessary for the structural dynamic verification.

Analysis 2D: code LSR 2D

Software LSR (Local Seismic Response 2D) can perform a 2D numerical modeling using a finite element approach, time domain, in total stresses. It uses also the Kelvin-Voigt subsoil model such as the more known computer code QUAD 4M. But, LSR 2D is more friendly with respect to QUAD 4M because the mesh calculation is easier and faster in case of complex geological background such as that of section B-B'. In the 2D analysis with linear equivalent and concentrated masses approach, the subsoil model is discretized in a mesh with triangular or preferably quadrangular shape elements. Mesh generation is one of the most significant steps of the analysis, depending from it both the accuracy of the solution and the computational burden. It can be said that more the mesh is dense more the solution is accurate and greater the time and memory required for processing. The use of an excessively coarse mesh results in a filtering of the high frequency components. The reason is that nodes too far apart cannot adequately model small wavelengths. Therefore, the height h of each element has to be chose as follows:

$$h \leq \left(\frac{1}{8} \div \frac{1}{5}\right)\frac{V_s}{f_{max}}$$

where: h is mesh step; Vs, the shear wave velocity; $fmax$, the maximum frequency considered in the analysis (usually equal to 20-25 Hz).
In this case study, the mesh generation was built with an adaptive approach, so as to preserve computational resources in favor of the control points identified for obtaining the output results (P34, P127, P159). The mesh step would increase from higher values starting from bedrock (equal to 4 m) and then level off at lower values (equal to 1 m), in the proximity of the control points. The overall balance is expressed by the following system of equations:

$$\boldsymbol{M}\,\ddot{\boldsymbol{u}} + \boldsymbol{C}\,\dot{\boldsymbol{u}} + \boldsymbol{K}\,\boldsymbol{u} = -\boldsymbol{M}\,\ddot{\boldsymbol{u}}_{\boldsymbol{b}}$$

where u is the vector of nodal displacements; M, K and C refer respectively to the matrix of masses, stiffness and damping; $\ddot{\boldsymbol{u}}_{\boldsymbol{b}}$, the time history of the acceleration input. The equations are solved by direct integration in the time domain with the Newmark method and with the CAA method (Constant Average Acceleration) which is stable and does not introduce any numerical damping. The seismic motion input $\ddot{ub}$ is applied simultaneously to the nodes of the bedrock base in the form of P and S waves with a vertical propagation. The section B-B' is bordered by outcropping bedrock, which implies the no use of viscous dampers in the lateral section edges (AA.VV., 2014) (Fig. 2).
The nonlinear soil behaviour is taken into account by performing linear equivalent analysis. The dissipative properties of the soil are modeled through the matrix dissipation C. It derives from the assembly of the dissipation matrices of the individual elements calculated according to the complete Rayleigh equation:

$$C_i = \alpha_{Ri} Mi + \beta_{R} iKi$$

where αRi βRi and are the Rayleigh coefficients and Mi, Ci and Ki the local matrices of the single element.
The adoption of the Rayleigh equations involves a frequency-dependent damping, which can affect appreciably the modeling results. To reduce this effect LSR 2D uses Rayleigh coefficients calculated according to two natural frequencies of soil deposit, ωn and ωm:

$$\alpha Ri = \xi i \; \frac{2\,\omega m * \omega n}{\omega m + \omega n} \qquad \beta Ri = \; \xi i \frac{2}{\omega m + \omega n}$$

where ξi is the viscous damping ratio of the i-th element; $\omega m = \omega 1$, the first natural vibration frequency of soil deposit; $\omega n = n\ \omega 1$, where n being the odd integer that approximates by excess the predominant frequency ratio of the seismic input ωIN and frequency $\omega 1$.

The software LSR 2D requires as input, for each soil the following parameters:

- the volume weight, shear modulus, damping at low strain, Poisson's ratio;
- the G/G_0 vs γ and D vs γ curves;
- the constant α for the calculation of the characteristic value of the shear deformation starting from the maximum value of $\gamma\ (t)$ (typically equal to 0.65).

Outgoing code provides:

- the maximum accelerations on all nodes;
- the maximum tangential stresses and strains in each element;
- the acceleration time history in the selected nodes (vertical and horizontal components).

Subsoil model data

We selected three sites (P34, P127, P159, P193) on the section B-B' (Preturo-Coppito) (Fig. 2). The P34 is placed in the western edge of the section B-B'. The used stratigraphy is of MOPS 2024 (Fig. 2), which is characterized by COL (E7) units laying upon the seismic bedrock (AA.VV, 2014) (MOPS corresponds to the Italian acronym "Microzone Omogenee in Prospettiva Sismica" - Gruppo di Lavoro MS, 2008 - which can be literally translated as "Homogeneous Microzones in Seismic Perspective" i.e. zones at fine scale characterised by seismic local effects. The P127 is placed in the valley center. and it represents the condition closer to a purely 1D modeling. The stratigraphy corresponds to that of the MOPS 2026 (Fig. 2), which is similar to that of the MOPS 2024, except to units thicknesses and Vs values (AA.VV, 2014). The point P159 is placed in east edge of the section B-B'. The used stratigraphy is of MOPS 2013 (Fig. 2), which is characterized by AT1 unit (C1, E2, E3, E4, E5, E6 lithologies), superimposed on bedrock or on LAC unit (F3, F4 lithologies) and ALL1 unit (E5 lithology) (AA.VV., 2014; Regione Abruzzo, 2012).

The G/G_0 vs γ and D vs γ curves for sands (E3, E4, E5 and E7 lithologies) and clays (F3 and F4 lithologies) are respectively from Seed and Idriss (1970) and Seed and Sun (1989). The G/G_0 vs γ and D vs γ curves for bedrock are from calculation codes EERA (Idriss and Sun, 1992) and LSR 2D (http://www.stacec.com/).

Results and conclusions

There are numerous cases in literature of numerical analyses that have addressed the local amplification phenomena resulting from valley and topographic effects. In our case study, the comparison between the response spectra and maximum amplitude in the output relative to the 1D and 2D models is in good agreement in the central zone of the valley (P127), where there are no morphological and stratigraphic irregularities (Fig. 2). While this comparison highlights values changes at the valley edges (P34, P159) (Fig. 2), evidencing an increase in amplitude and in the energy content at lower frequencies which is due mainly to seismic waves focus (Fig. 3). The results of 1D and 2D modeling show a remarkable correspondence between the resonance frequencies of valley-fill deposits obtained with several microtremor measurements and those calculated by numerical simulations. This correspondence confirms the validity of the subsoil model thus validating: (i) the bedrock depth; (ii) constant thickness and subhorizontal layering of valley-fill deposits in the valley center; (iii) the estimated Vs values; and (iv) the subsoil model setting for the calculation code LSR 2D (geotechnical parameters up to now used) (Fig. 3).

References

AA.VV.; 2014: *Progetto Pilota per la Microzonazione Sismica di Livello 1 del Comune di L'Aquila, zona Preturo-Sassa*. Regione Abruzzo.

Gruppo di lavoro MS; 2008: *Indirizzi e criteri per la microzonazione sismica*. Conferenza delle Regioni e delle Province autonome - Dipartimento della protezione civile, Roma, 3 vol. e Dvd

Gruppo di Lavoro MS–AQ; 2010: *Microzonazione sismica per la ricostruzione dell'area aquilana. Regione Abruzzo* - Dipartimento della Protezione Civile, L'Aquila, 3 vol e Dvd.

Hudson M.B., Idriss I.M. and Beikae M.; 1993: QUAD4M – *A computer program for evaluating the seismic response of soil structures by variable damping finite element procedures*. Center for Geotech. Modeling, Department of Civil and Environmental Engineering, University of California, Davis.
Idriss I.M., Lysmer J., Hwang R. and Seed B.H.; 1973: *Quad4 A computer program for evaluating the seismic response of soil structures by variable damping finite element procedures*: Open Report, University of California, Berkeley.
Idriss I.M. and Sun J.I.; 1992: *SHAKE91 – a computer program for conducting equivalent linear seismic response analyses of horizontally layered soils deposits*. University of California, Davis.
Regione Abruzzo; 2012: *Linee guida: standard di rappresentazione cartografica e archiviazione informatica, specifiche tecniche per la redazione degli elaborati cartografici ed informatici relativi al primo livello delle attività di Microzonazione Sismica* – Versione 1.2, L'Aquila, 30 Luglio 2012.
Sabetta F. and Pugliese A.; 1996: *Estimation of response spectra and simulation of non-stationary earthquake ground motions*. Bull. Seism. Soc. Am., **86**, 337-352.
Seed H.B. and Idriss I.M.; 1970: *Soil Moduli and damping factors for dynamic response analysis*. EERC-Report 70- 10, Berkeley, California.
Seed H.B. and Sun J.H.; 1989: *Implication of site effects in the Mexico City earthquake of September 19, 1985 for Earthquake-Resistant Design Criteria in the San Francisco Bay Area of California*. Report No. UCB/ EERC-89/03, Earthquake Engineering Research Center, University of California, Berkeley.

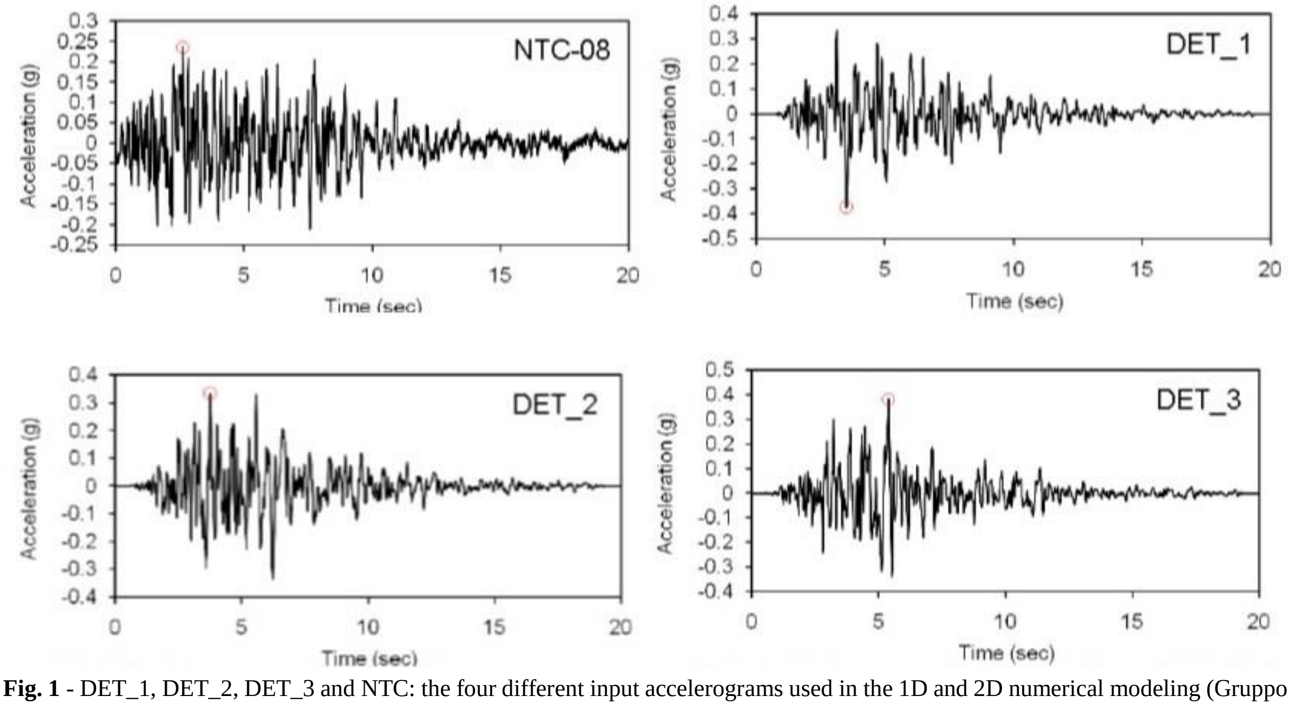

Fig. 1 - DET_1, DET_2, DET_3 and NTC: the four different input accelerograms used in the 1D and 2D numerical modeling (Gruppo di Lavoro MS–AQ, 2010).

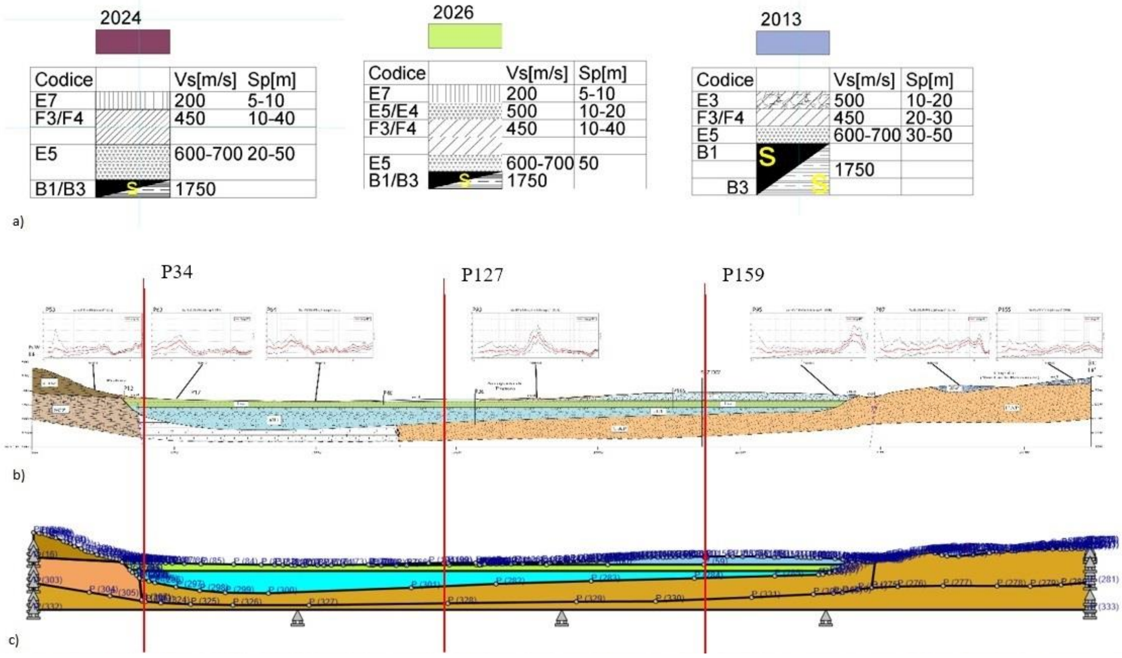

Fig. 2 - a) MOPS stratigraphies used in 1D and 2D modeling. B1 - structurally ordered layered rocks; B3 - layered rocks characterised by strong competence contrast due to alternating layers of rocks and pelites; E3 - sandy gravel; E5 - gravelly sand-; E7 - sandy silt-; F3 - clayey silt -; F4 - silty clay (AA.VV., 2014); b) section B-B' (Preturo-Coppito): AA.VV., 2014; c) section B-B': mesh obtained with the software LSR 2D.

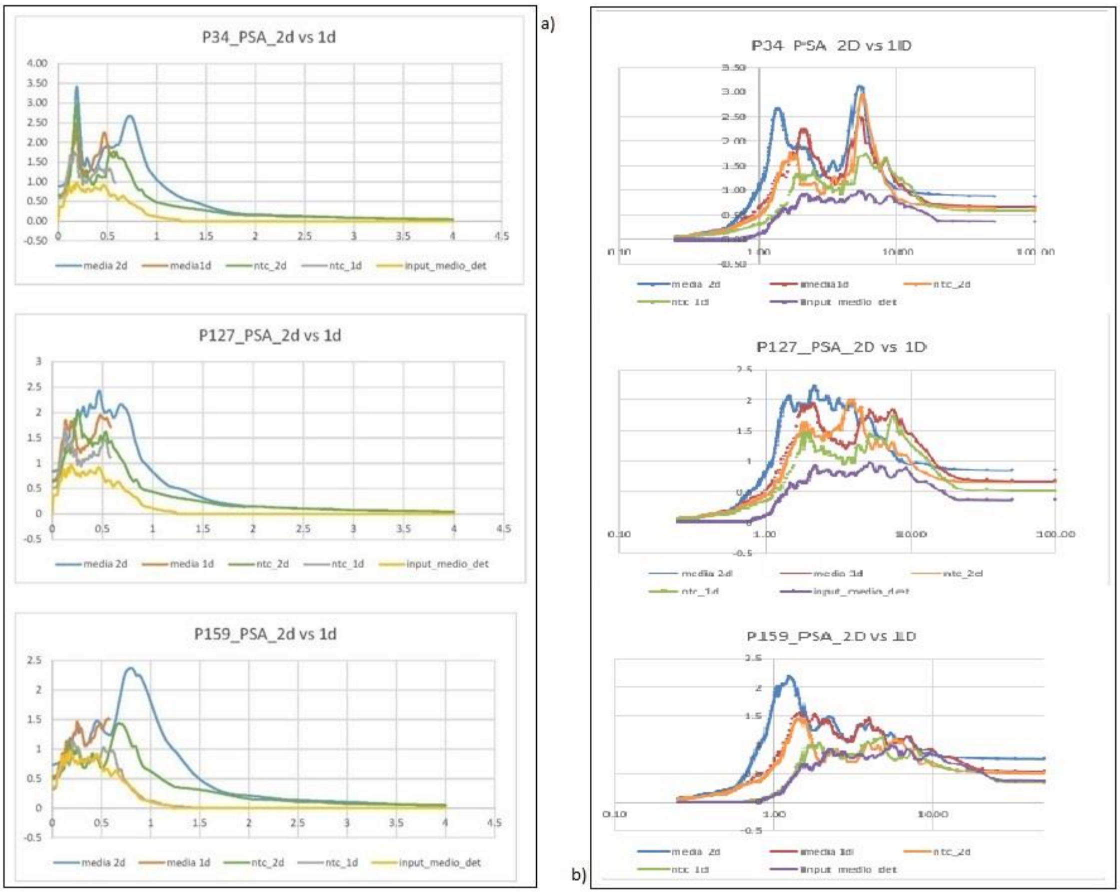

Fig. 3 - Comparison of the output PSA response spectra obtained with 1D and 2D numerical modeling as a function of the period (column a) and the frequency (column b) for the three analysed sites (P34, P127, P159). Red curve refers the average output DET_1, DET_2, DET_3 obtained with 1D modeling. Blue curve refers the average output obtained with 2D modeling. Gray and green curves respectively indicate the output obtained with 1D and 2D modeling by using the NTC input spectrum. Yellow curve indicates the average input DET_1, DET_2, DET_3 imposed on the bedrock (Gruppo di Lavoro MS-AQ, 2010).