A PROCEDURE FOR THE EVALUATION OF SEISMIC LOCAL EFFECTS IN LOMBARDIA (ITALY) FOR URBAN PLANNING

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ABSTRACT :

In the paper the application of a methodology for the evaluation of local effects in Lombardia Region (Italy) is shown. The purpose was to develop a procedure that may be easily repeated, to take into account local effects in urban planning. The procedure provides three levels of widening: the 1° level, a qualitative analysis, gives the identification of the areas characterized by the local effects. The 2° level, through a semi-quantitative analysis, gives, when the geologic, geophysical and geotechnical characteristics of a site are known, the possible level of the expected amplifications, using the performed correlation curves. The 3° level, characterized by a quantitative analysis, necessary in the case in which the application of the 2° level shows the inadequacy of the seismic code, gives the response spectra applying during the project design phase. Particularly the steps performed to have the correlation curves, of the 2° level, are shown. A series of geologic, geomorphologic and geotechnical analyses have been carried out, to identify the areas affected by site effects and to characterize the lithotechnical units. The expected seismic inputs have been calculated and numerical analyses using one-dimensional code, analyzing single soil column, and two-dimensional codes, working with boundary elements on sections, have been done. The results, in terms of elastic pseudo-acceleration spectra and amplification coefficients, provide some correlations between the geometric and geotechnical characteristics of the sites and the values of the amplification coefficients.

KEYWORDS: earthquake, numerical models, seismic local effects, amplification effects, planning, risk assessment

1. INTRODUCTION

The problem of the ground motion amplifications correlating with the site effects, during an earthquake, is well-known and different methods and approaches have been suggested to quantify these effects, using both numerical and experimental methods. In the case of experimental approaches, the evaluation of the amplifications is done through the analyses of the seismic registrations, that can be generated by strong earthquakes, by far earthquakes, by artificial sources and micro-tremors. These methods derive from the studies on the spectral analysis and on the method of spectral ratio and noise. In the case of numerical methods one-dimensional, two-dimensional and three-dimensional models can be used. Some of these models are very well tested, other are in a phase of testing. Clearly the choice of the methods and approaches, the working scale and the types of analyses depend on the objectives and goals of the work. In this case the objective was to give, to the Regional Government, a methodology that may be used repetitively at the level of urban planning, for this reason a procedure at different levels of widening has been pointed out.

2. PROCEDURE FOR THE EVALUATION OF THE SEISMIC LOCAL EFFECTS

The procedure consists in three levels of widening, the 1° and 2° levels are necessary in planning phase, while the 3° level is necessary, during the project design phase, in the case in which the application of the 2° level shows the inadequacy of the seismic code; the 3° level is necessary, also, for the instability scenarios.
The three levels are:

- 1° level is a qualitative approach and gives the identification of the areas characterized by the local effects, on the basis of the geologic, geomorphologic and geotechnical characteristics, using the Table describing the seismic hazard situations and the expected effects (Table 1). Starting from the geologic and geomorphologic maps of a site and using the Table 1, it is possible to perform the map of local seismic hazard, characterized by the individuation of the areas affected by amplification and instability phenomena.

- 2° level is a semi-quantitative analysis, in particular, on the basis of the map of local seismic hazard, of the geologic, geophysical and geotechnical characteristics and using the specific abacuses, the possible level of the expected amplifications could be evaluated. A series of specific abacuses have been performed in this project, the methodology to obtain them and their use are following described. The abacuses show the relationships between the values of the amplification coefficients and the geotechnical and geometric characteristics of the site. The results of the application of the 2° level allow the evaluation of the protection level of the seismic code. If the seismic code is not sufficient to take into account the real lithologic amplification of the site, the procedure provides the application of the 3° level.
- 3° level, characterized by a quantitative analysis, necessary during the project design phase, for the amplification scenarios in the case in which the application of the 2° level shows the inadequacy of the seismic code, and necessary for the instability and liquefaction scenarios. For the instability effects the analysis consists in the characterization of the landslides and in the quantification of the instability in static, pseudo-static and dynamic conditions. For the liquefaction effects the analysis consists in the geotechnical characterization of the soil and in the quantification of the potential level of liquefaction. Finally for the amplification effects the analysis consists in the quantification of the expected amplification using numerical or experimental analyses.

Table 1 Table of the seismic hazard situations and the relative expected effects

Code	Seismic Hazard Situation	Possible Expected Effects
Z1a	Recent landslides	Instability phenomena
Z1b	Ancient landslides	
Z1c	Zones affected by potential instability	
Z2	Saturated sands and clays	Liquefaction and permanent deformations
Z3a	Rocky cliffs	Ground motion amplifications due to morphological conditions
Z3b	Rocky ridges	
Z4a	Steep sloped valley filled with incoherent alluvium	Ground motion amplification caused by loose soil overlying a bedrock and showing high impedance contrast
Z4b	Slope deposits or talus cone	
Z5	Area affected by lithologic discontinuities	Differential behaviour

3. POINT OUT OF THE SPECIFIC ABACUSES USED IN THE 2° LEVEL

The methodology to obtain the specific abacuses for the evaluation of the amplification phenomena has been performed though the following steps:

- selection of the study area in the Region;
- redaction of the geologic and geomorphologic maps (1:5.000 scale);
- acquisition of the geotechnical and geophysical parameters;
- identification of the typical stratigraphic sequences and calculation of their dominant period; identification of the situations that can produce amplification effects due to morphologic condition such as rocky ridges and rocky cliffs;
- calculation of the expected seismic inputs in terms of elastic pseudo-acceleration response spectra and accelerograms;
- numerical analyses and choice of the amplification measures;
- implementation of the relationships between the values of the amplification coefficients and the geotechnical and geometric characteristics of the site.

3.1. Selection of the study area in the Region

The choice of the study area (Fig. 1) has been based on: the geologic and geomorphologic characteristics, the available data and the presence of the urban areas. Inside the study area geologic, lithologic and morphologic scenarios have been selected; in particular alluvial gravel deposits, glacial-lacustrine sandy silt deposits, eluvial and colluvial clay deposits and areas characterized by rocky cliffs and rocky ridges have been chosen.

3.2. Redaction of the geologic and geomorphologic maps

For each scenario the geologic and geomorphologic maps (one example is reported in Fig. 1) have been redacted (scale 1:5.000), using the available data and surveys. The geology of the areas is characterized by gravel, silt with sand and silt with clay deposits, the geologic bedrock is characterized by limestone and marl..

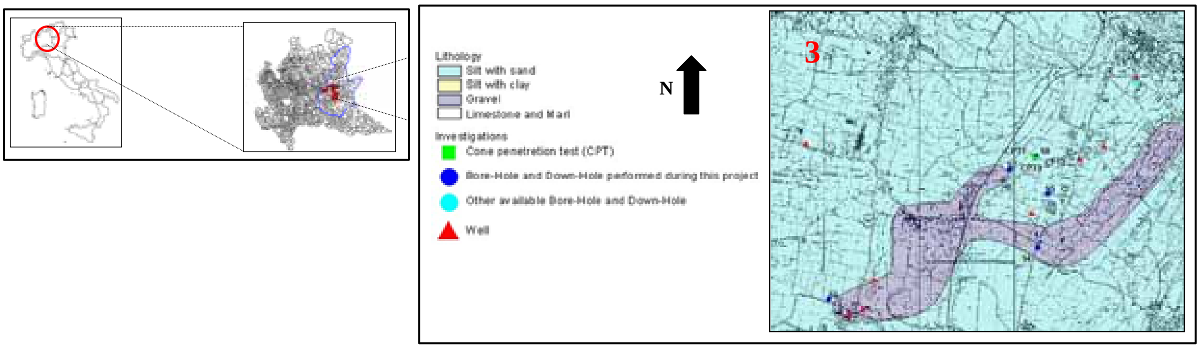


Fig. 1 Study area, lithologic map and location of the geotechnical site investigations

3.3. Acquisition of the geotechnical and geophysical parameters

The pre-existing geotechnical information have been collected and a series of new investigations have been done in the study areas: 8 bore-holes, 7 CPT tests, 5 SPT tests and 11 geotechnical laboratory tests, aimed to obtain the static and dynamic parameters, through soil characteristic tests, unconfined monotonic compression loading tests, monotonic loading triaxial tests, resonant column tests and cyclic loading torsional shear tests. In Fig. 1, for one of the test sites, the geotechnical site investigations are shown. The soil unit weigh (γ), the initial shear modulus (G_0), the initial damping ratio (D_0), the Poisson ratio (ν) and the relationships between shear modulus (G) and damping ratio (D) variation as a function of shear strain (γ), for each lithology, have been obtained through the geotechnical laboratory tests. In Table 2 the geotechnical parameters of the silt with clay and silt with sand deposits are reported and in Fig. 2 the relationships between shear modulus and damping ratio variation as a function of shear strain, for all the lithologies, are plotted: in particular for the gravel deposits the curves derive by Rollins (1998), for the silt with sand and silt with clay deposits the curves derive by the performed geotechnical analyses.
The pre-existing geophysical information have been collected and a series of new investigations have been done in the study areas: 7 down-holes aimed to obtain the velocity of shear (Vs) and longitudinal (Vp) waves. The values of the Vs at different depth (Z), for each lithology, are reported in Fig. 3. In particular, for the silt with sand and silt with clay deposits two behaviours of the shear waves velocity have been individuated, these behaviours have been used to identify two geophysical sequence types (type 1 and type 2). In the same Figure is, also, plotted the curve (black line) that represents the envelope of the different velocities obtained by the analyses.

Table 2 Main geotechnical characteristics

Parameter		Silt with clay	Silt with sand
Unit weight of soil	γ [kN/m^3]	19.5-20.0	18.5-19.5
Unit weight of solid particles	γ_s [kN/m^3]	25.7-26.7	26.0-27.9
Water content	w [%]	20-25	25-30
Liquid limit	w_L [%]	30-50	25-35
Plastic limit	w_P [%]	15-20	15-20
Plasticity index	I_P [%]	15-30	5-15
Void ratio	e	0.5-0.7	0.6-0.9
Degree of saturation	S_r [%]	90-100	90-100
Coefficient of earth pressure at rest	K_0	0.5-0.6	0.4-0.5
Compression index	C_c	0.15-0.30	0.10-0.30
Swelling index	C_s	0.02-0.06	0.03-0.05
Rate of secondary consolidation	C_a	0.001-0.005	0.002-0.006
SPT blow count	$Nspt$	15-30	0-20

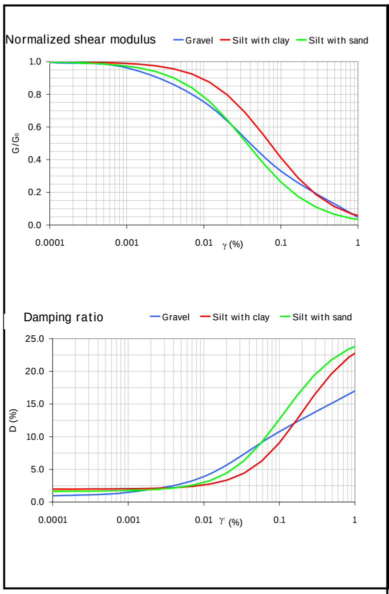


Fig. 2 Relationships between G/G_0 and D variation as a function of γ(%)

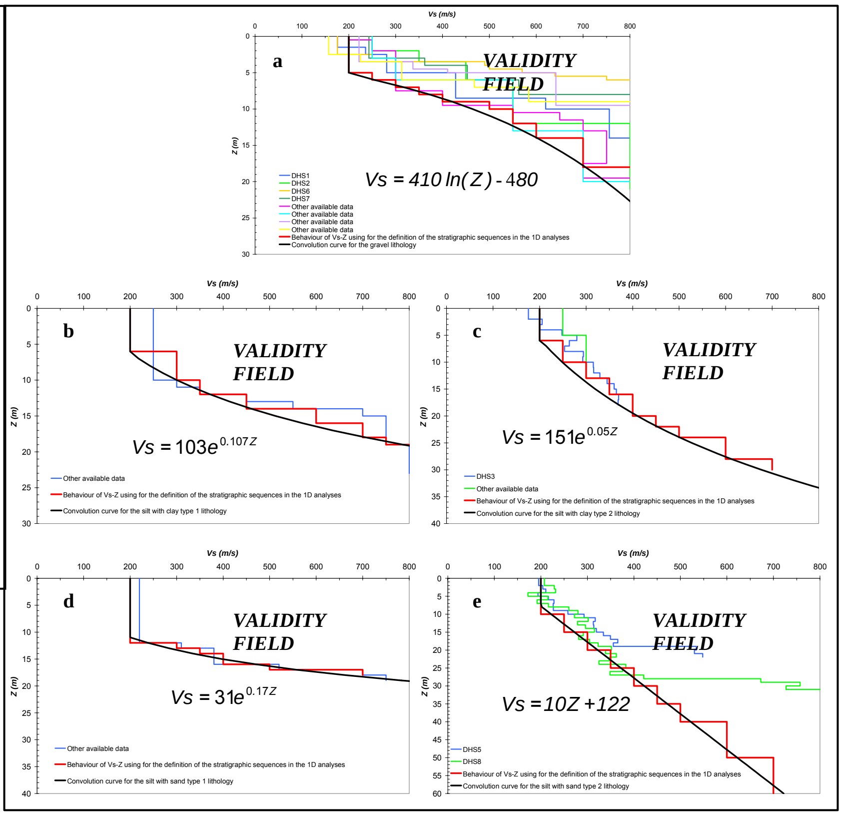


Fig. 3 Behaviour of the *Vs* at different depth (*Z*), respective envelope curves and validity field for each lithology: (a) gravel, (b) silt with clay type 1, (c) silt with clay type 2, (d) silt with sand type 1 and (e) silt with sand type 2

3.4. Identification of the typical stratigraphic sequences and morphologic condition

On the basis of the collected data, the geologic and geophysical 2D cross sections, relating to the complexity of the geologic and geomorphologic conditions, have been performed. The typical stratigraphic sequences, that can produce amplification effects due to lithologic conditions, on the basis of the lithology and the behaviour of the *Vs* at different depth, have been identified (Fig. 3 – red line). In particular five sets of sequences have been considered: gravel lithology, silt with clay lithology (type 1 and type 2) and silt with sand lithology (type 1 and type 2). For each lithology a series of geophysical sequences, varying the velocities and thickness, according to the collected data and to the envelope curves (Fig. 3 – black line), have been performed. For each sequence the dominant period has been calculated, using the following equation:

$$T = (4 \times \sum_{i=1}^{n} h_i) / ((\sum_{i=1}^{n} Vs_i \times h_i) / \sum_{i=1}^{n} h_i) \quad (3.4.1)$$

where *T* is the period, *Vs* and *h* are respectively the shear wave velocity and the thickness of the layer. The geophysical bedrock is reached when *Vs* is about 800 m/s, according to the Italian and European codes.
Using the geologic and geomorphologic maps, the situations that can produce amplification effects due to morphologic condition such as rocky ridges and rocky cliffs have been identified. Therefore a series of cliffs and ridges characterized by different morphological parameters as slope angle, length and height, have been selected.

3.5. Expected seismic input in terms of elastic pseudo-acceleration response spectra and accelerograms

For the definition of the seismic input a probabilistic approach has been adopted. On the basis of the expected maximum acceleration (a_{max}) in the Region, characterized by a return period of 475 years corresponding at 10% probability of being exceeded in 50 years, available from the Italian hazard map (Gruppo di lavoro 2004), two municipalities showing the lowest and highest values of a_{max}, have been chosen. The level of the seismicity for the Region can be considered as low-medium. For these municipalities the uniform pseudo-acceleration elastic response spectra, at 5% of critical damping, have been calculated applying the procedure reported in Gruppo di lavoro 2004. For each pseudo-acceleration elastic response spectrum three non-stationary accelerograms have been generated using the procedure proposed by Sabetta and Pugliese (1996). In Fig. 4 the uniform pseudo-acceleration elastic response spectra representing the highest and the lowest expected values of peak ground acceleration in the Region and two examples of the accelerograms used in the analyses are plotted.

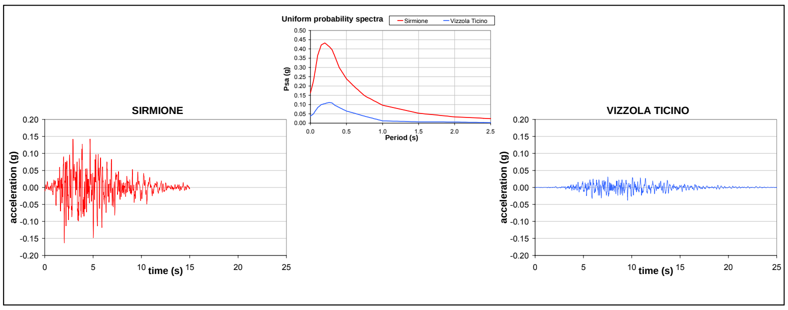


Fig. 4 Uniform pseudo-acceleration elastic response spectra and two examples of the accelerograms used in the analyses

3.6. Numerical analyses and choice of the amplification measures

One-dimensional (1D) and two-dimensional (2D) numerical analyses have been performed, in according to the geologic and geomorphologic conditions. In the case of stratigraphic sequences the 1D models have been applied, in the case of rocky ridges and rocky cliffs the 2D models have been used. The 1D numerical analyses have been performed using the code SHAKE91 modified (Idriss and Sun, 1992). The 2D analyses have been performed using a boundary elements method (ELCO, Callerio et al., 2000). For each situation, a series of elastic pseudo-acceleration response spectra are calculated; the spectral intensity (*SI*) (Housner, 1952) has been selected to represent the seismic amplification because it relates better to seismic structural behaviour than other ground motion parameters. Spectral intensity has been computed in the period ranges 0.1–0.5s and 0.5–1.5s:

$$SI_{0.1\text{-}0.5}(PSV) = \int_{0.1}^{0.5} PSV(T,\xi)dT \qquad SI_{0.5\text{-}1.5}(PSV) = \int_{0.5}^{1.5} PSV(T,\xi)dT \qquad (3.6.1)$$

where *PSV* are the pseudo-velocity spectral ordinates, *T* is the period and ξ is the damping, set to 5% of the critical damping. The spectral intensities were computed for the following seismic motions:

1. *SI* (input), spectral intensity of each reference spectrum;
2. *SI* (output), spectral intensity of each computed amplification spectrum. Then, the amplification coefficient (*Fa*) pertaining to local site conditions was defined on the basis of the ratio between the spectral intensity of output (*SI* output) and spectral intensity of input (*SI* input) (Pergalani et al., 1999; 2006).

The ranges 0.1-0.5s and 0.5-1.5s can be considered representative of the dominant period of the typical building of the area: the first range is representative of small, regular and rigid structures, the second of high and flexible structures.
Considering all the analyzed cases, some relationships between the values of the amplification coefficient (*Fa*) and the geotechnical and geometric characteristics of the site have been established, as a tool that allows to estimate the value of the *Fa*, in the case of availability of geologic and geotechnical data, without performing the analyses.

3.7. Specific abacuses of the amplification coefficients

In this section the most representative results, in term of *Fa* values, of the analyses are shown: the results obtained for the gravel lithology, silt with clay lithology and silt with sand lithology in the case of lithologic amplifications, and the results obtained for the rocky ridges and rocky cliffs in the case of morphologic amplifications.

3.7.1 Lithologic amplifications

The results of the analyses performed for each stratigraphic sequence have been plotted on a graph where the relationships between the values of amplification factor (*Fa*), in the two period ranges 0.1–0.5s and 0.5–1.5s, and the dominant period (*T*) of the sequences are shown (Fig. 5 – silt with clay). The results show a good correlation considering the period range 0.5-1.5s, instead the values considering the period range 0.1-0.5s present a scattering. This scattering has been eliminated grouping the couple values (*Fa*-*T*) in function of the value of the velocity of shear waves (*Vs*) and the thickness (*h*) of the surface layer, so three sets of data have been individuated. It is notice that the correlation coefficients (R^2), reported in the Figure, show a good fitting. For the period range 0.1-0.5s the choice of the curves is related to the value of the *Vs* and *h* of the surface layer, in Fig. 6, for the silt with clay lithology, the range of validity of each curve is shown. In particular the grey areas identify the situations in which the curves are not applicable, the areas characterized by black and white lines identify the situations in which the influence of amplification can be considered negligible due to the low thickness of the deposits and the numbered areas show the situations in which each curve can be considered appropriated.

Generally the influence on the results of the use of different accelerograms can be considered negligible: in fact the differences are limited in a variation of ± 0.1 of the *Fa* values. This behaviour can be explained considering the level of the shear strain at the end of the analyses, in fact, also applying the highest expected accelerograms, the reached level is low, showing a linear or not-linear stable behaviour.

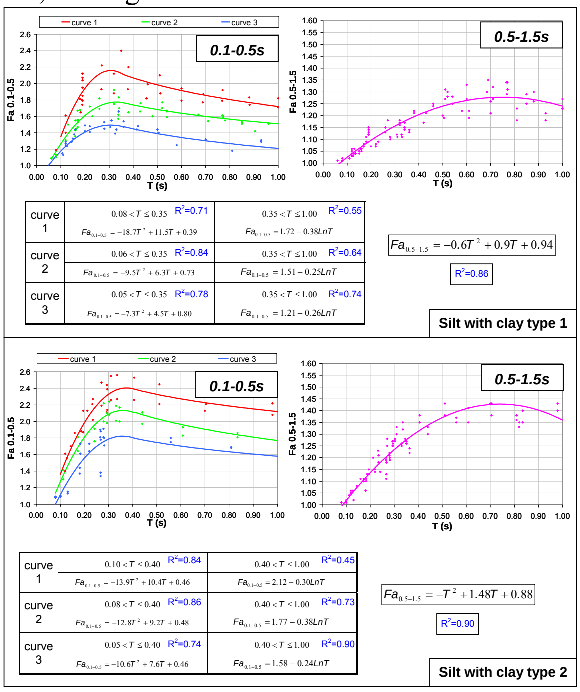


Fig. 5 Correlation curves between the values of *Fa* and *T* in the range period 0.1-0.5s and 0.5-1.5s, for the silt with clay lithology (type 1 and type 2)

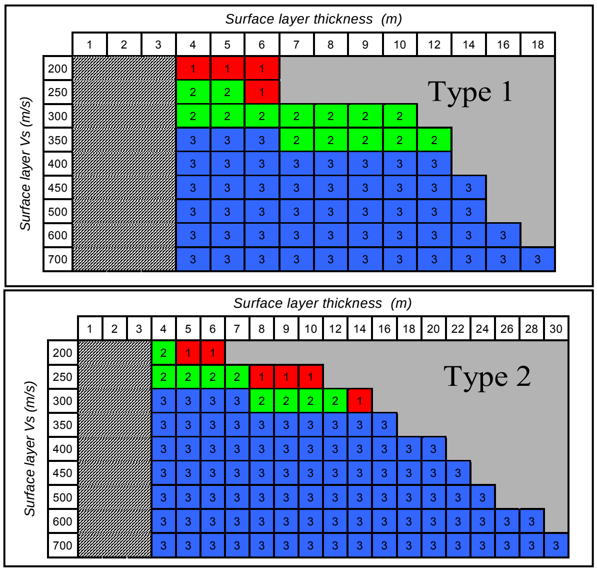


Fig. 6 Range of validity of each curve for silt with clay lithology

3.7.2 Morphologic amplifications

For the morphologic amplification the attention has been paid to the rocky ridges and rocky cliffs, in particular on the basis of real cases, characterized by topographic irregularities with the presence of rock, the typical situations have been identified and the numerical analyses, applying the 2D models, have been performed. The results have been checked, furthermore, applying the numerical analysis on some real cases. The check shows a good agreement between the results obtain on the real cases and the typical situations.

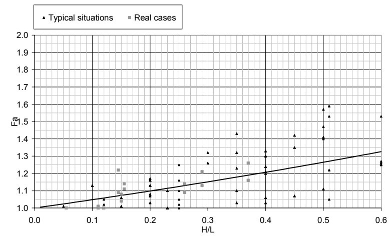
The rocky ridge is identified by geometrical characteristics: slope angle (α) ≥ 10°, base length (*L*) defined in correspondence of morphologic ruptures, top length (*l*), minimum elevation difference (*h*), maximum elevation difference (*H*) and ratio $h \geq 1/3\ H$. The rocky cliffs is identified by geometrical characteristic: slope angle (α) ≥ 10°, upper front angle (β), minimum elevation difference (*h*), maximum elevation difference (*H*) ≥ 10m, ratio $h < 1/3\ H$ and ratio $\beta \leq 1/5\ \alpha$. The analyses have been performed applying, to the rock, the values of shear waves ranging between 800-1500 m/s and values of unit weight between 22-24 kN/m^3.

The results in term of *Fa* values, in the two period ranges 0.1–0.5s and 0.5–1.5s, are calculated for the ridges on the top and have been correlated with the values of the ratio *H/L*; for the cliffs the results are calculated on the top of the cliffs and have been correlated with the values of *H* and α. In both cases the results, considering the period range 0.5-1.5s, present a large influence of the applied accelerograms, therefore they are not sufficient to represent in a univocal way the site response; for this reason the procedure has considered only the results of the period range 0.1-0.5s. The results for the ridges show a scattering considering the period range 0.1-0.5s and this scattering has been eliminated grouping the couple values (*Fa-H/L*) in function of two parameters: the morphology of the ridge and the base length. For the morphology of ridge, two situations have been considered:

- rounded ridges, characterized by a length on the top (*l*) quite similar (≥ 1/3) to the base length (*L*), the top is flat and the slope angle is (β) ≤ 10°;
- pointed ridges, characterized by a top length (*l*) very smaller to the base length (*L*).

For the rounded ridges the different couple values of Fa-H/L are not influenced by the values of the base length, therefore the correlation curve is unique (Fig. 7), instead for the pointed ridges four correlation curves have been individuated, depending on the values of the base length (Fig. 8). In the graphs some results of the analyses performed on both typical situations and real cases, are plotted. It is notice that the correlation coefficients (R^2), reported in the Figures, show a good fitting. The procedure provides that the *Fa* values are assigned to the top area, instead along the slope the values are scaled in a linear way, reaching the value 1 to the base of the slope.

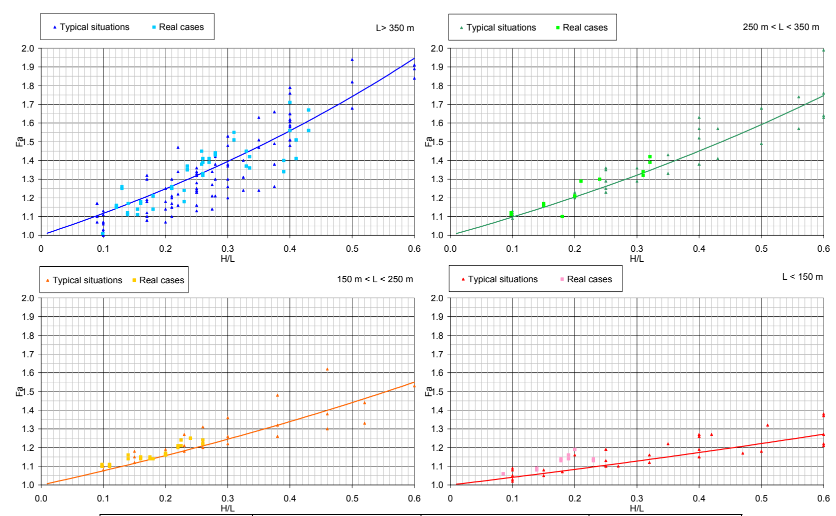
The results for the cliffs show a limited scattering considering the period range 0.1-0.5s and they allow to perform a Table (Fig. 9) in which the values of *Fa* are correlating to the values of *H* and α. The procedure provides that the *Fa* values are assigned to the top area near the rupture, instead along the upper front the values are scaled in a linear way, reaching the value 1 according to the length (A_i) of influenced area, and along the slope the values are scaled in a linear way, reaching the value 1 to the base of the slope.



$Fa_{0.1\text{-}0.5} = e^{0.47H/L}$

$R^2 = 0.47$

Fig. 7 Correlation curve and formula between the values of *Fa* and *H/L* in the range period 0.1-0.5s, for the rounded ridges



L > 350 m	250 m < L < 350 m	150 m < L < 250 m	L < 150 m
$Fa_{0.1\text{-}0.5} = e^{1.11\,H/L}$	$Fa_{0.1\text{-}0.5} = e^{0.93\,H/L}$	$Fa_{0.1\text{-}0.5} = e^{0.73\,H/L}$	$Fa_{0.1\text{-}0.5} = e^{0.40\,H/L}$
$R^2 = 0.84$	$R^2 = 0.87$	$R^2 = 0.83$	$R^2 = 0.69$

Fig. 8 Correlation curves and formulas between the values of *Fa* and *H/L* in the range period 0.1-0.5s, for the pointed ridges and for different values of base length (*L*)

Height range	*Slope angle range*	*Fa*	*Influenced area*
10 m ≤ H ≤ 20 m	10° ≤ α ≤ 90°	1.1	A_i = H
20 m < H ≤ 40 m	10° ≤ α ≤ 90°	1.2	$A_i = \frac{3}{4}H$
H > 40 m	10° ≤ α ≤ 20°	1.1	$A_i = \frac{2}{3}H$
	20° < α ≤ 40°	1.2	
	40° < α ≤ 60°	1.3	
	60° < α ≤ 70°	1.2	
	α > 70°	1.1	

Fig. 9 Table of the values of *Fa* relating to *α* and *H* in the range period 0.1-0.5s, for the rocky cliffs and relative influenced areas (A_i)

3.8. *The use of the abacuses*

Inside the project five abacuses, for the lithologic amplifications (gravel, silt with clay type 1 and 2 and silt with sand type 1 and 2) and two abacuses, for the morphologic amplifications (rocky ridges and rocky cliffs), have been pointed out. The use of the abacuses can be summarized through the following steps:

- for the lithologic amplifications:
  - identification of the lithology and choice of the respective abacus;
  - identification of the representative stratrigraphic sequences of the site;
  - comparison of the behaviour of the *Vs* at different depth of each stratigraphic sequence with the validity field of the abacus (Fig. 3), the experimental data must be into this validity field;

   - choice of the relative curves (*Fa*-*T*), for the period range 0.1-0.5s, through the characteristics (*Vs* and thickness) of the surface layer of each stratigraphic sequence;
   - calculation of the dominant period (*T*) of each stratigraphic sequence;
   - definition of the amplification coefficient (*Fa*) for each stratigraphic sequence, using the relative curves (*Fa*-*T*) for the two period ranges.
- for the morphologic amplifications:
   - identification of the morphologic scenarios (rounded ridges, pointed ridges, cliffs) and choice of the respective abacus;
   - identification of the geometric characteristics (H, L, h, l, α, β), choice of the relative curve or table;
   - definition of the amplification coefficient (*Fa*).

The obtained *Fa* values allow to evaluate the protection degree of the seismic code. In particular these *Fa* values can be compared with a similar parameter *S* calculated for each municipality. The *S* values are obtained by the ratio between the spectral intensity calculated on the spectrum of the seismic code and on the spectrum of the expected hazard (Gruppo di Lavoro, 2004) and represents the threshold value. If the *Fa* values exceed the threshold value the seismic code is not sufficient to take into account the real amplification of the site, consequently the procedure provide the application of the 3° level, shortly described in the paragraph 2.

4. CONCLUSION

In the paper a procedure for the evaluation of the seismic local effects is shown. The aim of the work was to point out a procedure that may be used repetitively at the level of urban planning, when only the geologic, geophysical and geotechnical characteristics of a site are known. The procedure provides three levels of widening. Particularly, in the paper, the steps performed to have the abacuses, of the 2° level, are described. Therefore, a series of geologic, geomorphologic and geotechnical analyses have been carried out, to identify the scenarios affected by the site effects and to characterize the lithotechnical units. The expected seismic inputs have been calculated and numerical analyses using one-dimensional code, analyzing single soil column, and two-dimensional code, working with boundary elements and analyzing the morphologic amplifications, have been done. The results of the analyses, in term of correlation curves between some geometric and geophysical characteristics and the values of the amplification coefficients, allow to the identification of the expected amplification coefficients. These abacuses can be used in situations, inside of the regional territory, characterized by similar geologic, geophysical and geotechnical conditions.
The expected amplification coefficients give elements for urban planning, both for urban general choice and for building design.

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