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Construction of a Level 2 microzonation abacus to evaluate local amplifications for the peri-Adriatic area in the Abruzzo region (Italy)

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ABSTRACT The paper illustrates the construction of abacuses for the semi-quantitative assessment of stratigraphic seismic amplification phenomena, applicable in the eastern Abruzzo region (central Italy). The abacuses provide three expected Amplification Factors (*Fas*): $Fa_{0.1\text{-}0.5}$, $Fa_{0.4\text{-}0.8}$, $Fa_{0.7\text{-}1.1}$, performed as the ratio between the integral of output and input, in the mentioned time intervals, considering the acceleration response spectra. The choice derives from the fact that these parameters are better correlated to the response of the buildings, characterised by their own different periods. To prepare the abacuses, a procedure was adopted that took into consideration the geological analysis of the area, the collection of all the available geophysical and geotechnical data, the choice of the seismic inputs representative of the seismic hazard, the identification of the main seismic stratigraphic sequences and the numerical analysis aimed at evaluating the *Fa*. The abacus consists of a series of tables prepared in order to take account of the stratigraphic variability in the area, as a function of the basic seismic hazard level and the vibration period interval to calculate the *Fa*. By knowing the stratigraphic and mechanical characteristics of the site and using the abacuses, the values of the *Fa* are obtained.

Key words: seismic microzonation, amplification factors, abacus, earthquake.

1. Introduction

In Italy, in the spirit of defining guidelines on which to hinge the Seismic Microzonation (SM) on the planning system of Regions and Municipalities (Aversa and Crespellani, 2016), guidelines and criteria to achieve SM have been standardised and published in Guidelines for the Seismic Microzonation - ICMS (Working Group ICMS, 2008, 2011; Moscatelli *et al.*, 2020) by the Conference of Italian Regions and Autonomous Provinces, and the Italian Civil Protection Department. In general terms, the Italian guidelines establish that the scale of implementation is 1:10,000 or greater and define three grades of approach to zonation. Level 1 is the preparatory level for the

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SM studies; it relies on collecting existing data, which are processed to divide the investigated area into qualitatively homogeneous zones from a seismic perspective. Level 2 is based on quick sub-soil exploration aimed at integrating existing data and introduces quantitative assessments of local seismic hazard via simplified methods; in Level 2 zoning for ground motion amplification, a simplified abacus can be used, and the results are expressed in terms of expected amplification factors (*Fa*s). In Italy, many regions have developed and adopted procedures to evaluate the *Fa*s using specific abacuses, among which the regions of Emilia Romagna (URL 1), Lazio (URL 2), Marche (URL 3), Liguria (URL 4), Toscana (URL 5), and Lombardia (URL 6) can be mentioned. Level 3 produces maps from the results of numerical analyses based on a detailed subsoil mechanical characterisation; this is done for areas characterised by high seismic hazard, soil and subsoil complexity, and instability and/or economic and social relevance (Pagliaroli, 2018; Pagliaroli *et al*., 2020; Pergalani *et al*., 2020).

The paper illustrates the procedure to prepare abacuses for the semi-quantitative evaluation of stratigraphic seismic amplification phenomena in Level 2 studies (Working Group ICMS, 2008, 2011), applicable in the Abruzzo area where the subsoil is formed mainly by the Mutignano formation (FMT). The construction of the regional abacus was carried out in accordance with the requirements of the ICMS but was adapted to the characteristics of the regional territory. Three expected *Fa*s have been calculated: $Fa_{0.1\text{-}0.5}$, $Fa_{0.4\text{-}0.8}$, $Fa_{0.7\text{-}1.1}$, performed as the ratio between the integral of output and input, in the mentioned time intervals, considering the acceleration response spectra (Presidenza del Consiglio dei Ministri, 2017). The choice derives from observing that these parameters are better correlated to the response of the buildings, characterised by their own different periods. The prepared abacuses can be used only for the evaluation of stratigraphic amplification phenomena and do not enable analysis of permanent instability phenomena.

The procedure for preparing the Level 2 regionalised abacuses entails the following fundamental steps:

- geological-stratigraphic characteristics of the area of application of the abacuses;
- choice of seismic inputs;
- choice of the numerical code;
- choice of the abacus structure;
- analysis of the data collected and identification of the seismic-stratigraphic sequences of analysis;
- numerical analyses;
- construction of abacuses;
- definition of thresholds and application of abacuses.

2. Geological-stratigraphic characteristics of the Abruzzo peri-Adriatic sector

The geological substrate of the Abruzzo peri-Adriatic sector consists of siliciclastic pelitic-arenaceous deposits of foredeep, passing vertically and laterally to shallow marine clays, sands, and shoreface conglomerates, represented by the FMT, which unconformably seal the structures of the Apennine chain and generally have parallel layers and sub-horizontal bedding (Fig. 1).

From the litho-stratigraphic point of view, the FMT shows, from bottom to top, different associations of facies that generally identify a trend of increase in grain size, from clays to sands and conglomerates, and of increase in thickness of the layers (coarsening/thickening upward). Based on the relationship between the various particle size fractions, in the 1:50,000 scale

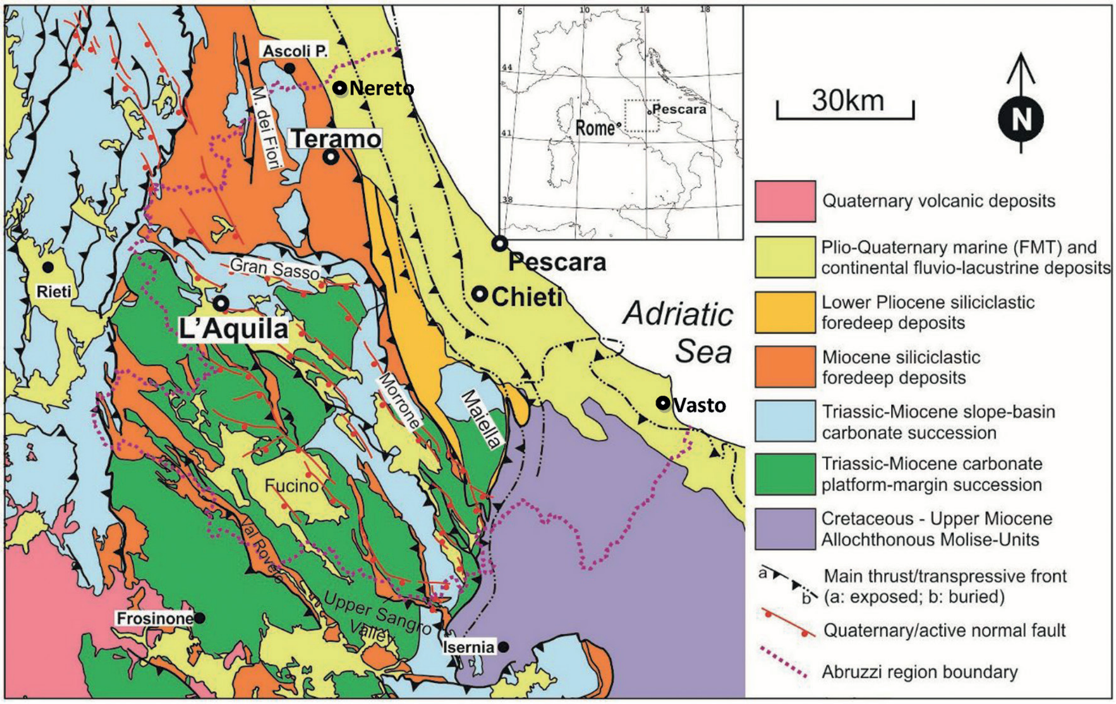


Fig. 1 - Geological-structural structure of the Abruzzo area (modified after Bigi *et al.*, 1992).

Geological Map of Italy, Sheet 361 Chieti (ISPRA, 2010b), the FMT has been divided into the following litho-facies associations:

- FMTa: pelitic-sandy association, consisting of grey-blue marly clays and thinly stratified silty clays with rare sandy levels and layers characterised by crossed structures and ripples, with abundant macrofossils such as gastropods, bivalves and corals; the sand to clay ratio is significantly lower than unity;
- FMTb: conglomeratic association, interlayered with the pelitic-sandy association, formed by well-cemented polygenic conglomerates, gravel levels, breccias and heterometric blocks in a clayey-silty matrix. The clasts are characterised by prevailing limestone and subordinate chert deriving from local carbonate successions;
- FMTc: sandy-pelitic association, which consists of an alternation of yellow silty sands and sands, with different degrees of cementation, and thinly laminated grey silty clays and clays; the thickness of the sandy layers increases, from bottom to top, passing from thin to medium and the sand to clay ratio is almost equal to 1 (generally less than 1 in the Teramo area, Fig. 1);
- FMTd: sandy-conglomeratic association, represented by a succession of yellowish sands and sandstones, frequently bioturbated, in medium to thick layers, alternating with lenses and layers of gravels and conglomerates formed by cm-sized calcareous and subordinate siliceous clasts. Both sands and conglomerates are typically organised in tabular sets and low-angle cross lamination can be observed. Symmetrical ripples and flaser-like stratification, typical of beach environments, are present in the sandy layers. Locally, there are mm- to cm-thick layers of grey pelite. Its thickness varies between 30 and 50 m;
- FMTe: sandy-pelitic association, consisting of yellowish sands and sandstones with medium-fine grain size, sand to clay ratio >> 1, thickness 0-120 m.

In the north Abruzzo sector, there is also an older member of the FMT named FMT1 of Middle Pliocene-Upper Pliocene age (e.g. Sheet 339 Teramo, of the 1:50,000 scale Geological Map of Italy, see Fig. 2), absent in the central-southern area due to a wide unconformity. Therefore, based on the ratio of coarse to fine-grained deposits, FMT1 can also be divided into:

- FMT1a: pelitic-sandy association, consisting of grey-blue marly clays and thinly stratified silty clays with rare sandy levels;
- FMT1b: conglomeratic association, clayey-sand and clay. The clasts are characterised by prevailing limestone (Fig. 2).

For seismic-stratigraphic purposes, the FMTc association is merged with FMTa due to the similar geological-technical characteristics. At the top of the FMT, an erosive surface marks the transition, in the Pleistocene, from a marine to continental environment, with the deposition of the Ripa Teatina unit (RPT). The RPT mainly crops out in the southern sectors of the Abruzzo region, often in correspondence of the reliefs at the watershed of the major rivers, where it

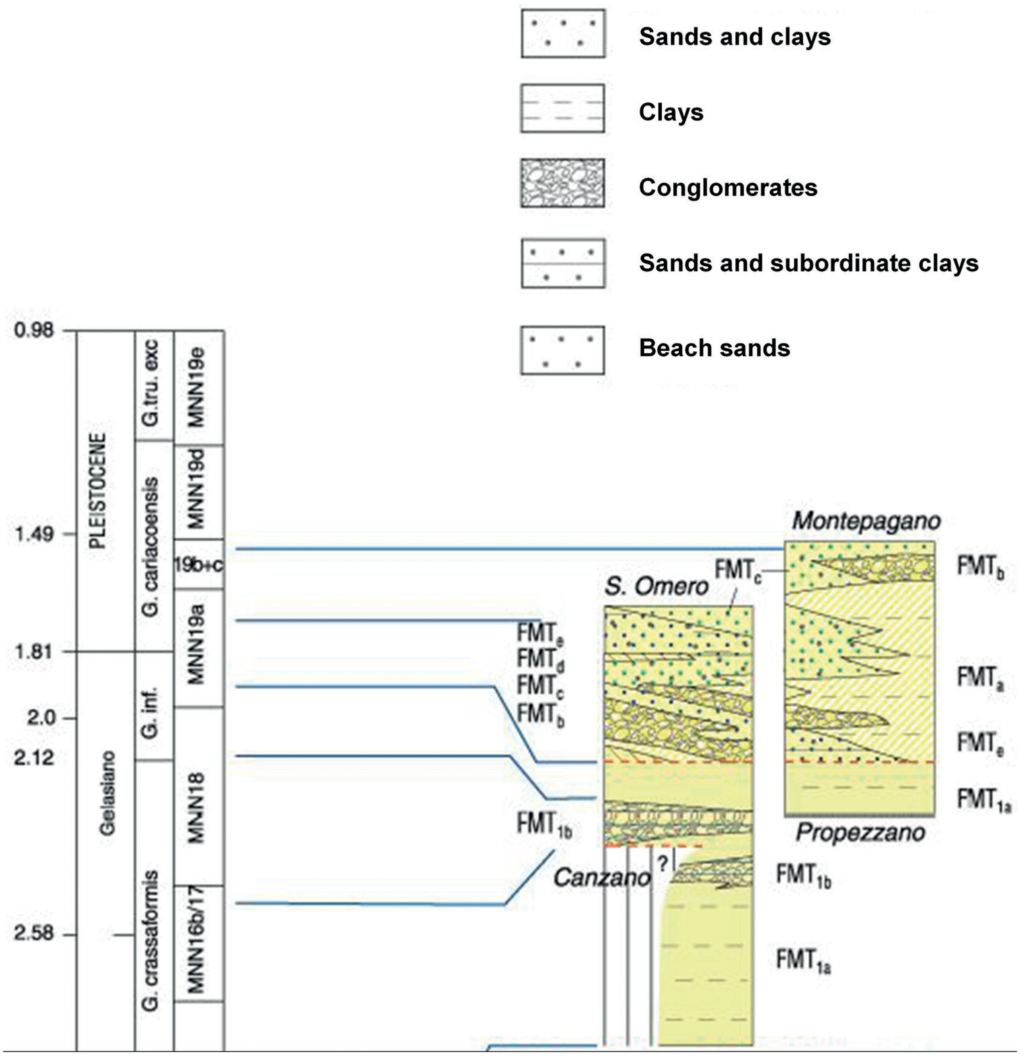


Fig. 2 - Extract from the Chrono-Stratigraphic Scheme of Sheet 339 Teramo, of the 1:50,000 scale Geological Map of Italy (ISPRA, 2010a), relating to the FMT, including the Canzano FMT1a and FMT1b members.

consists of fluvial-deltaic polygenic conglomerates, sometimes in sandy matrix, or sands and subordinately clays and silts of lagoon environment.

The Quaternary cover deposits crop out extensively throughout the peri-Adriatic area, formed mainly by fluvial sediments, alluvial fans, beach and, to a lesser amount, slope deposits.

Mostly based on the existence of morpho-lithostratigraphic and chronological relationships between the different orders of terraces, the lithofacies in the area can be distinguished as follows:

- Catignano Synthem (ACT), Middle Pleistocene;
- Majelama Valley Synthem (AVM), Upper Pleistocene;
- Holocene deposits (olo), Holocene.

The ACT mainly consists of heterometric conglomerates of alluvial origin, both grain-supported and, more rarely, matrix-supported; with lenses of fine sand and gravel levels. The upper part is deeply remodelled and eroded.

The AVM consists mainly of fluvial terraced deposits and for this reason it can be divided into three further sub-synthems. The AVMa sub-synthem consists of well-rounded clasts, in a silty sandy matrix, gravels and conglomerates. The thickness, organisation and lithology of the of the ACT and AVMa conglomerates, for the purpose of evaluating the amplification phenomena, are similar and attributed here to the same unit. The second sub-synthem (AVMb) consists of fluvial terraced sands and silts, with clay levels. The deposits of the third sub-synthem (AVMc) extensively crop out along the major alluvial plains. It is a mixed unit consisting of locally massive sands and silts in the upper part and coarse and very coarse gravels in the lower part.

The Holocene deposits are divided into fine- and coarse-grained lithofacies, referable to different genetic environments: the beach deposits are present continuously along the entire coast and are characterised by medium-fine sand, while the alluvial deposits are characterised by fluvial sands and gravels, with clays. The Holocene eluvial-colluvial deposits can directly overlay the beds of the marine succession (e.g. FMT) and/or the various continental Quaternary synthems and sub-synthems. They are distinguished by lithology because they consist of silts, sandy silts, clayey silts and are the product of the weathering of the clayey-sandy-conglomeratic deposits of the marine succession. At the base of the slopes and in correspondence with secondary valleys, they form wedges of deposits resting on the substrate, while thicknesses of several metres can be found as an eluvial layer, a ‘weathered formation’, above the ‘unweathered formation’.

The structure with undeformed layers and slopes very close to the horizontal of the FMT represents an almost unique condition compared to all other types of marine substrate emerging in Abruzzo. Due to this peculiarity, the FMT can be considered suitable, according to what is indicated in the ICMS, for the realisation of the regional abacus in the Levels 2 of seismic microzonation.

3. Choice of seismic inputs

To define the applied accelerograms in the numerical modelling aimed at constructing Level 2 abacuses, two representative sites of the minimum and maximum expected seismicity, considering a return period of 475 years, in the area of application of the abacuses, were chosen: Nereto (high seismicity) and Vasto (low seismicity). For each site, 7 registered accelerograms were chosen, appropriately scaled and modified, in order to make them compatible with the reference acceleration response spectrum expected in the sites and derived from technical code for the constructions NTC18 (Ministero delle Infrastrutture e Trasporti, 2018).

In detail, the compatibility between the average spectrum of registered accelerograms and the reference spectrum is defined in terms of -10/+30% of target ordinates in the period range 0.1-1.1 s.

The accelerogram choice was made by using the deaggregation obtained by the probabilistic seismic hazard analysis, following the approach used by Valentini *et al*. (2019), by employing the In-Spector software (Acunzo *et al*., 2014). To obtain the final spectrum-compatible accelerograms, the records were first scaled to the target *PGA* applying a constant scaling factor and records characterised by a scaling factor higher than 4 or lower than 0.25 were rejected. Moreover, the final selection was refined by applying additional preference criteria: only one component of the same recording station and events from Italian seismotectonic context.

The couple magnitude range/distance range was M_w 5.0-5.25/10-15 km for the Nereto site, and M_w 6.5-6.75/55-60 km for the Vasto site, and the selected accelerograms were obtained from the Itaca database (URL 7; Russo *et al*., 2022) using normal kinematics earthquakes and recordings at outcropping rock or very stiff soil (i.e. $V_{S30} \geq 700$ m/s) conditions.

The choice to use accelerograms compatible with the response spectra of the NTC18 was determined by the need to compare the *Fa*s values of the abacus with the corresponding thresholds of spectral acceleration (*Sa*) to evaluate the suitability of the amplification level obtained with the NTC18 compared to those suggested by the abacus. The *S* thresholds are defined as the ratio between the output integrals (subsoil category B-C-D-E) and input (subsoil category A) and calculated on the elastic acceleration response spectra derived from the NTC18.

Table 1 shows the list of selected accelerograms, for the two reference sites (Nereto and Vasto) and their scaling factor. Figs. 3 and 4 show the acceleration elastic response spectra at 5% of the critical damping of the single accelerograms, their average and the response spectrum expected for the sites (target) and referred to the subsoil category A (seismic bedrock) deriving from the NTC18.

Table 1 - List of selected accelerograms used in the analyses.

NERETO		
N° accelerogram	**Accelerogram label**	**Scaling factor**
1	Nereto_IT.AQP..HNE.D.IT-2009-0121	3.00
2	Nereto_IT.AQP..HNN.D.IT-2009-0121	3.25
3	Nereto_IT.AQP..HNN.D.IT-2009-0140	4.00
4	Nereto_IT.MTR..HNE.D.IT-2009-0084	4.00
5	Nereto_IT.VGG..HGE.D.IT-2012-0061	2.25
6	Nereto_IT.VGL..HGE.D.IT-2013-0005	4.00
7	Nereto_IT.VGL..HGN.D.IT-2013-0005	3.55
VASTO		
N° accelerogram	**Accelerogram label**	**Scaling factor**
1	Vasto_IT.AQK..HGE.D.EMSC-20161030_0000029	1.50
2	Vasto_IT.BNV..HNN.D.IT-1980-0012	2.54
3	Vasto_IT.GSA..HGN.D.EMSC-20161030_0000029	2.17
4	Vasto_IV.TRE1..HNE.D.EMSC-20161030_0000029	2.53
5	Vasto_IV.TRE1..HNN.D.EMSC-20161030_0000029	2.44
6	Vasto_MN.AQU..HLE.D.EMSC-20161030_0000029	3.76
7	Vasto_MN.AQU..HLN.D.EMSC-20161030_0000029	1.86

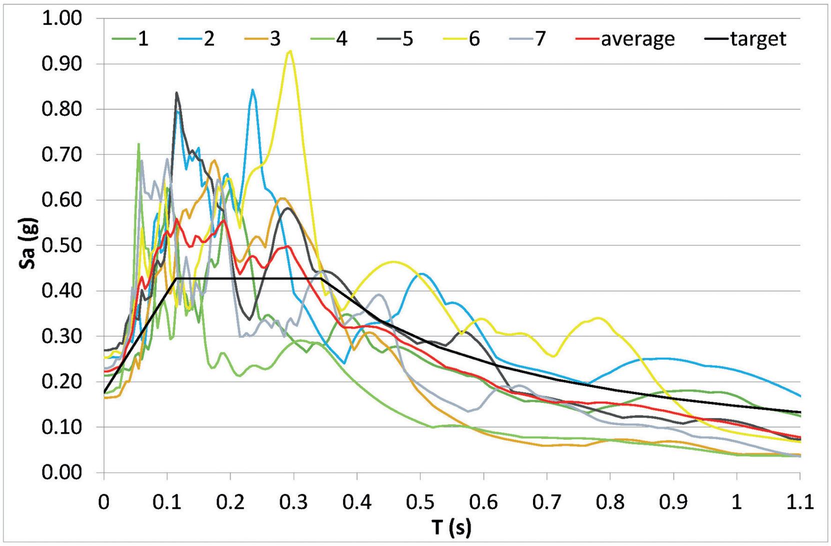


Fig. 3 - Acceleration response spectra of the single accelerograms, their average (red line), and the response spectrum NTC18 (black line) for the site of Nereto.

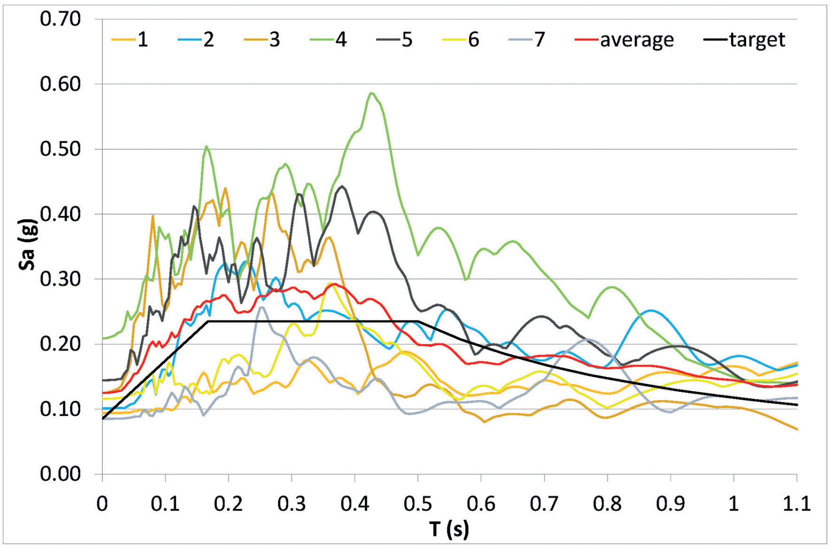


Fig. 4 - Acceleration response spectra of the single accelerograms, their average (red line), and the response spectrum NTC18 (black line) for the site of Vasto.

4. Choice of the numerical code

Concerning the objectives of this study, namely evaluating the seismic amplification for the lithological effects, a one-dimensional code was chosen, in particular STRATA (Kottke and Rathje, 2008), deriving from the SHAKE91 program (Idriss and Sun, 1992), which aims at analysing sites characterised by plane parallel layers, assuming the stratigraphy as laterally homogeneous.

The code uses the treatment of the stratified material to consider the vertical heterogeneity of the subsoil, using a continuous model. The physical model used is the one with continuous and homogeneous layers using the linearised viscoelastic Kelvin-Voigt behaviour and consists of *n* flat and parallel layers of infinite horizontal extension on a half-space corresponding to the seismic bedrock on which the input motion (S waves) is applied vertically: each layer is considered homogeneous and isotropic and is characterised by the thickness *h*, the density *r*, the initial shear modulus G_0 or shear wave velocity V_S and the initial damping ratio D_0.

The lower boundary (seismic bedrock) is considered deformable, to avoid the trapping, within the model, of the energy associated with the reflected waves and in order to take into account the loss of energy due to radiation or geometric damping; in fact, a perfectly rigid boundary completely reflects the waves at the surface, while in the case of a deformable boundary, part of the waves is transmitted into the underlying rock. Therefore, the code also requires the parameters of the seismic bedrock, that is the density r, the velocity of the S waves and the damping ratio *D* (considered constant), used to calculate the rock-soil seismic impedance contrast.

The program adopts the equivalent linear analysis to consider, in the solution of the dynamic equilibrium of the system, the non-linear behaviour: this analysis consists of running a sequence of complete linear analyses with subsequent updating of the stiffness and damping parameters until predetermined convergence criteria are satisfied. The calculation process is, therefore, iterative and operates in the frequency domain, using Fourier analysis; for each iteration or cycle the motion of the entire system is calculated.

5. Choice of the abacus structure

The basic structure of the regionalised abacuses reflects that expected in the ICMS.

The two input parameters of the regionalised abacuses are: the depth of the base substrate *H* and the equivalent average velocity V_{SH}, calculated with the following formula:

$$Vs_H = \frac{H}{\sum_{i=1}^{n} \frac{h_i}{Vs_i}} \qquad (1)$$

where:

V_{SH} = equivalent average velocity;
H = bedrock depth;
h_i = thickness of i-unit;
V_{Si} = velocity of *S* waves of i-unit;
n = number of units.

In the Level 2 abacuses, the values of the input parameters *H* and V_{SH} are generally discretised with steps of 5-10 m for *H* and 50-100 m/s for V_{SH}.

The output parameter of the regionalised abacuses, which represents the expected seismic amplification, is given by *Fa* defined on the acceleration elastic response spectra (*Sa*) as the ratio between the output and input integrals calculated in the period intervals (*T*) between 0.1-0.5 s, 0.4-0.8 s, and 0.7-1.1 s, considering a critical damping (ϑ) of 5%. These intervals, as mentioned, have been defined as representative of 3 different behaviours of the buildings according to their period of vibration, as proposed by the Ordinance n. 24 of 12 May 2017 following the seismic events of 2016-2017 (Presidenza del Consiglio dei Ministri, 2017; Moscatelli *et al*., 2020; Pagliaroli *et al*., 2020; Pergalani *et al*., 2020).

Stratigraphic, geophysical, and geotechnical data are required to carry out the numerical analyses; in particular, the values of thickness, density ρ, velocity V_S, the initial damping ratio D_0 and the relative decay curves of the normalised shear modulus G/G_0, and of damping ratio D, with the deformation γ, are required for each geophysical unit.

Within the study area, all available geophysical and geotechnical investigations have been collected, namely borehole stratigraphy, penetrometric tests, geophysical investigations (DH, MASW, seismic refraction), laboratory tests (index properties, granulometry, shear tests, oedometric tests), which have been archived and analysed and which have made it possible to identify the following seismic-stratigraphic sequences (Fig. 5).

The FMTa is present in all sequences as a basic litho-stratigraphic unit. Moreover, passive geophysical surveys (Boncio *et al*., 2011) indicate that within this formation, at a depth of about 150 m, values of V_S = 800 m/s are reached. The seismic bedrock was therefore defined at a depth of 150 m with V_S values of 800 m/s, which was extrapolated to all the seismic-stratigraphic sequences and was used for all the numerical modelling carried out on the various seismic-stratigraphic sequences, grouped in the typical sequences of Fig. 5, where the stratigraphy, the thicknesses, and the velocity values are reported.

As regards the non-linear behaviour of the materials, in terms of decay curves of the normalised shear modulus G/G_0 and of the damping ratio D with the shear strain γ, due to the lack of laboratory tests on specific samples of the deposits present in the area, we referred to decay curves available in the literature and considered representative of the lithology of interest (Table 2); the abbreviations shown refer to the legends of the 1:50,000 scale Geological Map of Italy (ISPRA, 2007), except for 'eluvium-colluvium'.

Table 2 - List of abbreviations, lithology and decay curves.

Abbreviation	Lithology	Decay curve
Olo	alluvial gravels	mean curves by Rollins *et al.* (1998)
RPT	Ripa Teatina unit, gravelly	
AVMa	Valle Maielama Synthem - type a, gravelly	
ACT	Catignano Synthem, gravelly	
FMTd	Mutignano Formation - type d, gravelly	
eluvium-colluvium	Silty materials	Offida S2C1 sample taken at a depth of 4 m (Centro MS, 2017)
AVMb	Valle Maielama Synthem - type b, silty	
shallow FMTa	Mutignano Formation - type a, silty	Teramo S1C1 sample taken at a depth of 6.6 m (Centro MS, 2017)
deep FMTa	Mutignano Formation - type a, silty	Castel di Lama S1C2 sample taken at a depth of 20 m (Centro MS, 2017)
AVMc	Valle Maielama Synthem - mixed	mean curves by Rollins *et al.* (1998); Offida S2C1 sample taken at a depth of 4 m (Centro MS, 2017)

Regarding the decay curves assigned to the deep FMTa, it should be noted that the test was carried out on material taken at a depth of 20 m by applying a confining pressure of the order of 250 kPa (Foti, 2017). This is the highest value, for this lithology, among those available within the Level 3 of Seismic Microzonation studies of the municipalities affected by the seismic events of 2016-2017 (Centro MS, 2017).

The selected samples were found to be compatible in terms of lithology and V_S with the analysed lithologies and derive from the analyses conducted in the context of Seismic Microzonation studies following the 2016-2017 events in central Italy (Centro MS, 2017). Figs. 6 and 7 show the decay curves of the normalised shear modulus G/G_0 and of the damping ratio D with the shear strain γ used.

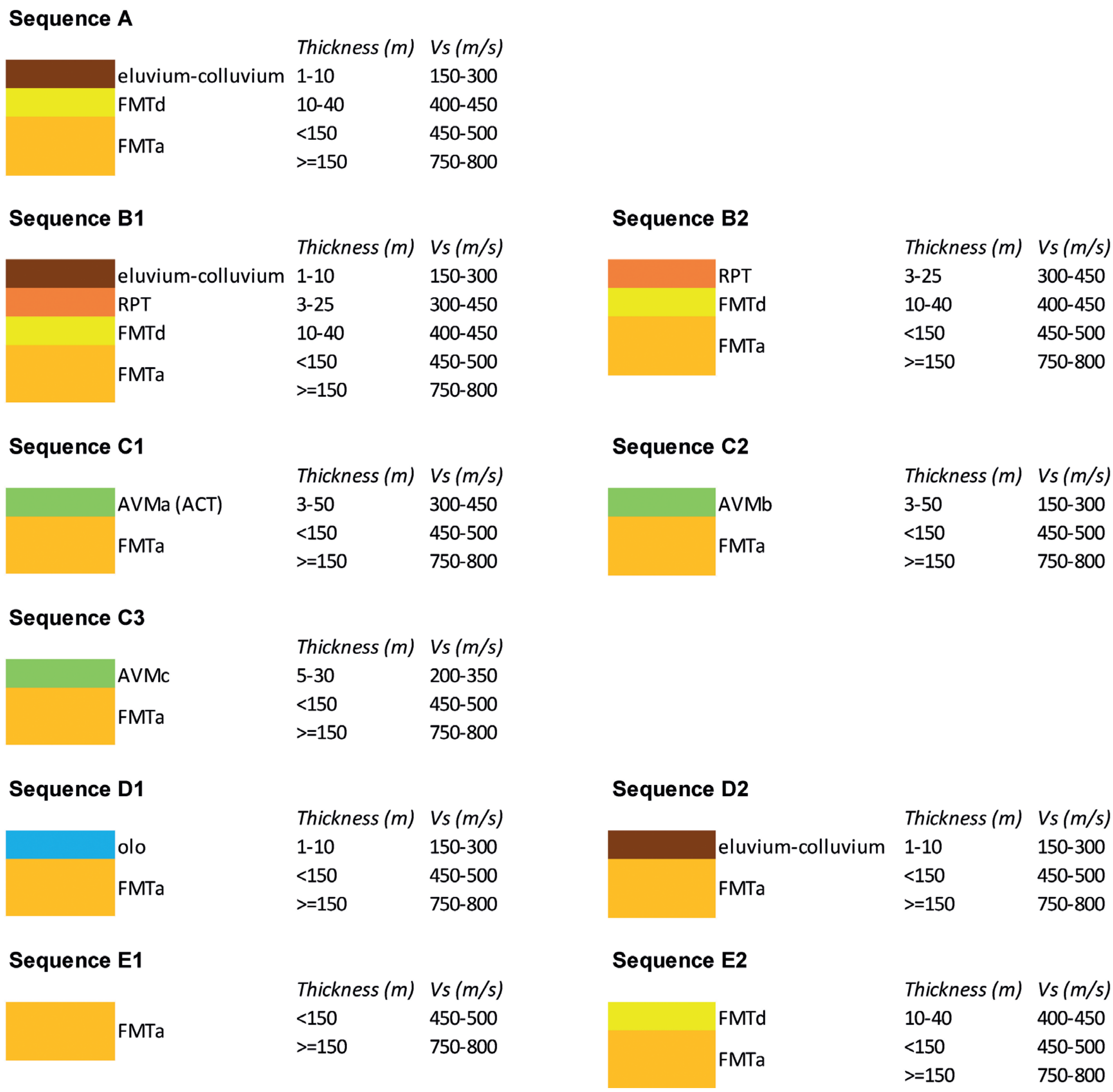


Fig. 5 - Analysed seismic-stratigraphic sequences.

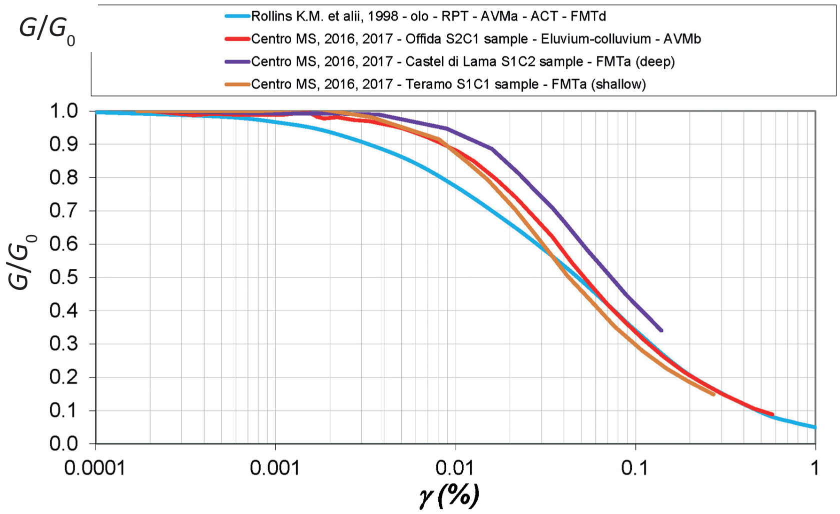


Fig. 6 - Decay curves of the normalised shear modulus G/G_0 with the shear strain γ.

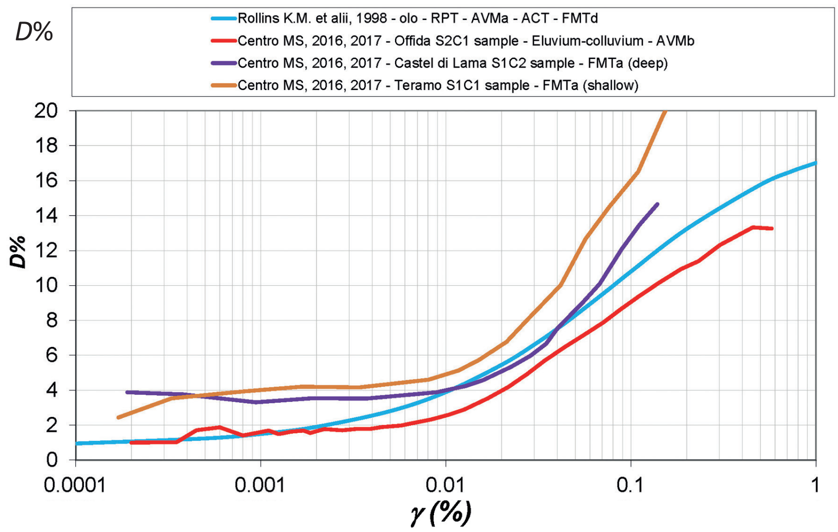


Fig. 7 - Decay curves of the damping ratio *D* with the shear strain γ.

6. Numerical analyses

Based on the above data, numerical analyses were performed using the chosen code and applying the two sets of selected accelerograms (2×7 accelerograms) to each stratigraphic sequence. For each stratigraphic sequence, using a deterministic approach, the thickness *h* and the velocity V_S of each geophysical unit were modified considering the relative variability.

The number of analyses for each stratigraphic sequence was variable according to the trend of V_S value with depth, and the thickness and number of geophysical units present in the sequence. In particular, for the sequences with higher variability and with a greater number of units, the number of analyses was higher than for those with less variability and with a smaller number of units.

For each stratigraphic sequence, therefore, different stratigraphic columns were identified, which were analysed and defined in terms of the V_{SH}-H couple; the results of the analyses are expressed in terms of the Factor *Fa*. For the construction of the abacuses, to each stratigraphic column, analysed applying the different accelerograms, was assigned the average value of *Fa.* This was calculated as the arithmetic average between the *Fa* deriving from the application of the seven accelerograms constituting each set and between the average *Fa* of the two sets of accelerograms used.

The observation of the average values of *Fa* has shown a substantial similarity between those obtained from the application of the more energetic accelerometric set (Nereto) and those obtained from the application of the less energetic accelerometric set (Vasto): the differences can be quantified in the order of 10-20% on the values of *Fa*, with only a few exceptions linked to the particularity of the stratigraphic column analysed (for example, high thicknesses of material at low velocity). Therefore, it was legitimate to analyse the results in a single database in order to obtain Level 2 abacuses, that are not dependent on the seismic hazard and therefore valid for the entire territory of application of the abacuses.

The analyses conducted on the various stratigraphic columns show expected shear strain levels g concentrated in the 0.01-0.05% range, which can be considered relatively low, and in any case, compatible with the equivalent linear approach implemented in the code.

7. Construction of the abacus

The first abacus concerned the seismic-stratigraphic sequence E1, which represents the 'base substrate' with the definition of the relative values of the *Fa*. A series of numerical analyses were then conducted within each seismic-stratigraphic sequence considered, by varying the velocity and thickness of the units above the 'base substrate'.

The decision to build Level 2 abacuses on the basis of the same structure proposed by the ICMS constrained using only two input parameters: V_{SH} (equivalent average velocity) and H (thickness of the sequence above the 'base substrate'). It should be noted that the same couple of V_{SH}-H can be generated by different combinations of thicknesses h and velocity V_s of the geophysical units constituting the stratigraphic column, to which different values of *Fa* correspond.

To obtain a two-parameter correlation between the value of *Fa* and the couple of values V_{SH}-H, the parameter T was introduced, the period of the stratigraphic column above the 'base substrate' defined as follows:

$$T = \frac{4\sum_{i=1}^{n} h_i}{\frac{\sum_{i=1}^{n} Vs_i h_i}{\sum_{i=1}^{n} h_i}} \qquad (2)$$

where:

T = dominant period of the stratigraphic column;
h_i = thickness of the i-unit;
V_{Si} = velocity V_S of the i-unit;
n = number of the units.

Each stratigraphic column analysed was, therefore, represented not only by the relative V_{SH}-H couple, but also by the T parameter and the relative *Fa* parameter. The *T-Fa* graphs were then performed, and different correlations were identified using polynomial functions of different order. These curves have been discretised with stepped curves with a step of *Fa* of 0.1, and, hence, the abacuses have been made by associating the different values of *Fa* to the corresponding values of the V_{SH}-*H* couple, of the sequences above the 'base substrate'.

Starting from the stratigraphic sequence E1, characterised by the presence of FMTa and which identifies the 'base substrate' for all the stratigraphic sequences, the numerical analysis was carried out considering the variability of the trend of the V_S with the depth, as represented in Fig. 8; in this case, the V_S of seismic bedrock was varied between 800 and 1100 m/s.

The results of the analyses in terms of *Fa*, are located in a limited interval of period *T* between 0.9-1.1 s, without showing a specific trend, therefore, for this sequence, a single representative value has been calculated corresponding to the average value of *Fa.*

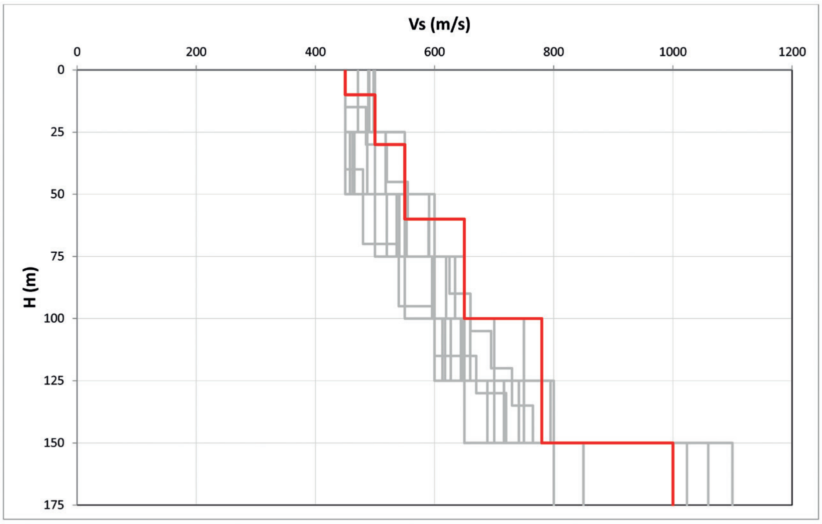


Fig. 8 - Variability of the V_S values with the depth *H* for the sequence E1 used in the analysis (the red line represents the behaviour of the sequence E1 applied in the numerical analyses of the other sequences).

The performed analysis identified the three different values of $Fa_{0.1\text{-}0.5}$, $Fa_{0.4\text{-}0.8}$, $Fa_{0.7\text{-}1.1}$, which are shown in Table 3, and represent the average value of all the performed analyses.

Table 3 - Values of the *Fas* for the sequence E1.

SEQUENCE E1	
$Fa_{0.1\text{-}0.5}$	1.2
$Fa_{0.4\text{-}0.8}$	1.4
$Fa_{0.7\text{-}1.1}$	1.6

For the other stratigraphic sequences, the analysis enabled identifying the stratigraphic columns in relation to the variability V_S and thickness *h* of the individual geophysical units, calculation of the dominant period *T* of the stratigraphic column, numerical analysis, identification of the trend line *T-Fa*, discretisation of the curve (abacus correlation) and construction of the corresponding abacus in terms of V_{SH} and depth H from the ground level to the top of the FMTa formation (base substrate), which is characterised by a total thickness of 150 m and is differentiated in the layers reported in Table 4, according to the average values of the sequence E1 and V_S of seismic bedrock equal to 1000 m/s.

Table 4 - Subdivision and characteristics of the layers of the sequence E1.

Layer of the 'base substrate'	Thickness (m)	Unit weight (kN/m³)	V_S (m/s)	Decay curve
1	25	21	450	Teramo S1C1
2	25	21	500	Castel di Lama S1C2
3	25	21	550	Castel di Lama S1C2
4	25	21	600	Castel di Lama S1C2
5	25	21	650	Castel di Lama S1C2
6	25	21	700	Castel di Lama S1C2
Seismic bedrock	-		1000	Linear *D*=0.5%

The scheme for each stratigraphic column for the numerical analyses is shown in Fig. 9.

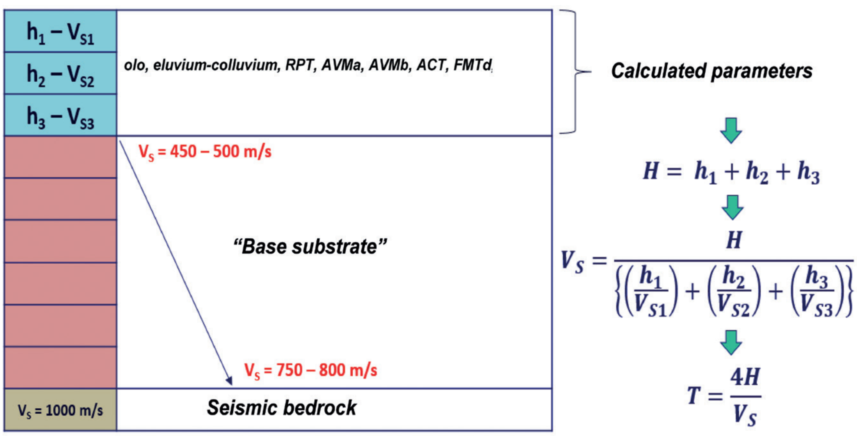


Fig. 9 - Scheme of each analysed stratigraphic column.

The stratigraphic units above the 'base substrate' can consist of a single unit (sequences E2 - D1 - D2 - C1 - C2), of two units (sequences C3 - B2 - A) and of three units (sequence B1), and are characterised by different variability in terms of thickness and V_S.

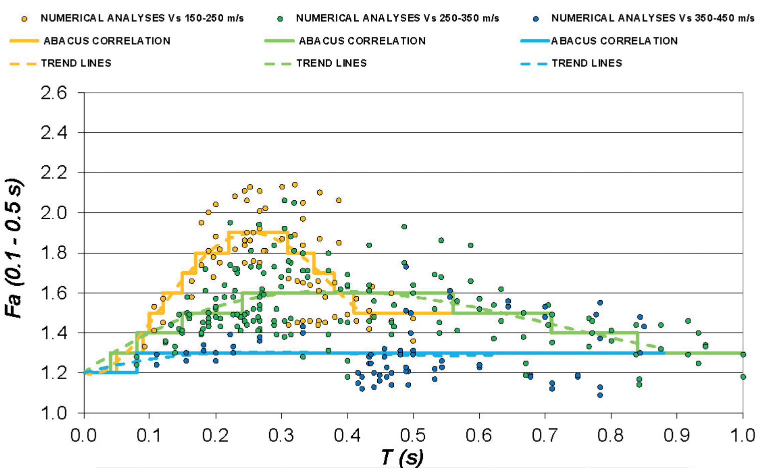
Each unit constituting the stratigraphic sequence was organised for the numerical analyses in n layers of thickness hn and V_{Sn}, from which the parameters H and V_{SH} were calculated as equivalent average.

Each abacus provides values of *Fa*, approximated to the first decimal number, which may be greater than or equal to the respective value provided for the 'base substrate' (sequence E1). The abacus requires as input data the thickness and the equivalent average velocity of the stratigraphic sequence above the 'base substrate'; therefore, its application requires the identification of the depth to the FMTa unit top.

For sequences E2 - C1 - C2 - D1 - D2 - B2, in which the stratigraphic sequence above 'base substrate' has values of $V_S \geq 300$ m/s or has values of $V_S < 300$ m/s but with thicknesses less than 15 m, the dispersion of the values in the graph *T-Fa* is contained and well-described by a single trend line.

On the contrary, for the sequences C3 - B1 - A, the dispersion of the values in the *T-Fa* graph is greater and requires the use of multiple trend lines, a function of the value of V_{SH}.

As an example, Fig. 10 shows the procedure and the abacus inherent in the sequence B1 for the value of $Fa_{0.1\text{-}0.5}$, particularly the graphs *T-Fa*, the tables of the values of the dominant period



T	Average *Vs* Eluvium-colluvium, RPT, FMTd VsH (m/s)				
Thickness Colluvum-eluvium, RPT, FMTd H (m)	200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
15	0.30	0.24	0.20	0.17	0.15
20	0.40	0.32	0.27	0.23	0.20
25	0.50	0.40	0.33	0.29	0.25
30	0.60	0.48	0.40	0.34	0.30
35		0.56	0.47	0.40	0.35
40		0.64	0.53	0.46	0.40
45		0.72	0.60	0.51	0.45
50		0.80	0.67	0.57	0.50
55		0.88	0.73	0.63	0.55
60			0.80	0.69	0.60
65			0.87	0.74	0.65
70			0.93	0.80	0.70
75			1.00	0.86	0.75

SEQUENCE B1

$Fa_{0.1\text{-}0.5}$	Average *Vs* Colluvum-eluvium, RPT, FMTd VsH (m/s)				
Thickness Colluvum-eluvium, RPT, FMTd H (m)	200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
15	1.9	1.6	1.5	1.3	1.3
20	1.6	1.6	1.6	1.3	1.3
25	1.5	1.6	1.6	1.3	1.3
30	1.5	1.6	1.6	1.3	1.3
35		1.5	1.6	1.3	1.3
40		1.5	1.6	1.3	1.3
45		1.4	1.5	1.3	1.3
50		1.4	1.5	1.3	1.3
55		1.3	1.4	1.3	1.3
60			1.4	1.3	1.3
65			1.3	1.3	1.3
70			1.3	1.4	1.3
75			1.3	1.4	1.3

Fig. 10 - Graph *T-Fa*, table of values *T* with the identification of the values of *Fa*, abacus $Fa_{0.1\text{-}0.5}$ for the sequence B1.

T in relation to V_{SH}-*H* (the different colours identify the periods of discretisation of the curve *T-Fa*), the identification of the values of *Fa* according to the discretization of the curve *T-Fa* and the final abacus in terms of V_{SH}-*H.*

In this case, given the low values of V_S in the surface geophysical unit and the high total thicknesses of the sequence, it was necessary to divide the obtained results from the analyses into three different groups in relation to the values of V_{SH} (150-250, 250-350, and 350-450 m/s), consequently using three different trend lines and their discretisation. The graph shows these curves and in the table of the periods, in different colours, the attributions of the periods to the different trend lines and their discretisation are shown.

In the Appendix, the abacuses for all the sequences are reported.

8. Definition of thresholds and application of abacuses

For all the municipalities of the Abruzzo region, the thresholds $Sa_{0.1\text{-}0.5}$, $Sa_{0.4\text{-}0.8}$ and $Sa_{0.7\text{-}1.1}$ have been calculated, defined as the ratio between the output integrals (subsoil category B-C-D-E) and input (subsoil category A) in the intervals between 0.1-0.5, 0.4-0.8, and 0.7-1.1 s and calculated on the elastic acceleration response spectra derived from the NTC18. Therefore, for each municipality, four different threshold values are provided referring to each category of subsoil other than A. The comparison between the value of *Fa* derived by the abacuses and the value of *Sa* allows defining the areas in which, during the planning phase, Level 3 of seismic macrozonation is required, and local seismic response studies during the design phase should be used, excluding the application of the simplified approach proposed in the NTC18. In particular, these areas are identified as those areas in which the value of *Fa* exceeds the value of *Sa*; this comparison must consider the nature of the semi-quantitative approach, through a tolerance of 0.1, i.e. 'overruns' of maximum 0.1 are allowed.

9. Conclusions

The paper illustrates the construction of abacuses for the semi-quantitative assessment of stratigraphic seismic amplification phenomena in the context of Level 2 microzonation studies (Working Group ICMS, 2008), applicable in the Abruzzo area where the thick clayey succession of the FMT, overlaid by cover deposits of different thickness and nature (alluvium, eluvium-colluvium, slop-derived, and beach deposits) is mainly present.

The Level 2, based on an intermediate level of sub-soil geophysical characterisation, introduces quantitative assessments of local seismic hazard via simplified methods; in Level 2 zoning for ground motion amplification, a simplified abacus is used, and the results are expressed in terms of expected *Fa*s.

The creation of the regional abacuses was carried out in accordance with the Guidelines for Seismic Microzonation (Working Group ICMS, 2008), with adaptation to the characteristics of the regional territory. In particular, three expected *Fa*s have been calculated: $Fa_{0.1\text{-}0.5}$, $Fa_{0.4\text{-}0.8}$, $Fa_{0.7\text{-}1.1}$, performed as the ratio between the integral of output and input, in the mentioned period intervals, considering the acceleration response spectra.

The first abacus is related to the seismic-stratigraphic sequence E1, which represents the 'base substrate', with the definition of the relative values of the *Fa*. The other abacuses are related to the different sequences characterised by different units above the 'base substrate'.

By knowing the stratigraphic characteristics of the site and using the abacuses, the values of the expected *Fa* are obtained.

In addition, for all the municipalities of the Abruzzo region, the thresholds $Sa_{0.1\text{-}0.5}$, $Sa_{0.4\text{-}0.8}$ and $Sa_{0.7\text{-}1.1}$ have been calculated, defined as the ratio between the output integrals (subsoil category B-C-D-E) and input (subsoil category A), deriving from the NTC18.

The comparison between the value of *Fa* derived by the abacuses and the value of *Sa* allows defining the areas in which, during the planning phase, the study of Level 3 and the study of local seismic response are required during the design phase, excluding the application of the simplified approach proposed in the NTC18. In particular, these areas are identified as those areas in which the value of *Fa* exceeds the value of *Sa*.

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Appendix: Abacuses for all sequences

SEQUENCE E1	
Fa 0.1-0.5	1.2
Fa 0.4-0.8	1.4
Fa 0.7-1.1	1.6

SEQUENCE E2		
Fa 0.1-0.5		VsH (m/s)
H (m)		400 ≤VsH≤450
	5	1.2
	10	1.3
	15	1.3
	20	1.3
	25	1.3
	30	1.2
	35	1.2
	40	1.2

SEQUENCE E2		
Fa 0.4-0.8		VsH (m/s)
H (m)		400 ≤VsH≤450
	5	1.4
	10	1.4
	15	1.5
	20	1.5
	25	1.5
	30	1.5
	35	1.6
	40	1.6

SEQUENCE E2		
Fa 0.7-1.1		VsH (m/s)
H (m)		400 ≤VsH≤450
	5	1.6
	10	1.6
	15	1.6
	20	1.6
	25	1.6
	30	1.6
	35	1.7
	40	1.7

SEQUENCE C1				
Fa 0.1-0.5		VsH (m/s)		
H (m)		300 ≤VsH<350	350 ≤VsH<400	400 ≤VsH ≤450
	3	1.2	1.2	1.2
	5	1.3	1.3	1.2
	10	1.4	1.3	1.3
	15	1.4	1.4	1.4
	20	1.4	1.4	1.4
	25	1.3	1.4	1.4
	30	1.3	1.3	1.4
	35	1.2	1.3	1.3
	40	1.2	1.2	1.3
	45	1.2	1.2	1.2
	50	1.2	1.2	1.2

SEQUENCE C1				
Fa 0.4-0.8		VsH (m/s)		
H (m)		300 ≤VsH<350	350 ≤VsH<400	400 ≤VsH ≤450
	3	1.4	1.4	1.4
	5	1.4	1.4	1.4
	10	1.5	1.5	1.5
	15	1.6	1.5	1.5
	20	1.6	1.6	1.6
	25	1.6	1.6	1.6
	30	1.7	1.6	1.6
	35	1.7	1.7	1.7
	40	1.6	1.7	1.7
	45	1.6	1.6	1.7
	50	1.6	1.6	1.6

SEQUENCE C1				
Fa 0.7-1.1		VsH (m/s)		
H (m)		300 ≤VsH<350	350 ≤VsH<400	400 ≤VsH ≤450
	3	1.6	1.6	1.6
	5	1.6	1.6	1.6
	10	1.6	1.6	1.6
	15	1.6	1.6	1.6
	20	1.7	1.6	1.6
	25	1.7	1.7	1.6
	30	1.7	1.7	1.7
	35	1.8	1.7	1.7
	40	1.8	1.8	1.7
	45	1.9	1.8	1.8
	50	1.9	1.8	1.8

SEQUENCE C2				
Fa 0.1-0.5		VsH (m/s)		
		150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
H (m)	3	1.4	1.3	1.3
	4	1.5	1.4	1.3
	5	1.6	1.4	1.4
	6	1.7	1.5	1.4
	7	1.8	1.6	1.5
	8	1.8	1.7	1.6
	9	1.9	1.8	1.6
	10	1.8	1.8	1.7
	11	1.7	1.9	1.8
	12	1.6	1.9	1.8
	13	1.3	1.8	1.8
	14	1.2	1.8	1.9
	15	1.2	1.7	1.9

SEQUENCE C2				
Fa 0.4-0.8		VsH (m/s)		
		150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
H (m)	3	1.4	1.4	1.4
	4	1.5	1.4	1.4
	5	1.5	1.5	1.4
	6	1.7	1.5	1.5
	7	1.9	1.6	1.5
	8	1.9	1.7	1.5
	9	2.1	1.7	1.6
	10	2.2	1.9	1.7
	11	2.3	2.0	1.7
	12	2.3	2.1	1.9
	13	2.3	2.2	1.9
	14	2.2	2.3	2.0
	15	2.0	2.3	2.1

SEQUENCE C2				
Fa 0.7-1.1		VsH (m/s)		
		150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
H (m)	3	1.6	1.6	1.6
	4	1.6	1.6	1.6
	5	1.7	1.6	1.6
	6	1.7	1.6	1.6
	7	1.7	1.7	1.6
	8	1.8	1.7	1.7
	9	1.9	1.7	1.7
	10	2.1	1.8	1.7
	11	2.2	1.8	1.7
	12	2.4	1.9	1.7
	13	2.8	2.0	1.8
	14	2.8	2.1	1.8
	15	2.9	2.2	1.9

SEQUENCE C3						
Fa 0.1-0.5		VsH (m/s)				
		200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	5	1.4	1.3	1.2	1.2	1.2
	10	1.8	1.4	1.4	1.3	1.3
	15	1.9	1.6	1.5	1.3	1.3
	20	1.6	1.6	1.6	1.3	1.3
	25		1.5	1.6	1.4	1.4
	30			1.5	1.4	1.4

SEQUENCE C3						
Fa 0.4-0.8		VsH (m/s)				
		200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	5	1.4	1.4	1.4	1.4	1.4
	10	1.8	1.5	1.5	1.4	1.4
	15	2.3	1.7	1.6	1.5	1.4
	20	2.5	1.9	1.8	1.5	1.5
	25		2.2	2.0	1.6	1.5
	30			2.2	1.6	1.6

SEQUENCE C3						
Fa 0.7-1.1		VsH (m/s)				
		200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	5	1.6	1.6	1.6	1.6	1.6
	10	1.7	1.6	1.6	1.6	1.6
	15	2.0	1.7	1.6	1.6	1.6
	20	2.3	1.8	1.7	1.6	1.6
	25		2.0	1.8	1.6	1.6
	30			2.0	1.7	1.6

SEQUENCE D1-D2

$Fa_{0.1-0.5}$	VsH (m/s)		
H (m)	150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
3	1.4	1.3	1.3
4	1.5	1.4	1.3
5	1.6	1.4	1.4
6	1.7	1.5	1.4
7	1.8	1.6	1.5
8	1.8	1.7	1.6
9	1.9	1.8	1.6
10	1.8	1.8	1.7

SEQUENCE D1-D2

$Fa_{0.4-0.8}$	VsH (m/s)		
H (m)	150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
3	1.4	1.4	1.4
4	1.5	1.4	1.4
5	1.5	1.5	1.4
6	1.7	1.5	1.5
7	1.9	1.6	1.5
8	1.9	1.7	1.5
9	2.1	1.7	1.6
10	2.2	1.9	1.7

SEQUENCE D1-D2

$Fa_{0.7-1.1}$	VsH (m/s)		
H (m)	150 ≤VsH<200	200≤VsH<250	250≤VsH ≤300
3	1.6	1.6	1.6
4	1.6	1.6	1.6
5	1.7	1.6	1.6
6	1.7	1.6	1.6
7	1.7	1.7	1.6
8	1.8	1.7	1.7
9	1.9	1.7	1.7
10	2.1	1.8	1.7

SEQUENCE B1

$Fa_{0.1-0.5}$	VsH (m/s)				
H (m)	200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
15	1.9	1.6	1.5	1.3	1.3
20	1.6	1.6	1.6	1.3	1.3
25	1.5	1.6	1.6	1.3	1.3
30	1.5	1.6	1.6	1.3	1.3
35		1.5	1.6	1.3	1.3
40		1.5	1.6	1.3	1.3
45		1.4	1.5	1.3	1.3
50		1.4	1.5	1.3	1.3
55		1.3	1.4	1.3	1.3
60			1.4	1.3	1.3
65			1.3	1.3	1.3
70			1.3	1.4	1.3
75			1.3	1.4	1.3

SEQUENCE B1

$Fa_{0.4-0.8}$	VsH (m/s)				
H (m)	200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
15	2.2	1.7	1.7	1.5	1.5
20	2.5	1.8	1.8	1.5	1.5
25	2.3	1.9	1.9	1.5	1.5
30	2.1	2.0	1.9	1.5	1.5
35		2.0	2.0	1.5	1.5
40		2.1	2.0	1.5	1.5
45		2.1	2.0	1.5	1.5
50		2.0	2.1	1.5	1.5
55		2.0	2.1	1.5	1.5
60			2.0	1.6	1.5
65			2.0	1.6	1.6
70			2.0	1.6	1.6
75			1.9	1.6	1.6

SEQUENCE B1

$Fa_{0.7-1.1}$	VsH (m/s)				
H (m)	200 ≤VsH<250	250 ≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
15	2.0	1.7	1.7	1.6	1.6
20	2.3	1.8	1.7	1.6	1.6
25	2.5	1.9	1.8	1.6	1.6
30	2.5	1.9	1.9	1.6	1.6
35		2.0	1.9	1.6	1.6
40		2.1	2.0	1.6	1.6
45		2.1	2.0	1.6	1.6
50		2.1	2.1	1.6	1.6
55		2.1	2.1	1.7	1.6
60			2.1	1.7	1.7
65			2.1	1.7	1.7
70			2.1	1.8	1.7
75			2.0	1.8	1.7

SEQUENCE B2				
Fa $_{0.1\text{-}0.5}$		VsH (m/s)		
		300 ≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	15	1.4	1.4	1.4
	20	1.4	1.4	1.4
	25	1.3	1.4	1.4
	30	1.3	1.3	1.4
	35	1.2	1.3	1.3
	40		1.2	1.3
	45		1.2	1.2
	50		1.2	1.2
	55		1.2	1.2
	60		1.2	1.2
	65		1.2	1.2

SEQUENCE B2				
Fa $_{0.4\text{-}0.8}$		VsH (m/s)		
		300 ≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	15	1.6	1.5	1.5
	20	1.6	1.6	1.6
	25	1.6	1.6	1.6
	30	1.7	1.6	1.6
	35	1.7	1.7	1.6
	40		1.7	1.7
	45		1.6	1.7
	50		1.6	1.6
	55		1.5	1.6
	60		1.5	1.6
	65		1.5	1.5

SEQUENCE B2				
Fa $_{0.7\text{-}1.1}$		VsH (m/s)		
		300 ≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	15	1.6	1.6	1.6
	20	1.7	1.6	1.6
	25	1.7	1.7	1.7
	30	1.7	1.7	1.7
	35	1.8	1.7	1.7
	40		1.8	1.7
	45		1.8	1.8
	50		1.8	1.8
	55		1.8	1.8
	60		1.8	1.8
	65		1.8	1.8

SEQUENCE A						
Fa $_{0.1\text{-}0.5}$		VsH (m/s)				
		200≤VsH<250	250≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	10	1.8	1.5	1.4	1.2	1.2
	15	1.9	1.6	1.5	1.3	1.3
	20	1.5	1.6	1.6	1.4	1.3
	25	1.5	1.6	1.6	1.3	1.4
	30		1.6	1.6	1.3	1.3
	35		1.5	1.6	1.3	1.3
	40			1.6	1.3	1.3
	45			1.5	1.3	1.3
	50			1.5	1.3	1.3

SEQUENCE A						
Fa $_{0.4\text{-}0.8}$		VsH (m/s)				
		200≤VsH<250	250≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	10	1.8	1.6	1.5	1.5	1.5
	15	2.3	1.7	1.6	1.5	1.5
	20	2.5	1.9	1.7	1.5	1.5
	25	2.3	2.0	1.9	1.5	1.5
	30		2.1	2.0	1.5	1.5
	35		2.2	2.1	1.5	1.5
	40			2.2	1.5	1.5
	45			2.2	1.6	1.5
	50			2.2	1.6	1.6

SEQUENCE A						
Fa $_{0.7\text{-}1.1}$		VsH (m/s)				
		200≤VsH<250	250≤VsH<300	300≤VsH<350	350≤VsH<400	400≤VsH≤450
H (m)	10	1.7	1.6	1.6	1.6	1.6
	15	2.0	1.7	1.7	1.6	1.6
	20	2.3	1.8	1.7	1.6	1.6
	25	2.5	1.9	1.8	1.6	1.6
	30		2.0	1.9	1.6	1.6
	35		2.1	2.0	1.6	1.6
	40			2.1	1.6	1.6
	45			2.2	1.7	1.6
	50			2.2	1.7	1.7