

AMPLIFICATION FACTORS TO MEASURE LOCAL SEISMIC EFFECTS IN URBAN AREAS

Giovanna VESSIA¹, Claudio CHERUBINI², Maurizio FERRINI³, Vincenzo DAPRILE⁴

ABSTRACT

Wave propagation due to seismic event causes modification in vibration predominant frequency, duration and amplitude, with respect to the wave form coming out of rock basement. These changes depend on dynamic shear response of superficial soil deposits, on geometric factors as interface and boundary positions and on the impedance ratio of adjacent soil layers. The seismic amplification can be dangerous in urban areas where the buildings can be destroyed by the “double resonance” phenomenon. In order to assess site effects several amplification factors are defined in literature. In this paper the most commonly used amplification factors have been discussed and compared in terms of their capacity of quantifying the amplification/deamplification of input motion due to soil filtering effect. Then the amplification factors are calculated at Fivizzano’s town. Such a site was chosen by Tuscany Region in the “VEL” project as a sample site where seismic methods and approaches were developed and improved for dynamic characterization of soil deposits, such as geotechnical and geophysical field tests, and for one-dimensional (1D) and two-dimensional (2D) numerical simulations. Moreover, in this study, results from a recently performed probabilistic hazard analysis are employed for the input motion of numerical simulations. The paper focuses on the values of the amplification factors drawn along the 2D section of the site under study. A possible use of the most efficient amplification factor is suggested.

Keywords: seismic amplification factor, site effects, VEL project, Fivizzano microzonation.

INTRODUCTION

Seismic microzonation, especially the study of local amplification effects, has been developed in many areas of Italian national territory, by means of different approaches: in situ experimental tests (microtremors, geophone arrays, etc.) and numerical simulations (1D, 2D and 3D based on superficial deposit characterization and seismic hazard studies). The first studies on this issue were carried out after the seismic event occurred in Friuli in 1976 and later at Ancona in 1981; after that an important CNR project (Faccioli, 1986) summarized this previous experience of seismic zonation and outlined few criteria for developing seismic response analyses in urban areas. Such pioneering studies pointed out the need for formulating some indexes to quantify the local amplification or deamplification effects of seismic wave propagation.

¹ PhD, Department of Civil and Environmental Engineering, Polytechnic of Bari, Italy, Email: g.vessia@poliba.it

² Professor, Department of Civil & Environmental Engineering, Polytechnic of Bari, Italy, CA.

³ Responsible in Chief, Office for Seismic Risk Prevention, Tuscany Region, Italy.

⁴ Engineer, Office for Seismic Risk Prevention, Tuscany Region, Italy.

In 1998 Tuscany Region supported the “VEL” project, focused on the “Evaluation of Local Site Effects” with the prominent objective to investigate dynamic properties of superficial formations where cities and villages are settled and try to quantify the local seismic response to put those centres exposed at high seismic risk under control. According to the purpose of the VEL project, this study investigates parameters that quantify the amplification effects in order to use them for urban planning in seismic regions. Therefore the case study of Fivizzano, province of Massa-Carrara can be used as a sample site where proposals of amplification measurements can be done thus contributing to the general discussion.

SEISMIC AMPLIFICATION INDEXES

The main point of local seismic response studies is to find an agreement on what the “site response” should mean. Boore (2004) outlines there are three types of measures commonly used: (1) the ratio between some measures of ground motion (e.g. Fourier spectrum, response spectrum) at a particular site and those at another site for a single earthquake or multiple earthquakes; (2) the ratio between some measures at some surface points and those concerning the input motion at some depth below the previous points; (3) the average of the motions at one site group compared with the average of those in another group from a given magnitude and distance. In this study the type (2) of site response measure is adopted; especially the formulations of amplification indexes are considered in order to represent the site response for engineering purposes.

As far as building design is concerned, the new design philosophy is tending to multi-level probabilistic structural performance criteria, replacing completely the simple force strength approach (Fajfar and Krawinkler, 1997). However, the implementation of all these new concepts requires the definition of a quantitative damage index and measure. Accordingly the work presented here reviews those factors which summarise the filtering effects of superficial deposits. This means that amplification factor should take into account the amount of energy that earthquakes transmit to structures, the predominant range of periods which could correspond to the structure natural periods, the duration of the shaking and the extension of the maximum/minimum peaks of acceleration, velocity and displacement. In this section, amplification indexes are presented as damage measures without any structural response data. Those indexes can be grouped into two types: peak parameters and integral parameters.

The first ones are: peak ground acceleration, PGA, and velocity, PGV and peak motion ratio referred to as R_1 :

$$R_1 = PGV / PGA \quad (1)$$

in most of the cases the PGA and PGV are replaced with the corresponding peak horizontal acceleration PHA and velocity PHV provided that acceleration records are registered by horizontal and vertical components while numerical analyses commonly evaluates the horizontal response to the SH waves.

The PHA value can also be correlated to earthquake intensity (Kramer, 1996). Ground motions with high peak acceleration are usually, but not always, more destructive than motions with lower peak acceleration. Very high peak accelerations that last for only a very short period of time may cause little damage to many types of structures while earthquakes with a very low PHA could produce an unexpectedly high level of destruction. The PHV seems to be a more representative measure of the earthquake intensity than PHA as it is directly connected with the energy demand (Housner, 1982). The peak motion ratio PGV/PGA is indicated by different authors as being a measure of destructiveness (Zhu et al., 1988; Meskouris et al., 1992): the ground motions with larger damage potential show higher PGV/PGA values. Although such peak values are very useful parameters, they provide no information on the frequency content or duration of the motion.

The integral parameters are obviously much more effective in measuring the energy content of a seismic event. Among others there is the root mean square acceleration a_{rms} , which can be defined as:

$$a_{rms} = \sqrt{\frac{1}{T_d} \int_0^{T_d} [a(t)]^2 dt} \quad (2)$$

where t denotes the time, $a(t)$ is the ground acceleration series, T_d is the duration of the ground shaking. Various methods have been suggested to assess the duration of the strong motion, among others the Trifunac duration can be adopted. Such parameter, defined by Trifunac & Brady (1975), is the time interval between the points at which 5% and 95% of the energy in a ground motion have been delivered. The a_{rms} can be very useful for engineering purposes because the integral is not strongly influenced by large, high-frequency accelerations and because it is influenced by the duration of the motion. Nonetheless the root mean square acceleration doesn't take into account the period content of the motion.

Another integral parameter formulated for taking the fundamental periods of the most common structures into account, is Housner spectral intensity SI (Housner, 1952) which is defined within two ranges of periods:

$$SI(PSV)_1 = \int_{0.1}^{0.5} PSV(T, \xi) dT \quad (3a)$$

$$SI(PSV)_2 = \int_{0.1}^{2.5} PSV(T, \xi) dT \quad (3b)$$

where the PSV is the pseudo velocity spectrum, T is the period and ξ is the 5% damping ratio assumed. Since many structures have fundamental periods between 0.1s and 2.5s, the response spectrum ordinates in this period range should provide an indication of the potential response of these structures. Moreover, for the most rigid structures the Housner spectral intensity is formulated in a narrower range of fundamental periods, that is 0.1s and 0.5s (Equation 3a). Hence, SI seizes important aspects of the amplitude and frequency content in a single parameter but it doesn't consider the time duration of the motion.

Arias Intensity (Arias, 1970) is an integral parameter influenced by amplitude and duration of ground motion and it is defined as:

$$I_a = \frac{\pi}{2g} \int_0^{\infty} [a(t)]^2 dt \quad (4)$$

where g is the gravity acceleration and $a(t)$ is the time-history acceleration. Since it is obtained by integration over the entire duration rather than over the duration of strong motion, its value is independent of the method used to define the duration of strong motion. Moreover, Arias intensity can be related to energy content (Fardis, 1995) whereas it does not take into account structure fundamental periods.

There is another integral parameter, related to the Arias Intensity, called Saragoni factor P_D (Saragoni et al., 1989):

$$P_D = \frac{\pi}{2g} \frac{\int_0^{t_e} a_g^2(t) dt}{v_0^2} = \frac{I_a}{v_0^2} \quad (5)$$

where I_a is the Intensity Arias, v_0 is the number of zero crossings of the record in the time unit. Saragoni (1989) has shown that P_D is a more effective measure of earthquake destructiveness (in terms of the expected ductility of the structure) as shown by the excellent agreement of their correlation studies with the observed damage in the Chilean earthquake of 1985.

Cosenza and Manfredi have proposed a damage factor I_d (Cosenza & Manfredi, 1997) that is related to the energy content of the earthquake:

$$I_d = \frac{2g}{\pi} \frac{I_A}{PGA \cdot PGV} \quad (6)$$

where g is the gravity acceleration; I_A is the Arias Intensity; PGA is the peak ground acceleration and PGV is the peak ground velocity. Such a factor considers the duration of the earthquake, although it is a measure that cannot be predicted with any certainty, which largely influences the level of structural damage. Moreover I_d takes account of the peak values of acceleration and velocity but, again, it doesn't consider the similarity between predominant periods of motion and fundamental periods of structures.

The brief review of the most used amplification factors reveals that none of them considers all the main features of the local site response. Nonetheless they all are calculated for the case study of Fivizzano in order to assess their capacity of measuring local site response.

THE CASE STUDY OF FIVIZZANO

Geological context

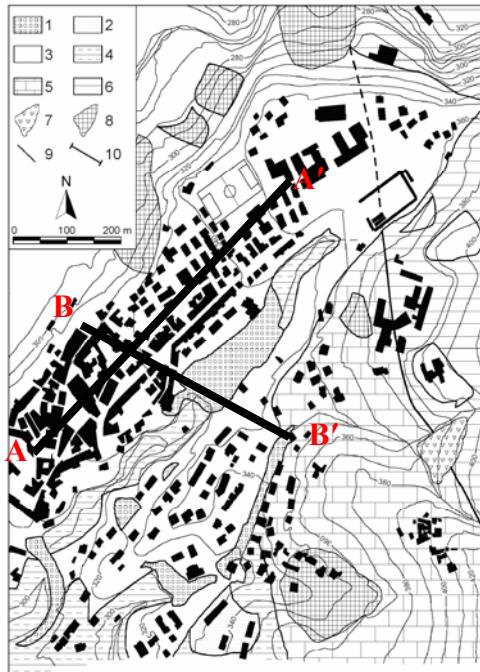


Figure 1. Simplified geological map of Fivizzano, Tuscany: 1) fill (Holocene), 2) detrital deposits (Holocene), 3) alluvial deposits (Holocene), 4) “Argille e Calcari” formation (Upper Cretaceous - Middle Eocene), 5) “Grosso del Vescovo” limestones (Lower Eocene), 6) “Macigno” formation (Upper Oligocene Lower Miocene), 7) landslide, 8) fault.

The study deals with the microzonation activity in Fivizzano, where a wide geological, geophysical and geotechnical experimental campaigns have been performed up to now. Figure 1 shows a geological plan of Fivizzano centre. The major part of Fivizzano is placed on a terrace alluvium on the left of the hydro-graphic Rosaro stream which is the most important river of the area.

The southern portion of the area is characterized by a substratum constituted by the Canetolo's Unit: "Argille e Calcari" formation (Upper Cretaceous - Middle Eocene) and the "Gropo del Vescovo" limestone (Lower Eocene) which is outcropping on the eastern part of the area. These lithotypes are in a tectonic contact (via an important structural element on a regional scale) with the "Macigno" sandstone (Tuscany non-metamorphic formation) cropping up in the north-eastern sector. The Quaternary coverings are formed by reclaimed lands, refilled grounds, detrital deposits and terraced alluvial deposits. Another feature that one may observe in the most sheer zones of the area is the presence of some active and dormant gravity phenomena.

Experimental investigations

Fivizzano is considered as a test site for training different approaches and their connections, in local seismic response studies. Accordingly a large investigation campaign of prevalent field tests has been performed up to now. Figure 2 shows the location of in-situ tests while Table 1 summarises all the field tests performed. Moreover, dynamic tests (resonant column and cyclic torsional shear test) were performed in laboratory to evaluate the shear modulus reduction function $G(\gamma)/G_0$ and the damping function $\xi(\gamma)$ for soil coverings. The multidisciplinary experimental results are used to characterize the site, that is measuring geomechanical properties of superficial deposits and reconstruction of two-dimensional lytho-stratigraphic sections for one dimensional (1D) and two dimensional (2D) numerical simulations. A numerical microzonation study on Fivizzano site was already presented (Cherubini et al., 2004a-b) although it was based on a synthetic time-history accelerogram. For this study a different input motion is employed.

Table 1. Summary of the tests performed in the experimental campaign in Fivizzano town.

Tests performed	Fivizzano
soundings	14 (tot. = 593.7m)
Down Hole in P and SH waves	9 (tot. = 470.3m)
Refraction survey in P and SH waves	24 (tot. = 2872m)
Seismic reflection survey in HR	4 (tot. = 567m)

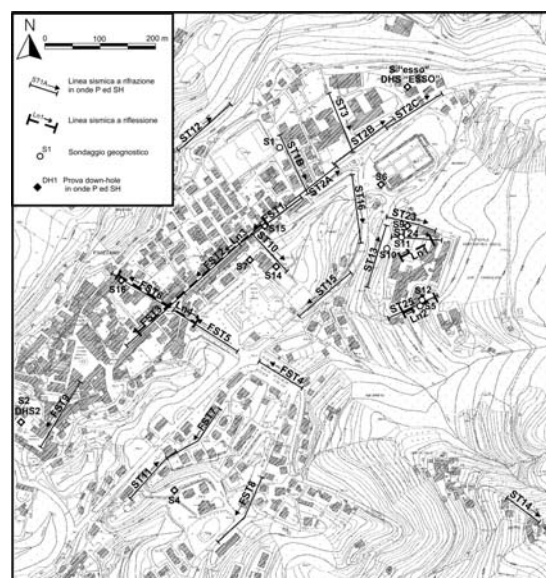


Figure 2. Location of in-situ geophysical and geotechnical tests.

Input motion

A recent probabilistic seismic hazard study has been developed by Lai et al. (2005) in Lunigiana and Garfagnana territories in order to update the input motion for site response numerical analyses. All

seismic events occurred within a circle having a radius of 200km, centred in Lunigiana and Garfagnana areas, were taken into consideration. Accordingly the latest version of seismic genetic zonation ZS9 proposed by INGV (GdL MPS, 2004) and the parametric catalogue of Italian earthquake CPTI-04 (GdL CPTI, 2004) were used to calculate natural time-history accelerograms on rock for the return periods of 2475, 475 and 72 years. Such records (14 for horizontal components and 7 for vertical components) are compatible with spectra suggested by Italian seismic building codes (OPCM n 3274, 2003). Within the report (Lai et al., 2005) all the details on this study are available. Table 2 reports the main features of the twelve horizontal records considered for 475 years of return period, while only one is used for evaluating the amplification indexes recalled in the first section of this paper. Such accelerogram, which shall be representative of all accelerograms, is scaled to the maximum expected acceleration value at Fivizzano, that is 0.25g. In this study only one record (referred to as 642x in Table 2) among others is considered since the aim of this paper is to discuss the use of the amplification factor in seismic design of buildings.

Table 2. Main features of the 14 horizontal accelerograms from probabilistic seismic hazard study in Lunigiana and Garfagnana areas (After Lai et al., 2005).

Code	Name	Dist. (km)	Date	M _b	M _L	M _s	M _w
232X-Y	Montenegro (aftershock)	21	24/05/1979	5.7	6.2	6.34	
280X-Y	El Asnam - North Algeri	20	30/10/1980	5.3	4.6	4.71	
642X-Y	Umbro-Marchigiano (aftershock)	23	14/10/1997	5.3	5.5	5.60	5.6
854X-Y	Umbro-Marchigiano (aftershock)	21	03/04/1998	5.1	5.2	4.80	5.1
855X-Y	Umbro-Marchigiano (aftershock)	18	05/04/1998	4.7	5.1	4.40	
1314X-Y	Atene (Greece)	23	07/09/1999	5.8		5.60	5.9
	Coyote Lake	9	08/06/1979		5.7	5.60	5.70

Numerical simulations

Figure 3 shows the litho-stratigraphic section AA' whose orientation is shown in Figure 1.

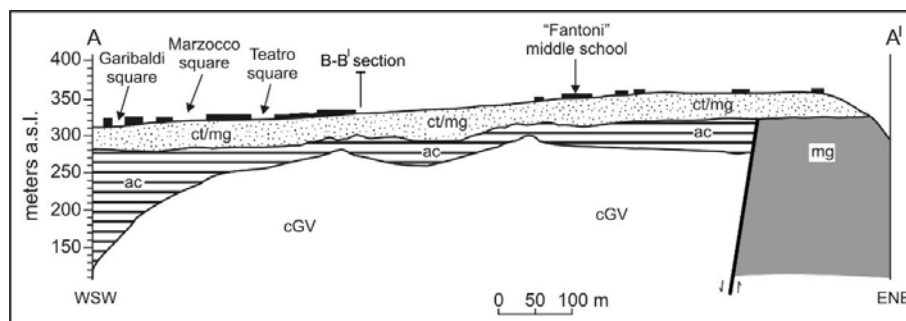


Figure 3. Geological section used for 2D site response analyses: rp = fill; ct/mg = alluvial deposits (Holocene); mg = “Macigno” formation (Upper Oligocene-Lower Miocene); cGV = “Gropo del Vescovo” limestones (Lower Eocene); ac = “Argille e Calcari” formation (Upper Cretaceous – Middle Eocene); / = Fault.

Along this section, from which the numerical model is drawn (see Figure 4), the vertical sections related to the 1D simulation have been placed. Results from 1D and 2D analyses were compared for the same input motion at ten superficial nodes as illustrated in Figure 4. 1D analyses were performed by ProShake (EduPro, 1996) whereas 2D with Quake/W (GEO-SLOPE International, 2004).

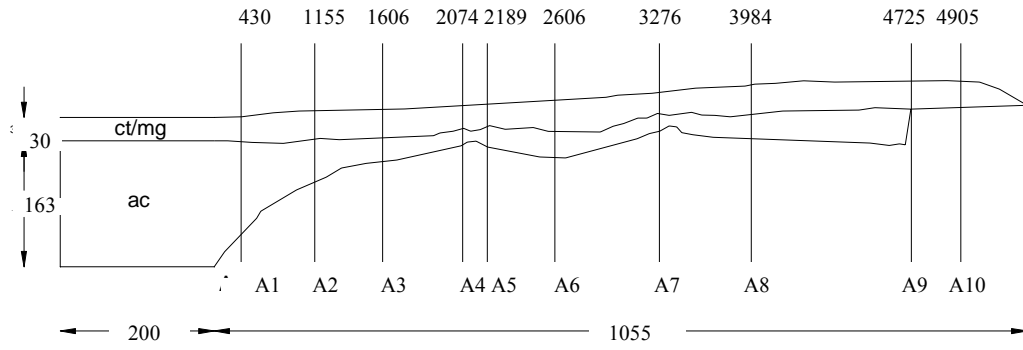


Figure 4. Locations of surface receivers to monitor dynamic response at section AA for one-dimensional analysis – beginning with A on the bottom- and two-dimensional analyses – number of nodes at the top.

Here are main assumptions in 2D simulations:

- Only SH wave propagation is taken into account;
- The soil constitutive behavior under earthquake loading is linear equivalent of viscoelastic type;
- The bedrock is considered as an elastic and semi-infinite continuum.

For further details on numerical simulations, refer to Cherubini et al. (2004a).

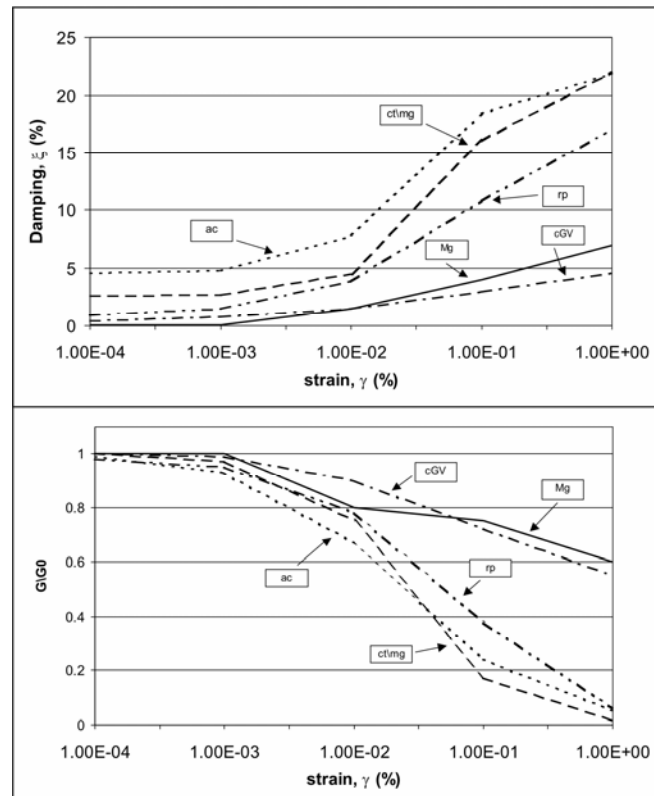


Figure 5. Shear modulus and damping ratio degradation curves used for one and two dimensional site response analyses.

The curves G/G_0 and the damping trend $\xi(\gamma)$ used, for linear equivalent behaviour of soils in numerical simulations are reported in Figure 5 and they are calculated by Ferrini et al. (2001).

Physical and dynamic properties of different lithologies covered by the 2D analyses are summarized in Table 3.

Table 3. Material properties used for numerical analyses.

Lithology	V_P (m/s)	V_{SH} (m/s)	Unit weight (kN/m^3)
ct/mg	1163	597	18.6
ac	2623	839	20.6
cGV	3795	1556	25.5
mg	2602	1702	24.5

ASSESSMENT OF AMPLIFICATION INDEXES

Response spectra from site response analyses versus code spectrum

Before discussing on the amplification factor capability of interpreting Fivizzano's seismic response, it is necessary to compare 1D and 2D results in terms of response spectra of accelerations as shown in Figures 6 and 7. It can be seen that peaks from 1D are almost half those from 2D analyses even if up to 0.6s period the spectra from this study are all higher than the code spectrum proposed by Italian seismic building code (OPCM n° 3274, 2003). For 2D analyses the amplification period interval increases to 0.9s with peaks of 2.7g. The location of the nodes where the highest peaks occur, cannot be predicted in advance due to the reflection and refraction phenomena. Such phenomena cannot be reproduced by 1D analyses where the spectrum shapes are all similar and are strictly dependent on the layer thickness. Therefore one-dimensional analyses suffer from the simplified conditions that are the soil layers are all parallel and horizontal. This assumption is not confirmed at Fivizzano site (Figure 4).

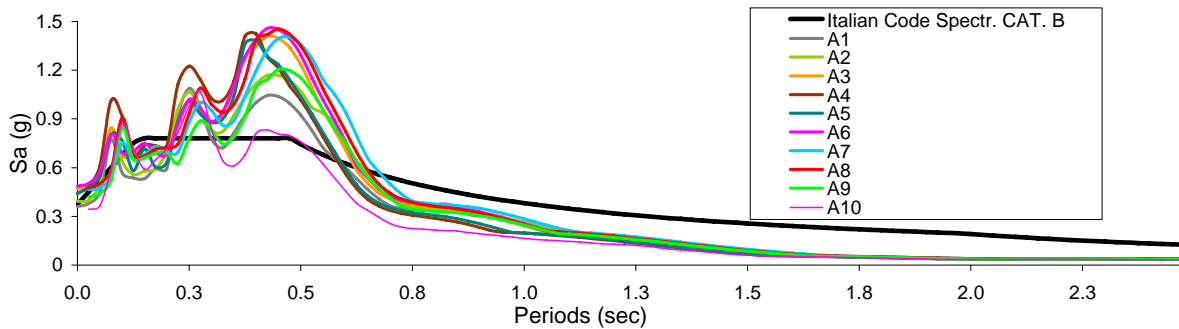


Figure 6. Comparison between Italian code spectra and 1D output spectra from site response analyses at Fivizzano town.

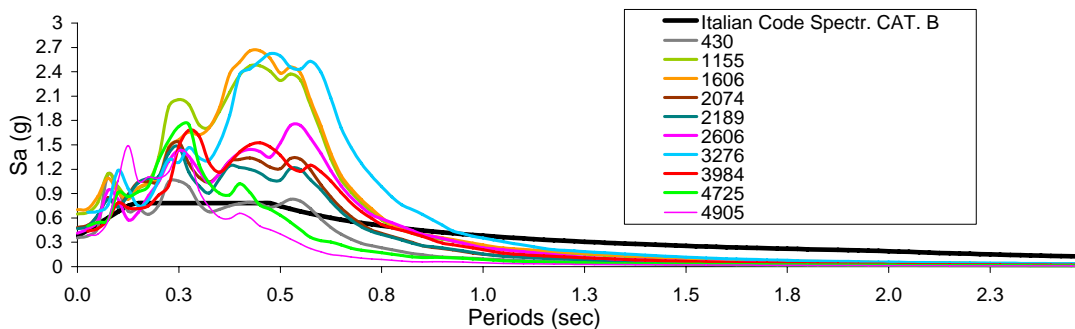


Figure 7. Comparison between Italian code spectra and 2D output spectra from site response analyses at Fivizzano town.

Thus 2D results are considered narrower to the actual site response, although measurements by geophone arrays are needed to prove those predictions. The code spectrum is calculated for B soil category that is, according to the parameter V_{S30} based on the shear wave velocity values of soils (Table 2) and their thicknesses (Figure 4). Moreover, the B spectrum also depends on the S factor which interprets the site amplification effect. For B soils, S is equal to 1.25 but, in this case, it seems

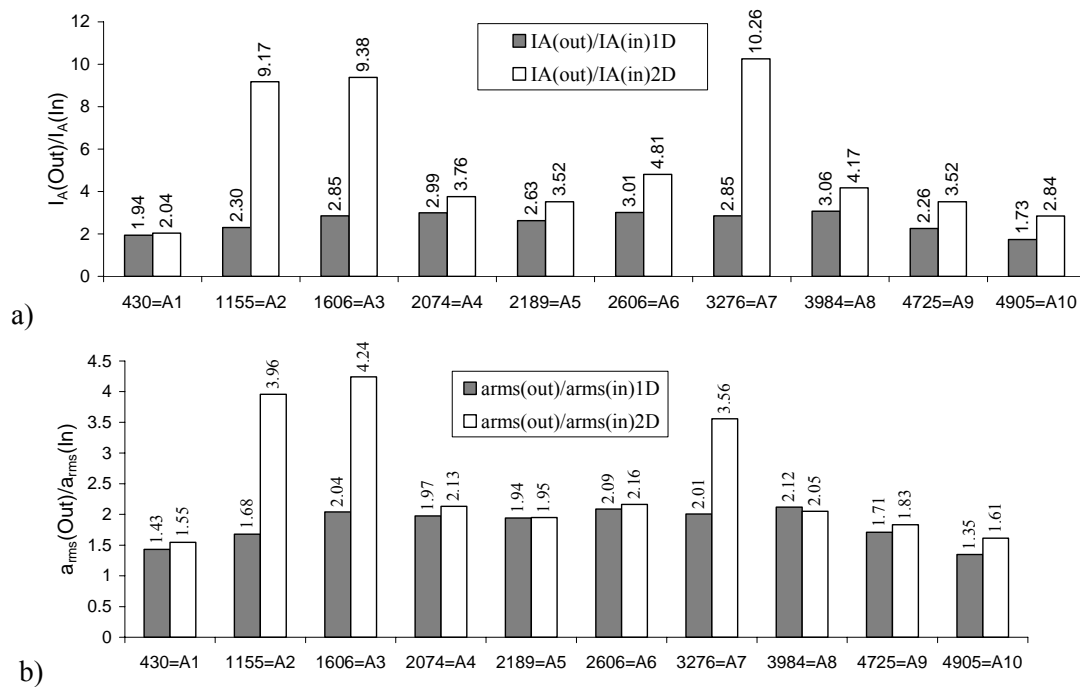
to be completely ineffective. Accordingly it could be substituted by amplification indexes calculated by site response analyses but the choice of the most efficient amplification index is under discussion. The next paragraph tries to give a contribution to such issue.

Evaluation of amplification indexes

The numerical study is focused on the evaluation of the most commonly used amplification index for measuring the site response in terms of structure potential damage. The factors recalled in Equations 2-6 are calculated here for Fivizzano's case studied. It is worth noticing that input motion heavily affects these types of study, so that comparisons of amplification factors shall be calculated with respect to a chosen accelerogram. Accordingly, Figure 8a-e show 5 ratios of amplification factors which are obtained by dividing output values by the input value of each factor, calculated at control points (Figure 4) and for the same input motion. The comparison of these factors show different measures of site response. The analysis of the values is developed here in detail.

As far as Arias Intensity is concerned, the ratios between output values got at nodes of control and the input value are sketched in Figure 8a. These ratios for 1D simulation slightly vary from point to point whereas 2D ratios rapidly increase at those nodes where acceleration response spectra have the biggest peaks. Moreover, this behaviour is sheared by all other amplification indexes as shown in Figure 8a-d. A difference in the trend values is pointed out by Figure 8e where Cosenza-Manfredi damage factors are reported. Such a difference can be justified by the formulation of this factor (Equation 6), where the energy content of the time-history accelerogram is normalized by two peaks, that are PGA and PGV. Accordingly, Cosenza-Manfredi damage factor gives the lowest amplifications among the factors considered and these values are 1.4 on average for 2D analyses and 0.86 for 1Ds.

On the contrary, the highest amplification factors are the ratios of Saragoni index (Figure 8d). It proposes both for 1D and 2D analyses very high values of ratios which vary from point to point up to about 27, 30 and 49 at those nodes where 2D highest amplifications are always calculated.



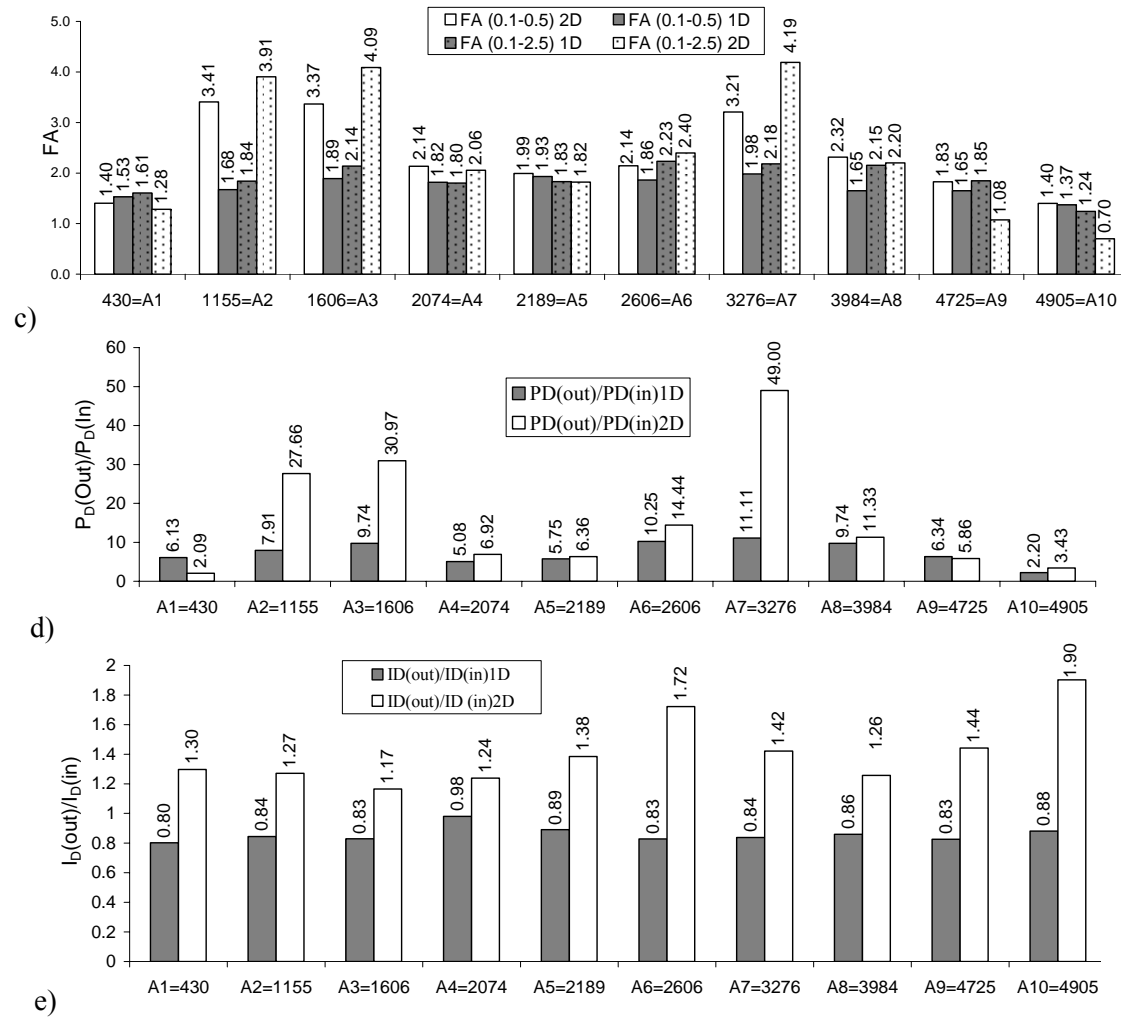


Figure 8. Amplificator indexes ratio between Output and Input values, calculated at Fivizzano site for 1D and 2D analyses: a) Arias intensity ratio; b) Root mean square acceleration ratio; c) Housner amplification factor referred to two period interval: 0.1s-0.5s and 0.1s-2.5s; d) Saragoni index ratio; e) Cosenza-Manfredi factor ratio.

Furthermore the ratio of factors reported in Figures 8b,c appears to give similar results although those parameters seem to have diverse meanings. These ratios are: a_{rms} calculated by Equation 2 and FA, that is $(SI_1)_{out}/(SI_1)_{in}$, indicated as FA_1 , and $(SI_2)_{out}/(SI_2)_{in}$, FA_2 , obtained from Equations 3a,b. FA are drawn from the ratio of the energy contents measured by velocity response spectra while the root mean square acceleration ratios $(a_{rms})_{out}/(a_{rms})_{in}$ come out from the root mean square of the energy content calculated by the time-history accelerogram in the time unit. Accordingly these ratios reach similar values even though the three highest peaks of $(a_{rms})_{out}/(a_{rms})_{in}$ are always greater than FA_1 and FA_2 . FA_1 , calculated between 0.1s and 0.5s, in this case studied, are always less than FA_2 for 1D and 2D simulations in nodes 1115, 1606 and 3276 (Figure 9c), while in other nodes the results of the comparison are not always the same. It means that, where the amplifications are very high, the response at longer periods is always amplified while for less amplification accelerations, low periods are generally magnified.

Finally, from the remarks on the amplification index ratios, it is worth noticing that $(a_{rms})_{out}/(a_{rms})_{in}$ and FA_1 and FA_2 are the parameters that seem to similarly interpret the amplification effects of Fivizzano site response in terms of values. On the contrary, Arias intensity and Saragoni index ratios only follow the general trend but their values are much higher. Moreover, the ratios of Cosenza-Manfredi damage factor seem neither following the common trend nor the amplification values. The latter are the lowest among the calculated values.

In order to make a proposal for seismic design, the author suggest to replace the S factor (that is 1.25 for B soil) with the average value of FA_2 from the three highest values of 2D simulations (that is 4.0) to the B soil spectrum suggested by seismic code. Figure 9 illustrates the final spectrum which seems to follow the actual Fivizzano site response.

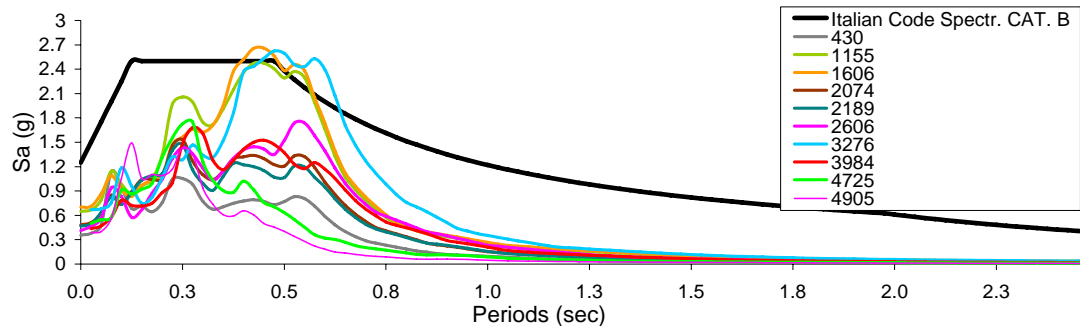


Figure 9. Comparison between Italian code spectrum where S is substituted by FA_2 from 2D analyses and 2D output spectra from site response analyses at Fivizzano town.

CONCLUSIONS

The study presented here refers to the site response analyses at Fivizzano carried out inside the activities of the VEL project supported by Tuscany Region. Such study was focused on the evaluation of the most used amplification factors, to test their capacity of interpreting the overall amplification phenomenon at the site under study. Results are discussed and compared. Moreover, an attempt is made to propose an alternative index to the site factor suggested by seismic codes, S.

The proposal drawn from this study must, however, be strengthened by a wider numerical investigation on several input motions and compared with field actual accelerogram registrations.

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