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COMPARISON BETWEEN THE RESULTS OF SITE EFFECTS USING NUMERICAL AND EXPERIMENTAL ANALYSES IN CITTA' DI CASTELLO (ITALY)

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SUMMARY

In the paper the results of the numerical and experimental analyses, in a site of the Umbria Region (Città di Castello - PG), finalized to the evaluations of site effects, are shown. The aim of the work was to compare the two types of analyses, to give some methodologies, that may be used at the level of urban planning, considering these aspects. Therefore a series of geological, geomorphological (1:5.000 scale), geotechnical and seismic analyses have been carried out, to characterize the lithological units and to identify the areas affected to site effects. The expected seismic inputs are been individuated and two-dimensional numerical analyses have been done. An experimental analysis, using the registrations of small events, has been done. The results, for the two approaches, were performed in terms of elastic pseudo-acceleration spectra and amplification factors, as a ratio between spectral intensity, calculated using the pseudo-velocity spectra, in the periods of 0.1-0.5 s and 0.1-2.5 s of output and input. The results have been analyzed and compared, to give a methodology that may be exhaustive and precise.

INTRODUCTION

The problem of the amplifications correlating with the site effects, during an earthquake, is well-known and different methods and approaches have been point out to have a quantification of these effects, using both numerical and experimental approaches.

In the case of experimental approaches, the evaluation of the amplifications is done through the analyses of the seismic registrations, which 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. The spectral ratios are performed as a ratio between the registrations of a site and the registrations of a referent site on bedrock [1, 2, 3] and as a ratio between the horizontal and vertical component, using both earthquakes [4, 5] and noise [6].

In the case of numerical methods one-dimensional 1D, two-dimensional 2D and three-dimensional 3D models can be used. Some of these models are very well tested, other are in a phase of testing [7, 8, 9].

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Clearly the choice of the methods and approaches, the working scale and the types of analyses depends 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 both the experimental and numerical approaches have been applied, than analyses and comparisons between the two methods are been performed [10, 11, 12].

DATA COLLECTED FOR THE ANALYSES

In the frame of the project the following data have been collected:

- geological data deriving from geological surveys and bore-holes, finalized to draw up the geological map (1:5000 scale) and geological cross sections [13];
- geotechnical parameters: soil unit weigh, initial shear modulus, initial damping ratio, Poisson ratio, and relationships between shear modulus and damping ratio variation as a function of shear strain; the pre-existing geotechnical information have been collected and a series of new investigations have been done in the study area: 7 bore-holes, 8 CPT tests, 2 SPT tests and 15 geotechnical laboratory tests aimed to obtain the static and dynamic parameters, as soil characteristic tests, unconfined monotonic compression loading tests, monotonic loading triaxial tests, resonant column tests and cyclic loading torsional shear tests [14, 15];
- geophysical parameters [15]; the pre-existing geophysical information have been collected and a series of new investigations have been done in the study area: 5 down-holes and 1 cross-holes aimed to obtain the velocity of S and P waves;
- 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, because the area, affected by the earthquakes sequence, is located in a region with several dissected seismic structures, still not very well known and identified as defined seismic sources. The probabilistic approach also fits with the aim of the project that is the evaluation of a set of parameters to be entered in codes for building restoration and future building construction. Seismic input has been defined as the uniform probability spectra with a return period of 475 years corresponding at 10% probability of being exceeded in 50 years. Since most of the site amplification analyses required accelerations as reference input, non-stationary time-histories matching both the reference spectra and the peak ground accelerations have been generated [16].

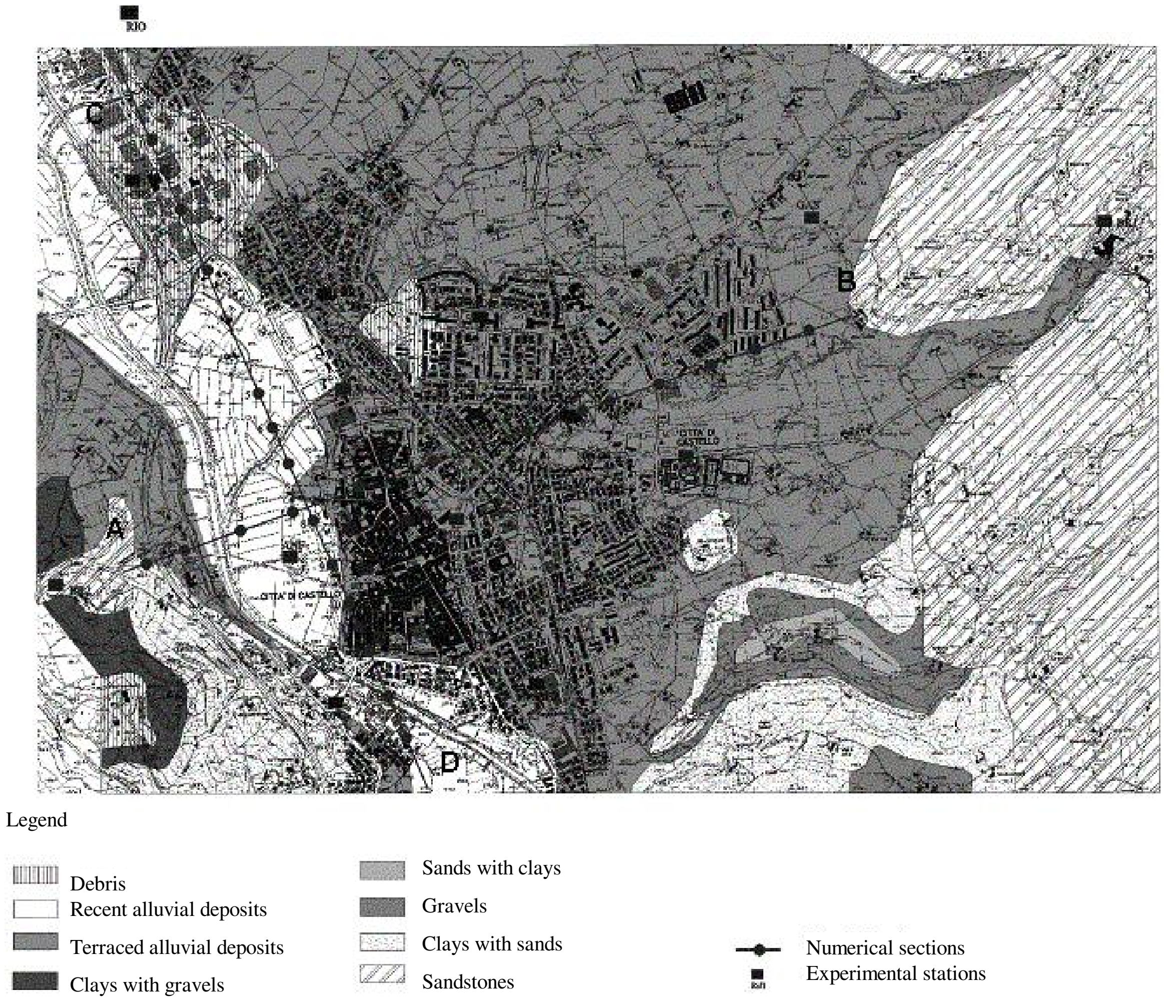
The studied site (Città di Castello) is located in the “Alta Val Tiberina Umbra” (Umbria Region); the geology of the locality is characterized by debris, recent alluvial deposits, terraced alluvial deposits, gravels, clays with sands, clays with gravels and sand with clays (Map 1). The geometry of the layers is complex by the presence of a deep distensive fault interesting the bedrock (sandstones) and by the presence of lateral narrows of deposits; the width of the valley is 3200 m.
The analyses were performed along 2D cross sections, relating to the complexity of the geologic and geomorphologic conditions and to the urban settlements.

NUMERICAL ANALYSES

To perform the numerical analyses the following information have been collected and the following numerical code has been selected.

Geotechnical parameters

In Table 1 the applied geotechnical parameters, for each lithological units, have been reported: the soil unit weight (γ), the velocity of *S* waves (Vs), the velocity of *P* waves (Vp), the initial shear modulus (G_0),

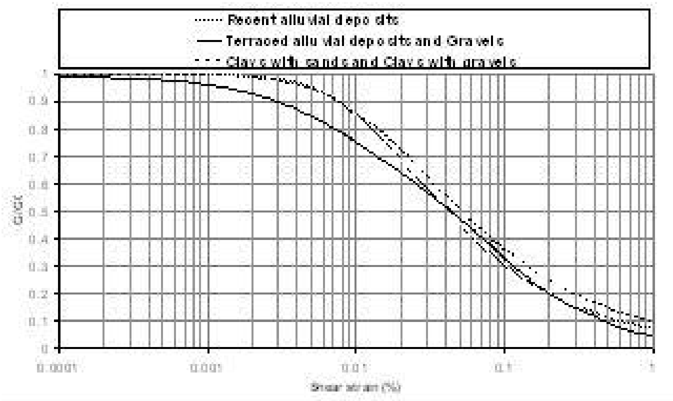


Map 1. Geological map, analyzed cross sections and registration sites

the initial damping ratio (D_0), and the Poisson coefficient (ν), deriving from geotechnical and geophysical investigations. In Fig. 1 and 2, for each lithological units, the relationships between the normalized shear modulus (G/G_0) decay and damping ratio (D) variation as a function of the shear strain (γ), deriving from geotechnical investigations, are represented.

Lithological units	**Parameters**					
	γ **(kN/m^3)**	***Vp*** **(m/s)**	***Vs*** **(m/s)**	G_0 **(MPa)**	D_0 **(%)**	ν
Recent alluvial deposits	19.0	550	220	94	2.8	0.40
Terraced alluvial deposits	19.0	730	270	141	1.0	0.42
Gravels	19.5	1550	370	272	1.0	0.47
Clays with sands – 1 (0-20 m)	20.0	1600	440	395	1.9	0.46
Clays with sands – 2 (20-50 m)	20.5	1800	540	609	1.9	0.45
Clays with sands – 3 (> 50 m)	20.5	2300	700	1024	1.9	0.45

Table 1. Table of the geotechnical parameters



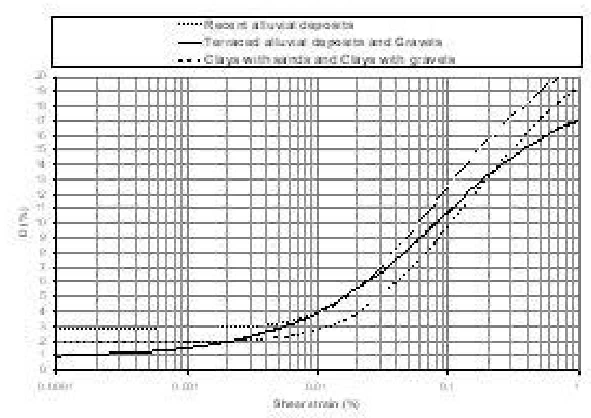


Fig. 1. Normalized shear modulus decay (G/G_0) with shear strain (γ)

Fig. 2. Damping ratio increasing (D) with shear strain (γ)

Numerical code and characteristics of the analyzed sections

Considering the geometry and the geology of the site, a two-dimensional analysis using a finite element method [17] has been performed. The used code allows to model any sections characterized by different materials, and to analyze the non-linear response of soil, using the equivalent linear analyses.

The geophysical model has been performed [14] and two cross sections have been analyzed (Map 1):

- the A-B section characterized by WSW-ENE orientation, length of 3200 m, presence of recent alluvial deposits, terraced alluvial deposits and clays with sands (Fig. 3); the section has been divided in 2458 elements and 2478 points, each element has an height of 4 m and a width of 20 m;
- the C-D section characterized by NW-SE orientation, length of 3000 m, horizontal layers, presence of recent alluvial deposits, terraced alluvial deposits, gravels and clays with sands (Fig. 4); the section has been divided in 3825 elements and 3934 points, each element has an height of 4 m and a width of 40 m.

The bedrock is characterized by sandstones with γ=22.0 kN/m^3, Vp=2100-3100 m/s and Vs=1100 m/s.

The seismic input is characterized by a peak ground acceleration of 0.201 g, a duration of 20 s and a predominant period of 0.365 s (Fig. 5).

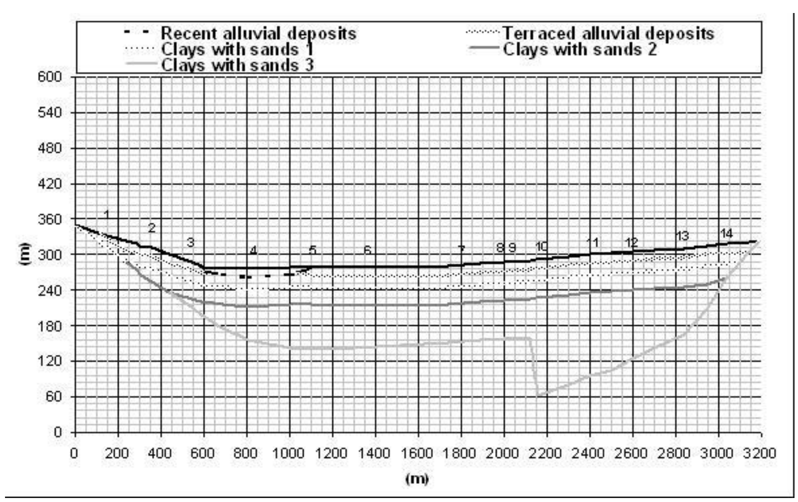


Fig. 3. Schematic representation of the analyzed A-B section

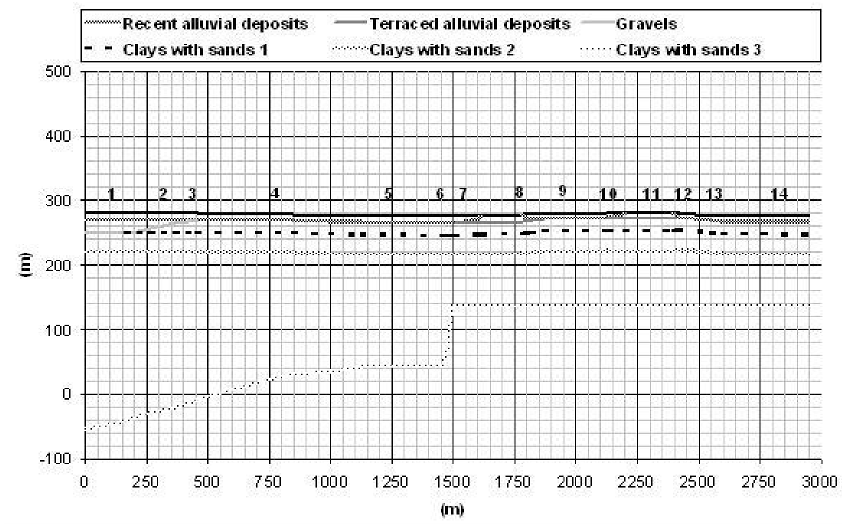


Fig. 4. Schematic representation of the analyzed C-D section

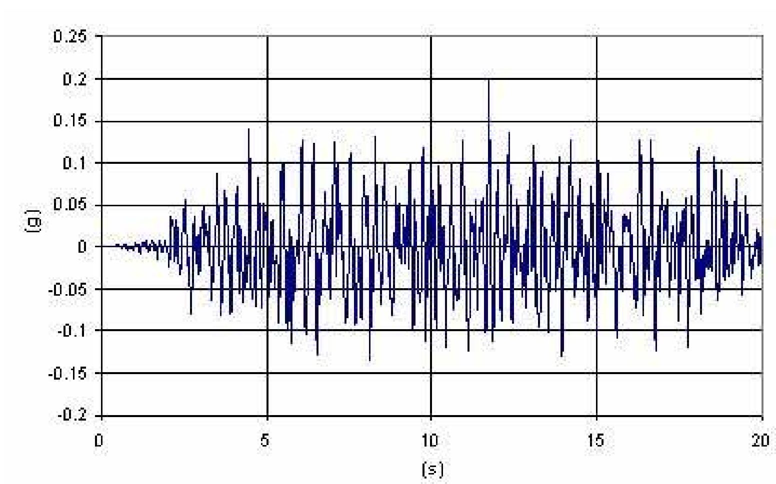


Fig. 5. Calculated accelerogram

Results of the analyses

The results of the analyses, in various points of sections, are drawn in a series of elastic pseudo-acceleration response spectra. For each elastic response spectra, the spectral intensity (*SI*) has been calculated using the elastic pseudo-velocity response spectra, considering two values 0.1-0.5 s and 0.1-2.5 s [18] and the 5% of critical damping. 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) [19, 20, 21, 22].

In the Fig. 6 a, b and 7, the results concerning the A-B section are reported, in term of elastic pseudo-acceleration response spectra and amplification coefficients (*Fa*). As shown the *Fa* values are very high, probably caused by the geometry of the valley and the high thickness of the deposits. Interesting is the effect of the fault: near this line the *Fa* values are low.

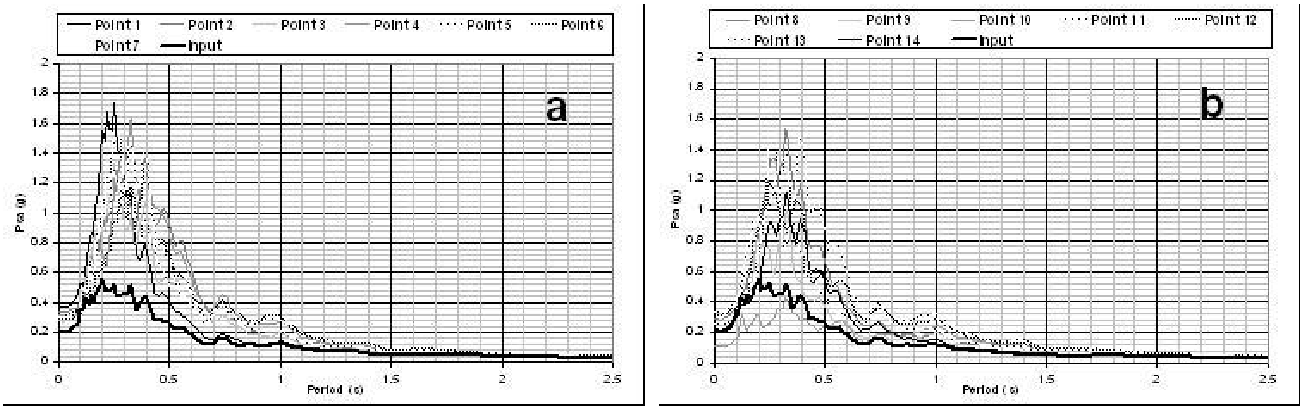


Fig. 6 a, b. Pseudo-acceleration elastic response spectra obtained by the numerical analysis

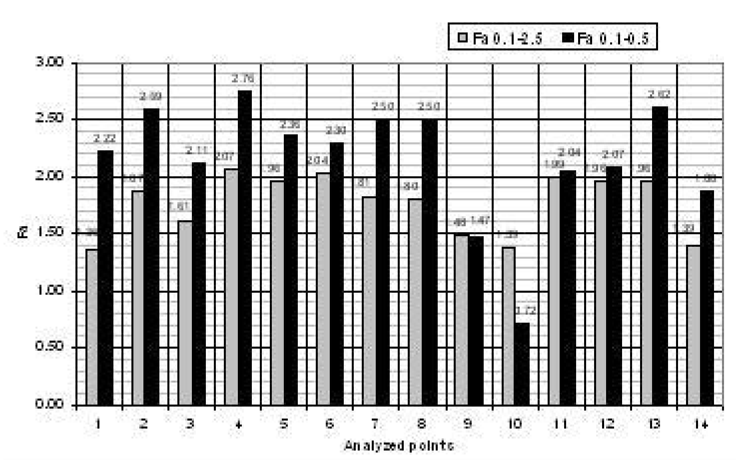


Fig. 7. Values of the amplification coefficient (*Fa*) considering the periods between 0.1-0.5 s and 0.1-2.5 s, obtained by the numerical analysis

Considering the results using the period between 0.1-0.5 s, the *Fa* values are higher than 2 and can be summarized as:

- *Fa* equal to 2.7-2.8 in presence of recent alluvial deposits;
- *Fa* equal to 2.3-2.5 in presence of terraced alluvial deposits, with the depth of bedrock equal to 130 m;
- *Fa* equal to 2.0-2.1 in presence of terraced alluvial deposits, with the depth of bedrock equal to 150-230 m;
- *Fa* equal to 1.5 near the fault;
- *Fa* equal to 2.3-2.6 near the lateral narrow of the valley.

Considering the results using the period between 0.1-2.5 s, the *Fa* values can be summarized as:

- *Fa* equal to 2.0-2.1 in presence of recent alluvial deposits;
- *Fa* equal to 1.8-2.0 in presence of terraced alluvial deposits, with the depth of bedrock equal to 130-230 m;
- *Fa* equal to 1.3-1.5 near the fault;
- *Fa* equal to 1.3-1.4 near the lateral narrow of valley.

In the Fig. 8 a, b and 9, the results concerning the C-D section are reported, in term of elastic pseudo-acceleration response spectra and amplification coefficients (*Fa*). As shown the amplification values are coherent with the value of the previous section. Also in this case the lowest values are near the fault.

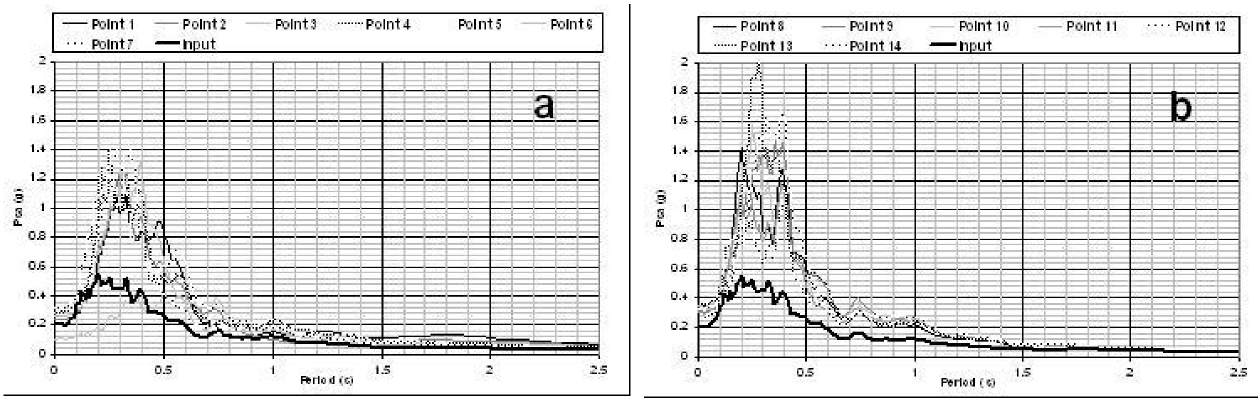


Fig. 8 a, b. Pseudo-acceleration elastic response spectra obtained by the numerical analysis

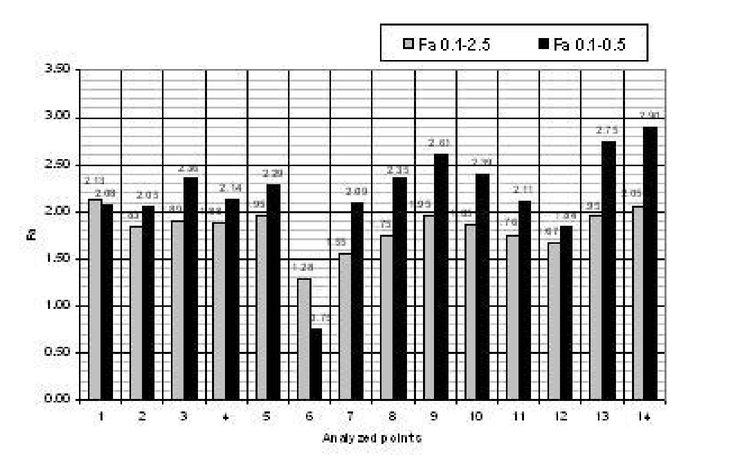


Fig. 9. Values of the amplification coefficient (*Fa*) considering the periods between 0.1-0.5 s and 0.1-2.5 s, obtained by the numerical analysis

Considering the results using the period between 0.1-0.5 s, the *Fa* values are higher than 2 and can be summarized as:

- *Fa* equal to 2.6-2.9 in presence of recent alluvial deposits, with the depth of bedrock equal to 140 m;
- *Fa* equal to 2.2-2.3 in presence of recent alluvial deposits, with the depth of bedrock equal to 230-270 m;
- *Fa* equal to 2.1-2.2 in presence of terraced alluvial deposits, with the depth of bedrock equal to 140 m;
- *Fa* less than 1.0 near the fault.

Considering the results using the period between 0.1-2.5 s, the *Fa* values can be summarized as:

- *Fa* equal to 1.8-2.0 in presence of recent alluvial deposits, with the depth of bedrock equal to 140-270 m;

- *Fa* equal to 1.7-1.8 in presence of terraced alluvial deposits, with the depth of bedrock equal to 140 m;
- *Fa* equal to 1.2-1.4 near the fault.

  The values of *Fa* considering the period between 0.1-0.5 s can be summarized as:
- in the southern and in the southern-western area the *Fa* value is between 2.6-2.8;
- in the northern-western area the *Fa* value is between 2.1-2.3;
- in the central area the *Fa* value is between 2.3-2.5, excluding the area near the fault where the values are lower;
- in the eastern area the *Fa* value is between 2.6-2.7.

  The values of *Fa* considering the period between 0.1-2.5 s can be summarized as:
- in the western area the *Fa* value is between 1.8-2.1;
- in the northern area the *Fa* value is between 1.9-2.1;
- in the central and in the eastern area the *Fa* value is between 1.7-2.0, excluding the area near the fault where the values are lower.

EXPERIMENTAL ANALYSES

The acquisition of the data has been done in two phases, from April to December 2000, during which the amplification values have been calculated in 20 different sites. Among these two, BR1 and BR2 located on sandstone, have been chosen as references sites (Map 1). The analyzed sites are approsimatevely located along the same lines defined as A-B and C-D sections in the numerical analyses.

The collected data set consisted of 111 low magnitude (Ml = 4.3) earthquakes recorded by digital system Lennartz Mars88/FD coupled with three component Mark L4C/3D seismometers with a natural frequency of 1Hz, that operated in a trigger configuration. The sampling rate was set at 0.016 s (62.5 Hz). Moreover, two six channels recorders Kinemetrics K2, equipped with three component Lennartz L3D lite seismometers with a natural frequency of 1Hz, have been utilized.

The analyses performed consisted in the evaluation of the spectra and spectral ratios [6]. The first step in the analysis was the hand picking of P and S waves, P arrival has been picked on the vertical component and S on the horizontal components. Then the spectra were computed considering a time window of 16.38 s long starting from the beginning of the S wave train, which in the frequency domain give computed spectra between 0-25 Hz. A smoothing factor has been applied to the spectra in order to stabilize them before calculating the site/bedrock ratios. Spectral ratios has been computed for each site using spectral ratio estimation both reference site techniques and between horizontal and vertical component (receiver function).

The amplification factors (*Fa*), defined as the ratio between the spectral intensity of the site and the spectral intensity of the input, for the NS and EW components and for the average of the two components, have been calculated, using the transfer functions obtained with the spectral ratio model [21, 23, 24, 25]. The procedure considers as input data the seismic input at the bedrock (the same of the numerical analysis) and the transfer functions at the sites. The first steps was the evaluation of the elastic pseudo-acceleration spectrum of the input, this spectrum has been reproduced at the site, operating a convolution in the frequency domain, considering that the transfer function of the site is characterized by a modulus equal to the transfer function experimentally determined and phase equal to zero for the considered frequency interval.

Then the pseudo-acceleration, pseudo-velocity and displacement response spectra for the input and the site have been calculated, using the 5% of critical damping. For each elastic pseudo-velocity response spectra, the value of spectral intensity (*SI*) in the period 0.1-0.5 s has been calculated and finally the amplification coefficient *Fa* has been performed.

Results of the analyses
In Fig. 10 a, b and 11 a, b, the elastic pseudo-acceleration spectra of the input and the sites are reported.

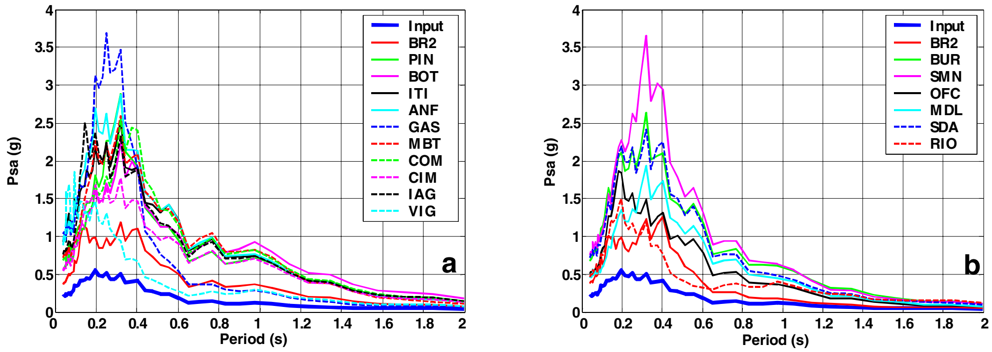


Fig. 10 a, b. Pseudo-acceleration elastic response spectra obtained by the experimental analysis considering as a bedrock the BR1 site, relating to the first (a) and second (b) phase of acquisition

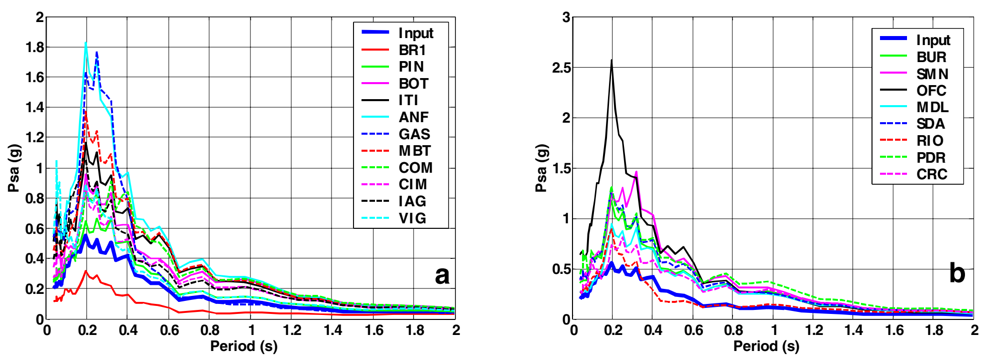


Fig. 11 a, b. Pseudo-acceleration elastic response spectra obtained by the experimental analysis considering as a bedrock the BR2 site, relating to the first (a) and second (b) phase of acquisition

In Table 2 and 3 the amplification factors (*Fa*) and the peak ground acceleration (*Pga*), deriving from the analyses of the registered data, are reported. In Table 2 the *Fa* and *Pga* value considering as bedrock the BR1 site for the NS, EW and for the average of the two components, are shown. To average the two components, the transfer function of the site has been calculated using the geometric average of the spectral ratio for the two components. In Table 3 the same values, considering as bedrock the BR2 site, are represented. As shown, the values of the amplification factors, considering the two sites, are different for a factor equal to 2, even if the BR1 and BR2 sites show the transfer functions as bedrock site.
The variation of the *Fa* values, considering as bedrock the BR1 site, is between 2.29 and 5.51 (Table 2). The highest values are been registered in the site near to the bedrock: eastern side (GAS) and in the site characterized by alluvial deposits and near to the bedrock: western side (ANF). Similar results can be observed considering as a bedrock the BR2 site (Table 3), the corresponding values of *Fa* are 2.51 (GAS) and 2.74 (ANF); also the site (OFC), characterized by the presence of the contact between bedrock and alluvial deposits, shows high amplification values.
The peak ground acceleration values, considering as the bedrock the BR2 site (Table 3), are between 0.24-0.63 g, and the mean values are about 0.5 g.

Site	*Pga* NS (g)	*Fa* NS	*Pga* EW (g)	*Fa* EW	*Pga* NS+EW (g)	*Fa* NS+EW
BR1	0.201	1	0.201	1	0.201	1
BR2	0.39	2.41	0.35	1.98	0.37	2.22
PIN	0.66	4.18	0.71	4.36	0.68	4.24
BOT	0.54	3.82	0.57	3.52	0.54	3.63
ITI	0.94	4.35	0.91	4.39	0.92	4.37
ANF	0.95	4.93	0.95	5.07	0.95	5.00
GAS	1.02	5.78	1.05	5.25	1.03	5.51
MBT	0.71	4.36	0.73	4.41	0.72	4.37
COM	0.66	4.65	0.51	3.66	0.57	4.10
CIM	0.55	3.32	0.56	3.17	0.55	3.24
IAG	0.73	4.33	0.82	4.78	0.76	4.46
VIG	0.90	3.96	0.84	2.35	0.88	2.35
RIO	0.46	2.68	0.47	2.06	0.46	2.29
BUR	0.63	4.24	0.73	4.64	0.67	4.40
SMN	0.72	5.18	0.82	6.01	0.75	5.48
OFC	0.68	4.12	0.39	2.98	0.50	3.12
MDL	0.46	3.19	0.43	2.96	0.44	3.07
SDA	0.67	4.24	0.76	4.65	0.71	4.40
PDR	-	-	-	-	0.88	4.06
CRC	-	-	-	-	0.54	2.78

Table 2. Acceleration values and amplification factors considering as bedrock the BR1 site (the Pga in the bedrock is 0.201 g)

Site	*Pga* NS (g)	*Fa* NS	*Pga* EW (g)	*Fa* EW	*Pga* NS+EW (g)	*Fa* NS+EW
BR1	0.11	0.43	0.12	0.52	0.11	0.47
BR2	0.201	1	0.201	1	0.201	1
PIN	0.23	1.15	0.26	1.28	0.24	1.21
BOT	0.31	1.41	0.38	1.75	0.34	1.56
ITI	0.49	1.68	0.55	2.14	0.51	1.88
ANF	0.48	2.32	0.65	3.30	0.55	2.74
GAS	0.51	2.34	0.58	2.72	0.54	2.51
MBT	0.43	1.84	0.49	2.36	0.45	2.08
COM	0.24	1.54	0.28	1.73	0.27	1.62
CIM	0.25	1.24	0.30	1.51	0.27	1.36
IAG	0.35	1.44	0.45	1.99	0.39	1.69
VIG	0.55	1.44	0.61	1.42	0.55	1.39
RIO	0.21	1.08	0.30	1.27	0.25	1.15
BUR	0.31	1.69	0.40	2.12	0.35	1.89
SMN	0.34	2.06	0.44	2.69	0.38	2.35
OFC	0.61	3.08	0.68	3.44	0.63	3.21
MDL	0.24	1.46	0.28	1.71	0.26	1.57
SDA	0.35	1.86	0.42	2.18	0.39	2.00
PDR	0.41	1.90	0.50	2.21	0.44	2.03
CRC	0.25	1.34	0.30	1.45	0.27	1.39

Table 3. Acceleration values and amplification factors considering as bedrock the BR2 site (the Pga in the bedrock is 0.201 g)

The site of Città di Castello is characterized by high amplifications, and the results can be summarized in the following points:

- the western and eastern areas show the highest amplification values;

- the northern area (RIO, CRC) is characterized by amplification lower than the southern area (ANF, OFC);
- the central area is characterized by a modifications of the amplification values, probably caused by a variation of the characteristics of the deposits or by a variation of the depth of the bedrock.

ANALYSES AND COMPARISON OF THE RESULTS DERIVING FROM THE TWO ANALYSES

The comparison of the values of *Fa* obtained by the numerical and experimental analyses, considering the results using the range of 0.1-0.5 s, has been done and are shown in Fig. 12. In particular in the Fig. 12 the results of the A-B section are shown; in the figure it is notice that the results of the numerical analysis and the results of the experimental analysis, considering the BR2 bedrock, are similar; on the contrary an amount of differences can be observed applying the BR1 bedrock. This behavior can be explained considering the difference between the geological characteristics of the BR1 and BR2 sites: in the first case the sandstone are massive with high velocity, in the second case the sandstone are stratified with low velocity. Consequently the results of the experimental analyses are due to the difference of the seismic impedance.

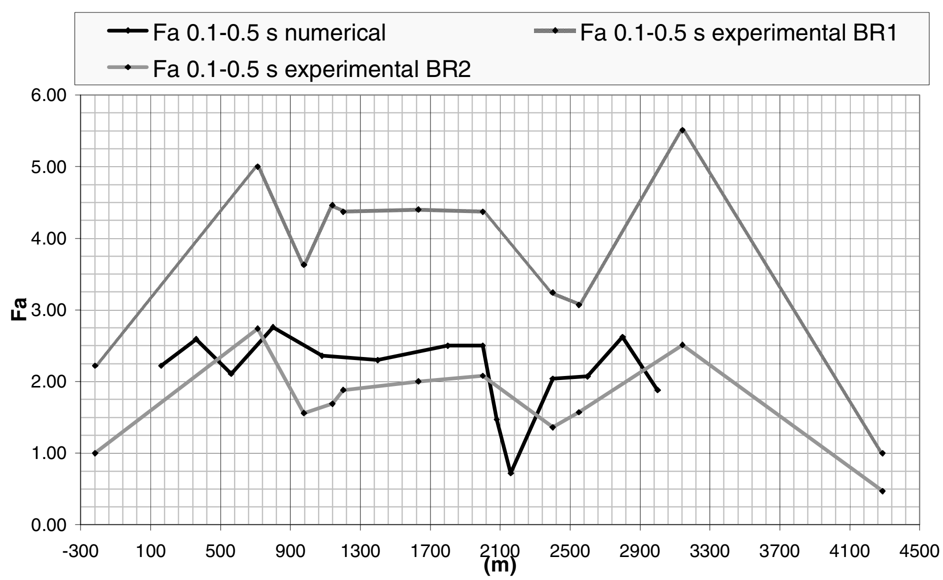


Fig. 12. Comparison between the results of numerical and experimental analyses: A-B section

Therefore comparing the results of the numerical analyses and the results of the experimental analyses, considering the BR2 site (more similar to the bedrock of the numerical analyses), it is possible to notice that the results of the two approaches are coherent. The trend of the *Fa* values along the valley is quite similar, it is notice that, in particular, close to the fault the results show lower values, considering both numerical and experimental analyses. Generally the differences are mainly due to the lack of the stations in a certain number of points, the differences in the values of amplification point by point can be explained considering that the experimental data refer to low energy input and so the behavior of the materials can be considered linear, more than the numerical analyses.

To check this behavior a numerical analysis test applying a small earthquake registered (Ml equal to 4.3, NS component, Fig. 13), on the A-B section, has be performed. The seismic input is characterized by a peak ground acceleration of 0.00146 g, a duration of 30 s and a predominant period of 0.20 s. The results shown that the obtained values are quite similar to these obtained in the previous numerical analysis, using the calculated seismic input (Fig. 14); therefore an other numerical analysis has be done, in the same section, applying the calculated seismic input and adopting a linear model: the results show small differences by the previous ones (Fig. 14). The conclusion that can be done is that the behavior of the materials are quite linear applying the different inputs.

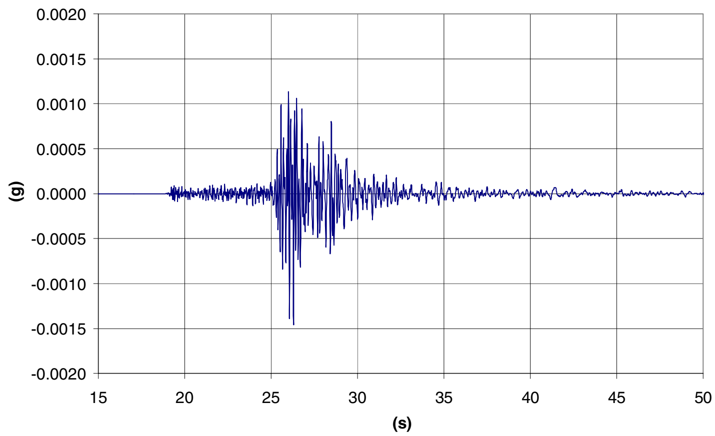


Fig. 13. Registered accelerogram

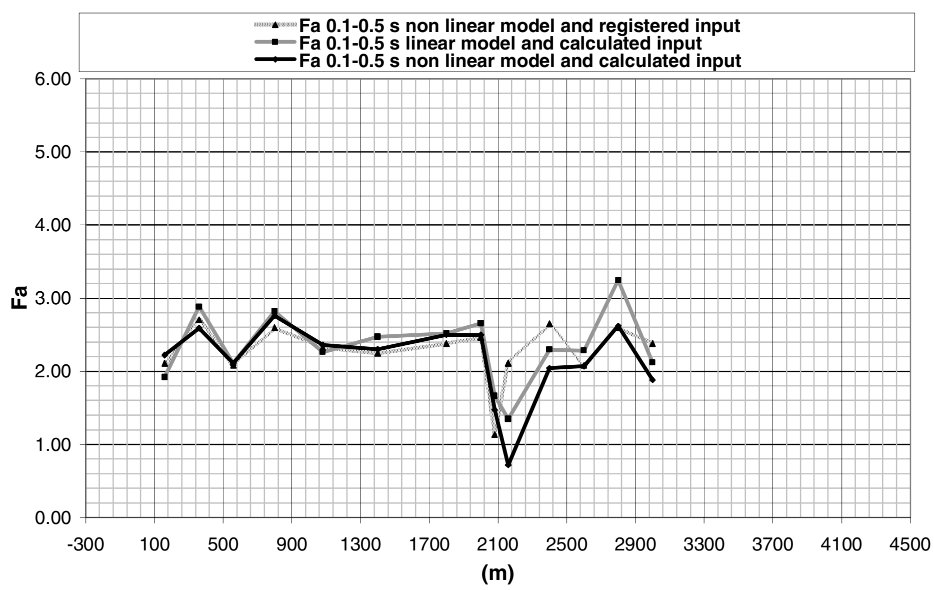


Fig. 14. Comparison between the results of numerical analyses on A-B section: applying the calculated seismic input, the registered small earthquake and adopting a linear model

To explain the results of the experimental analysis considering the BR1, a numerical analysis, applying a *Vs* to the bedrock higher than 1100 m/s has be performed. These tests have considered different values as 2500 m/s, 3500 m/s and the results show a trend that can reach the values of the experimental analysis, showing an influence of the choice of the characteristics of the bedrock (Fig. 15). In this case, however, so high values of the bedrock doesn't appear realistic, so the final values that should be considered are the results due to the application of the *Vs* equal to 1100 m/s, for the numerical analysis, and the application of the BR2 for the experimental analysis.

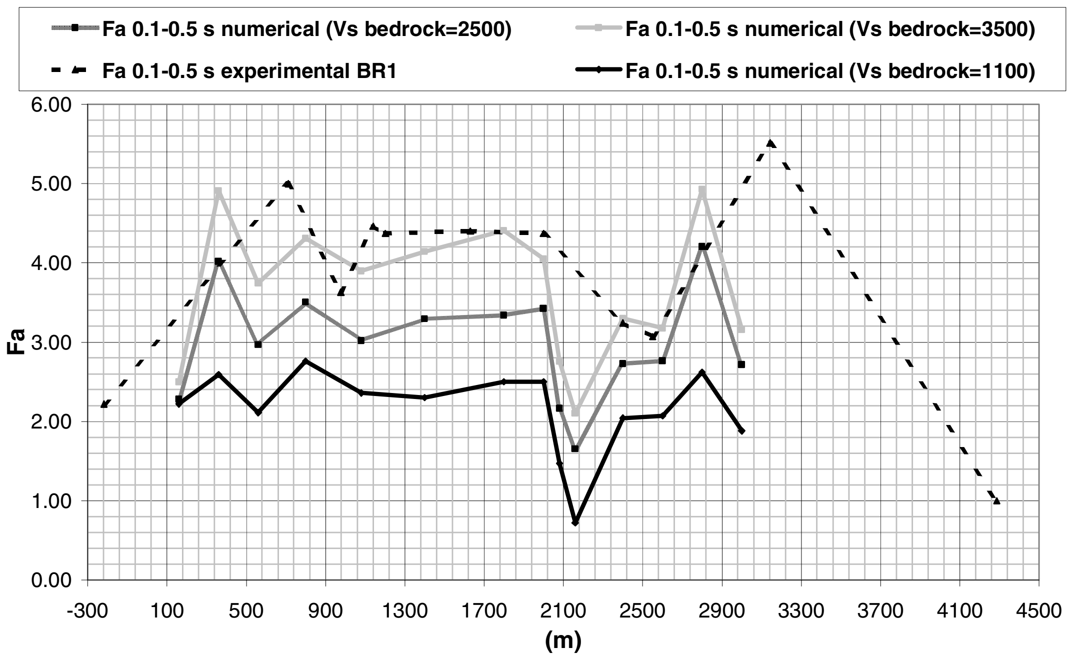


Fig. 15. Comparison between the results of numerical and experimental analyses on A-B section: applying the BR1 bedrock and different values of bedrock Vs

Therefore considering the spatial distribution of the results the following indications can be done:

- the western and eastern areas, characterized by the presence of lateral narrows of deposits, show the highest values of the amplifications;
- the northern area shows lower amplification values than the southern area, and these discontinuity can be caused by a fault that can produce a variation on the depth of the bedrock;
- the historic center show higher amplification than the close areas, caused by the presence of terraced alluvial deposits;
- the discontinuities on the results, considering the experimental analyses, show that the deep morphology of the areas is complex, this complexity are not considered in the numerical analysis, this fact can caused the differences on the results of the two types of analyses.

CONCLUSIONS

The conclusions can be summarized in the following points:

- the results of the two approaches are coherent;
- the significance of the choice of the characteristics of the bedrock;
- the differences between the two approaches are: the use of the numerical analysis is easy and quick but, in this case, the use of 2D analysis produces a simplification of real geometry; the use of experimental analysis allows to consider the 3D conditions, but the registrations of events characterized by low energy, do not allow to consider, in some cases, the non linear behavior of materials, moreover it is necessary to perform the registrations for a period depending from the seismicity of the region (1 month - two years);

- the possibility of integration of the two methodologies allows to perform a complete analysis, using the advantages of the two methods.

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