

## Influence of the magnitude, distance and natural period of soil in the strong ground-motion

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**ABSTRACT:** The knowledge of ground motion predominant frequencies, besides of its amplitude, is an important factor on the engineering point of view, since design of structures requires this kind of information. In relation with this fact, the natural period of soil for each site is an influent parameter to be taken into account, but unfortunately that data not always is available. In this paper we have studied, on the one hand, the frequency dependence of movement for the Friuli and Campano-Lucano earthquakes, in 1976 and 1980 respectively. Attenuations laws as function of magnitude and hypocentral distance have been developed for the response spectra, in terms of pseudo-velocity and acceleration, after a simple classification of soil, by using of the ENEA Data Bank. The behaviour of the different frequencies, in the range of engineering interest, is examined for each class of soil, in order to establish the intervals where each parameter is more critical. On the other hand, an analysis of the natural period of soil has been done for those sites where the necessary information is available (Cross-hole data). For these places, we have found a good fitness between the predominant period of Fourier spectrum, the hypocentral distance and the natural period of soil. The parameters estimated through this analysis may be used, as well as those related to the attenuation laws, in later studies with prediction purposes.

### 1. INTRODUCTION

The ground motion recorded in a site may be considered as a contribution of three factors: radiation at the source,  $F(\omega)$ , attenuation through the travel path,  $T(\omega)$ , and local amplification of site under the recording station,  $S(\omega)$ . Therefore, the parameter which characterizes the ground motion,  $GM(\omega)$ , may be expressed as:

$$GM(\omega) = F(\omega) * T(\omega) * S(\omega) \quad (1)$$

The combination of these three factors fixes the amplitudes distribution of movement, as well as its spectral composition. For this reason, the latest trends in prediction subject are aimed at estimating the amplitude of motion as a function of parameters representatives of source, medium and site, for different frequencies.

In this paper, we have inferred ground motion models in terms of pseudo-spectral acceleration (PSA) and velocity (PSV), for frequencies of 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12.5, 20 and 25 Hz. All of them correspond to a critical damping of 5%. The research is based on data of Friuli earthquakes of 1976 and Irpinia earthquakes in 1980. These laws have given information about the influence of the model parameters- Magnitude, hypocentral distance, and soil conditions -in the amplitudes and frequencies of motion.

### 2. STRONG MOTION DATA ANALYZED

The data used in this study were taken from the ENEA-ENEL Strong Motion Database. These data consist of corrected accelerograms, response spectra, and the corresponding information about local magnitude,  $M_l$ , epicentral distance,  $R$ , focal depth,  $h$ , and the parameter representative of soil conditions,  $S$ .

From values of  $R$  and  $h$ , the hypocentral distance  $R_h$  has been estimated. In this way, we have introduced the focal depth in the analysis, in order to improve the results, since the influence of this parameter in the ground motion at close distances from small to medium crustal earthquakes is an important factor. (Ambraseys and Bommer, 1991)

The parameter  $S$  responds to a simple classification and takes values  $S=0$  for hard and rock sites,  $S=1$  for intermediate soil and  $S=2$  for soft soil, following the common trend adopted by different authors (Joyner and Boore, 1981; Kawashima et al, 1986). This classification has been revised for those stations where cross-hole information is available. The magnitude  $M_l$  has been chosen for the analysis, because it is the most suitable for the distance range of the majority of records.

The maximum of the two horizontal components is taken in the study. The data set consists of 62 records for Friuli earthquakes and 84 for Campano-Lucano shocks. The first one contains records corresponding to a magnitude range between 4.2 and 6.5; their epicentral

distances vary between 2 and 192 Km and their peak ground accelerations, PGA, oscillate from 10.8 and 395 cm/s<sup>2</sup>. The stations are settled: 14 on site S=0, 23 on soil S=1 and 16 on site S=2.

The magnitude range of the Campano-Lucano earthquakes is 4.7-6.5, their epicentral distances vary from 3.4 and 142 Km and the PGA range is 13-334 cm/s<sup>2</sup>. The soil conditions for these records are distributed as follows: 50 stations on site S=0, 10 on site S=1 and 12 on soil S=2.

### 3. REGRESSION ANALYSIS AND ATTENUATION MODELS

The procedure applied for regression of the spectral parameters, in terms of pseudo-spectral velocity, PSV, and pseudo-spectral acceleration, PSA, follows the commonly applied Ln-linearization of the exponential form of the ground motion model.

From the expression for the harmonic wave amplitude in an infinite elastic half-space:

$$A = \frac{A_0}{R^b} e^{aM + qf} \quad (2)$$

taking logarithms and identifying coefficients, it is obtained:

$$\text{Ln } A = c_1 + c_2 M_1 + c_3 \text{Ln } R_h + c_4 R_h \quad (3)$$

where: A is the observed ground motion amplitude

$R_h$  is the hypocentral distance

$c_1, c_2, c_3, c_4$  are the coefficients to be estimated in the analysis.

In the model assumed, the term  $c_3 \text{Ln } R_h$  represents the attenuation by geometrical spreading of the waves front, while  $c_4 R_h$  represents the anelastic attenuation (Dahle et al, 1990).

In our study, a constant  $R_0$  is introduced, which represents the ratio with attenuation zero. Its value is calculated by empirical process and contributes to a better fitting. On the other hand, in order to introduce the soil effect in the model, we have attempted to insert the parameter S in the equation. Thus, the expression originally adopted is:

$$\text{Ln GM} = c_1 + c_2 M_1 + c_3 \text{Ln}(R+R_0) + c_4 (R+R_0) + c_5 S \quad (4)$$

where S= 0, 1, 2 ; according to the soil classification already explained.

The fit with this model gives low significance values for the coefficient  $c_5$ , probably because S is a discrete variable with short range of values. In this way, a first conclusion of this attempt is the preference for separating the data in classes, attending to soil conditions, and the further estimation of independent laws for each type, instead of taking the global sample and inferring laws as function of  $R_h, M_1$  and S.

With these considerations, the model finally adopted in our study takes the form:

$$\begin{aligned} \text{Ln PSA}(\omega) \\ \text{or} \\ \text{Ln PSV}(\omega) \end{aligned} = c_1 + c_2 M_1 + c_3 \text{Ln}(R_h+10) + c_4 (R_h+10) \quad (5)$$

where  $R_0 = 10$  Km is the value found with better fitness, with same exception which can be observed in the tables.

The coefficients  $c_1, c_2, c_3, c_4$  have been calculated by regression analysis.

The goodness of fitting is evaluated by a signification test of the coefficients, as well as the estimation of the quadratic regression coefficient  $R^2$ . Besides, the residual distribution has been analyzed in order to verify the hypothesis of the method: media zero and constant sigma.

#### 3.1 attenuation laws inferred

With the procedure above we have obtained the PSV and PSA attenuation laws, for the regions of Friuli and Irpinia, considering each class of soil independently. For each one, the fit at all the frequencies indicated has been carried out, being the independent variables the magnitude  $M_1$  and the hypocentral distance  $R_h$ , while the one dependent is PSV or PSA for the frequency fixed.

However, only the fitness with coefficient  $R^2$  bigger than 0.80, standard errors smaller than 25 % and high signification levels have been considered valid as attenuation models. With these criteria, the PSV and PSA laws for Friuli earthquakes are presented in tables 1 and 2, respectively, where appear only the models with good fitness. For Irpinia region the study has been done for PSA giving, in general, worse fits than those found for Friuli region. The correspondent laws are shown in table 3. The following has been observed:

- The PSA attenuations adjust to the adopted model of equation (5) for the frequency range 0.1 - 25 Hz in rock sites (S=0), while in those intermediates (S=1) the good fitness corresponds to 5 and 6 Hz, and in the softest soils (S=2) are only found good results at frequencies smaller than 2 Hz.

- The spectral velocity, PSV, presents attenuation according to the model chosen in the range 0.1 to 10 Hz for S=0. There are only good fitness for frequencies smaller than 1 Hz for sites S=1 or S=2.

Taking into account that within each group no representative factor of soil effect is introduced in the regression equation, we will interpretate the results as follows:

- The hard sites don't seem to present attenuation or amplification for spectral acceleration in the whole frequency range studied. Thus, the movement is only a function of magnitude and distance for these sites. We could also deduce a linear soil effect, without variation with  $M_1$  or  $R_h$ .

- Something similar occurs with the spectral velocity, but now the frequency range with lineal behaviour goes down below 10 Hz. This fact is easily justified by the different frequencial composition of the velocity spectrum, displaced to the intermediate frequencies, with respect to the acceleration.

- The softest soils only adjust to the proposed models for low frequencies, similar to the natural one of these

Table 1. PSV models for Friuli earthquakes in rock (S=0), intermediate (S=1) and soft soils (S=2)

$$\ln \text{PSV}(\omega) = c_1 + c_2 M_1 + c_3 \ln(R_h + 10) + c_4 (R_h + 10)$$

$\omega$ (Hz)	$c_1(\omega)$	$c_2(\omega)$	$c_3(\omega)$	$c_4(\omega)$
<b>S = 0</b>				
0.1	6.01	1.84	-4.61	0.03
0.2	5.28	2.02	-4.67	0.03
0.5	6.82	2.17	-5.43	0.04
1.0	6.15	1.74	-4.40	0.04
2.0	9.15	1.76	-5.43	0.04
3.0	8.14	1.75	-5.07	0.04
4.0	6.57	1.73	-4.53	0.03
5.0	7.30	1.35	-4.13	0.03
6.0	5.76	1.14	-3.34	0.03
7.0	8.48	1.07	-4.17	0.03
8.0	4.84	0.91	-2.77	0.02
9.0	3.84	0.64	-2.01	0.01
10.0	4.21	0.44	-1.85	0.01
<b>S = 1</b>				
5.0	-11.6	1.02	4.59	-0.23
6.0	-7.34	1.20	2.12	-0.14
<b>S = 2</b>				
0.1	0.93	1.39	-2.26	0.02
0.2	0.48	1.46	-2.20	0.01
0.5	2.90	1.83	-3.65	0.04
1.0	0.47	1.64	-2.36	0.02

Table 2. PSA models for Friuli earthquakes in rock (S=0) and soft soil (S=2)

$$\ln \text{PSA}(\omega) = c_1 + c_2 M_1 + c_3 \ln(R_h + R_0) + c_4 (R_h + R_0)$$

$\omega$ (Hz)	$c_1(\omega)$	$c_2(\omega)$	$c_3(\omega)$	$c_4(\omega)$	$R_0$ (Km)
<b>S=0</b>					
0.1	-5.60	2.09	-2.24	0.02	0
0.2	-5.88	2.74	-2.98	0.02	0
0.5	-3.26	2.73	-3.28	0.02	0
1.0	4.14	1.82	-3.32	0.02	10
2.0	11.0	1.75	-5.24	0.05	10
3.0	9.64	1.48	-4.11	0.03	10
4.0	9.34	1.53	-3.98	0.03	10
5.0	9.71	1.34	-3.76	0.03	10
6.0	8.09	1.16	-2.89	0.02	10
7.0	12.22	1.02	-3.99	0.03	10
8.0	9.73	0.86	-2.94	0.03	10
9.0	8.82	0.80	-2.54	0.02	10
10.0	9.86	0.70	-2.73	0.02	10
12.5	8.79	0.84	-2.64	0.02	10
20.0	7.99	1.03	-2.83	0.02	10
25.0	7.82	1.08	-2.87	0.02	10
<b>S=2</b>					
0.1	-4.74	1.59	-1.73	0.02	0
0.2	-4.98	1.90	-1.81	0.02	0
0.5	-3.43	2.21	-2.37	0.03	0
1.0	-2.58	1.88	-1.42	0.01	0
2.0	5.48	1.04	-2.21	0.02	10

types of soils. This can be attributed to the fact that the amplification effect is linear only for those frequencies. For higher frequencies, the behaviour doesn't seem regular and may change with the magnitude and the hypocentral distance.

- Although particular laws have been deduced for each class of soil, they have only been formulated as function of  $M_1$  and  $R_h$ , and the result found indicates the need for including other term in the equation, which reflect explicitly the local amplification for frequencies higher than the soil own frequency, where the behaviour is not linear. The election of this term is complicated, since it must consider the possible interaction between the magnitude and the distance in the effect.

As an example, the graphic representations of isolines  $\text{PSV} = f(M_1, R_h)$  and  $\text{PSA} = f(M_1, R_h)$  for rock sites at two frequencies from Friuli records are shown in figures 1 and 2.

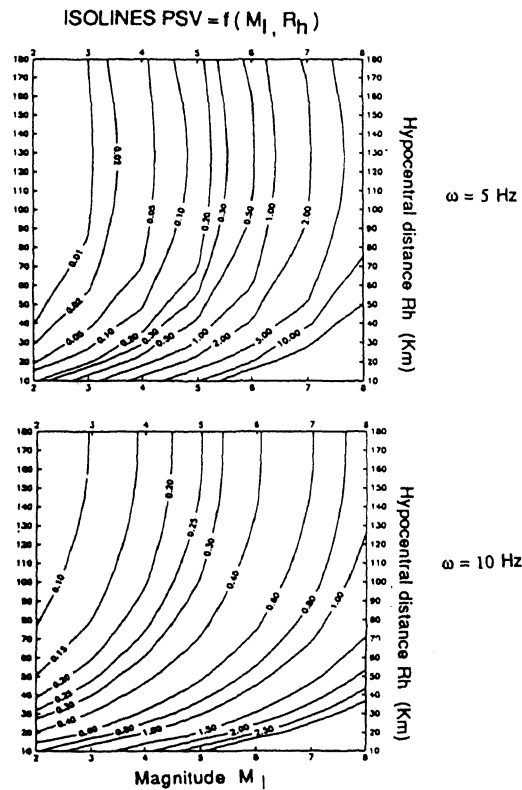


Figure 1. Ground motion models PSV as function of  $M_1$  and  $R_h$  from Friuli earthquakes in rock sites (S=0)

#### 4. INFLUENCE OF MAGNITUDE AND DISTANCE IN THE RESPONSE SPECTRA

An analysis of the influence of  $M_1$  and  $R_h$  in the spectral parameters for different frequencies of movement is presented in the following paragraphs.

Table 3. PSA models for Campano-Lucano earth.  
 $\text{Ln PSA}(\omega) = c_1 + c_2 M_1 + c_3 \text{Ln}(R_h + 10) + c_4 (R_h + 10)$

$\omega$ (Hz)	$c_1(\omega)$	$c_2(\omega)$	$c_3(\omega)$	$c_4(\omega)$
<b>S = 0</b>				
0.1	-11.31	1.03	2.28	-0.05
0.2	-10.81	1.29	1.89	-0.04
0.5	-6.10	1.22	0.82	-0.02
1.0	-1.95	1.07	0.05	-0.01
2.0	4.21	0.63	1.10	-0.02
3.0	2.24	0.46	0.20	-0.01
4.0	0.46	0.33	1.21	-0.04
5.0	1.56	0.34	0.83	-0.03
6.0	1.43	0.24	1.13	-0.04
7.0	2.15	0.22	0.91	-0.04
8.0	1.45	0.24	1.09	-0.04
9.0	1.14	0.26	1.11	-0.04
10.0	0.66	0.30	1.21	-0.04
12.5	0.19	0.30	1.31	-0.05
20.0	0.41	0.30	1.07	-0.04
25.0	1.28	0.29	0.75	-0.03
<b>S = 1</b>				
5.0	1.01	0.44	0.83	-0.02
6.0	4.26	0.27	0.01	-0.01
<b>S = 2</b>				
0.1	20.77	0.6	-7.42	0.09
0.2	20.82	0.72	-6.99	0.08
0.5	29.12	0.67	-8.94	0.10
1.0	17.37	0.59	-4.74	0.04

The analysis has been done, at the first place, for rock sites, where the lineal behaviour is found, from data corresponding to Friuli earthquakes. We have observed that PSA increases from 0.1 to 5 Hz, and decreases for frequencies greater than 5 Hz. The variation is bigger for short distances and it is found a critical value, about  $R_h = 20$  Km, where the graphics present a change of slope.

Something similar occurs with PSV, but the frequency range where this parameter increases is 0.1-2 Hz, being nearly constant between 2 and 5 Hz and decreasing to 10 Hz. The graphic representation of PSA versus  $R_h$  at logarithm scale is shown in figure 3, for the frequencies of 5 and 10 Hz.

In the representation of PSA or PSV versus  $M_1$  it is not possible to observe any determined trend. For high magnitudes, greater than 6, different levels of amplitude are put together, because at this range we have records in far and near field. This fact indicates the inconvenience of analysing the influence of magnitude independently of distance. The same result is observed for  $R_h < 20$  Km, where values for big and small magnitudes are represented together.

For the softest sites,  $S=2$ , it is noted that the spectral amplitude, concerned to PSV and PSA, only shows variations in the range 2-25 Hz and distances smaller than 20 Km. The frequencies lower than 2 Hz are hardly attenuated with distance. On the other hand, for frequencies lower than 5 Hz, the amplitude in soft soils

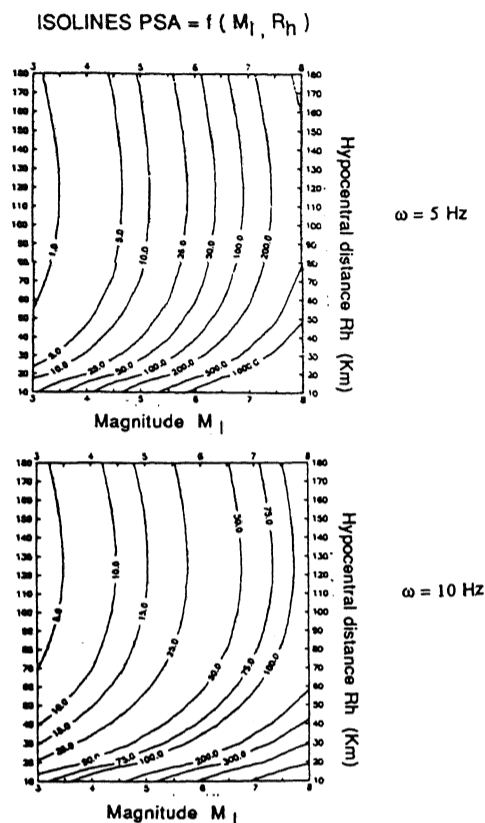


Figure 2. Ground motion models PSA as function of  $M_1$  and  $R_h$  from Friuli earthquakes in rock sites ( $S=0$ )

is bigger than the one found in rock. This seems to respond to a major amplification of soil in this range, in agreement with the results of many authors who confirm the existence of a cross-over period, near 0.2 s

Over this period the amplification on soft soil is greater than the ones on rock, and the relation is inverted for smaller periods (Trifunac, 1976; Joyner and Boore, 1982).

Another fact observed is the nearly linear relationship between  $M_1$  and PSV for the smaller frequencies,  $\omega=0.5$  Hz, in the softer sites. This result is different to that found in rock sites or in soft soils for frequencies bigger than 0.5 Hz. It is in this way that the dependence with distance was shadowed for lower frequencies in soft soil. In figure 4 it is shown the relationship between PSV and  $M_1$  for  $\omega = 0.5, 1$  and 10 Hz and may be observed the quoted effect.

##### 5. PREDOMINANT PERIOD OF MOVEMENT AND NATURAL PERIOD OF SOIL

In order to characterize the soil effect more accurately than through a simple assignation of a factor  $S$ , we have

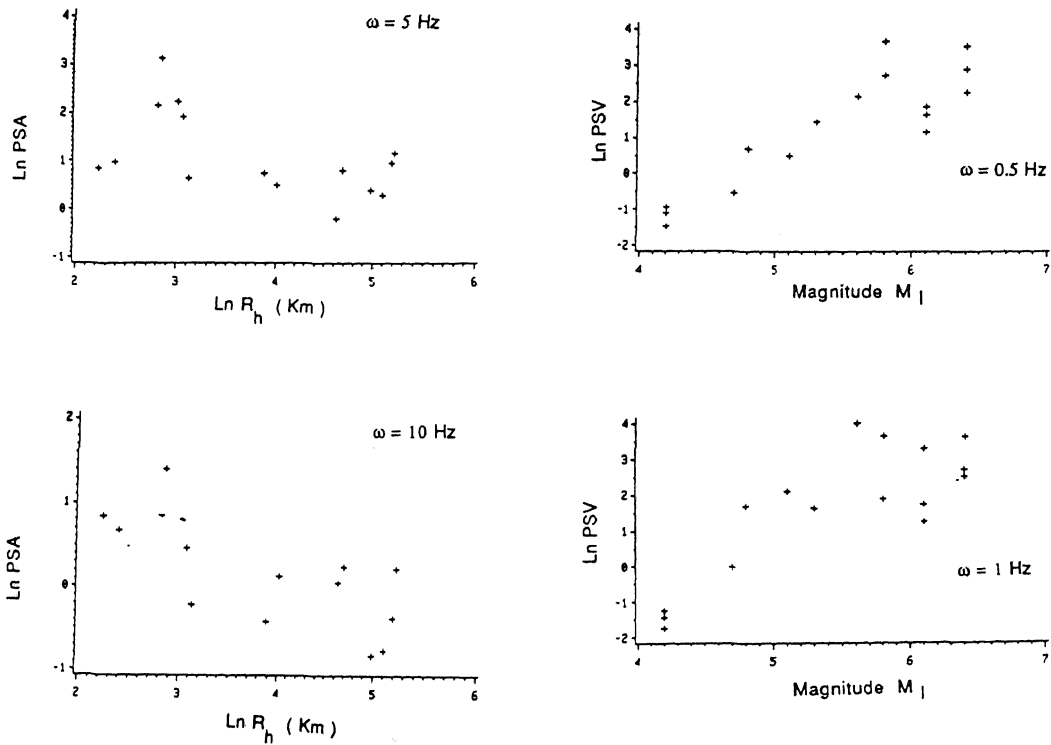


Figure 3. Pseudo-spectral acceleration versus hypocentral distance from Friuli earthquakes in rock sites ( $S=0$ )

estimated the natural period of soil in those locations where the necessary information is available. Such are, essentially, the data about thickness and shearing waves velocity for the layers under the recording station.

As it is well known, the fundamental period of a layer may be determined, approximately, by mean of the expression:

$$T_i = 4 H_i / \beta_i \quad (6)$$

where  $H_i$  is the thickness and  $\beta_i$  the shearing waves velocity. The first peak in the amplification function appears at this period, since  $T_i \beta_i = \lambda$  represents the wave length for constructive interference between the incident radiation and the one reflected in the top (Trifunac, 1990).

In short, when there are several layers above the bed rock, the natural period may be estimated by integration of the previous expression (6).

In our study we have applied this procedure to calculate the natural period of soil, in sites where data of cross-hole are available, with the corresponding values of  $\beta_i$  and  $H_i$ . In particular, the natural frequencies or periods are determined in four locations where a big number of stations are settled. All of them are recording stations of Friuli earthquake. The frequencies estimated for those sites  $\omega_s$ , as well as the class of soil  $S$  assigned in the study are:

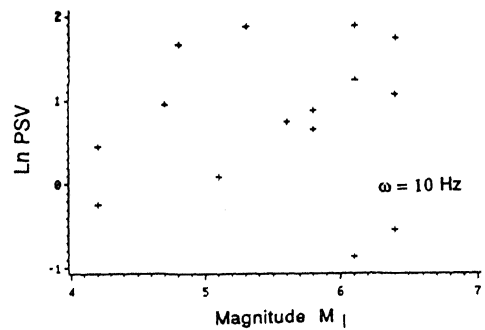


Figure 4. Pseudo-spectral acceleration versus magnitude from Friuli earthquakes in soft sites ( $S=2$ )

S. Rocco	$\omega_s = 7 \text{ Hz}$	$S = 0$
Forgaria-Cornino	$\omega_s = 5 \text{ Hz}$	$S = 1$
Tomba di Buia	$\omega_s = 2.2 \text{ Hz}$	$S = 2$
Maiano	$\omega_s = 2 \text{ Hz}$	$S = 2$

As an example about the cross-hole data which are the starting information for the computation of periods, in figure 5 the velocities profiles for three locations, are shown.

The second step in this analysis has aimed at studying the relationship between the natural period of soil and the predominant period of movement. The dependence of magnitude and distance has also been analyzed.

With this procedure, we try to get information about frequencial composition of movement, complementary with that of the amplitude models already obtained. Following this goal, we have checked different relationships between predominant frequency  $\omega_p$  and the one natural of soil  $\omega_s$ , together with the magnitude and distance. The test has been done taking each one of the independent variables,  $M_1$ ,  $R_h$  and  $\omega_s$  or a combination of them, in order to obtain the more critical influence. The goodness of fitting is evaluated on the same way that was done in the study of amplitudes. The more reliable adjustment corresponds to the following relationships:

Sites S=0  

$$\omega_p = 3.1 R_h - 50.4 \text{Ln } R_h + 16.4 \omega_s \quad (7)$$

Sites S=1  

$$\omega_p = -0.15 M_1 + 0.77 R_h - 10.37 \text{Ln } R_h + 3.89 \omega_s \quad (8)$$

Sites S=2  

$$\omega_p = 2.28 M_1 - 1.47 R_h + 29.7 \text{Ln } R_h - 31.24 \omega_s \quad (9)$$

From the analysis of coefficients we must get the conclusions:

- For each class of soil, the more critical parameter in the predominant period is the natural frequency of soil.
- The distance presents also an important influence on the period of movement, although its weight is minor than the one of  $\omega_s$
- The magnitude doesn't seem to affect hardly the predominant period in rock sites, but shows a little contribution in the softer soils, always minor than  $\omega_s$  and  $R_h$ .
- The best fit is obtained, in all cases, between  $\omega_p$  versus  $\omega_s$  and  $R_h$ . Thus, it is not convenient to neglect the contribution of the two terms in the frequencial composition of ground motion.

The variation of  $\omega_p$  with  $R_h$  for the previous locations: S.Rocco, Forgaria and Tomba di Buia has been analyzed. We can note that in the first one  $\omega_p$  varies between 0.5 and 11 Hz, in Forgaria this range is limited from 3 to 6 Hz for the majority of observations and in the last location  $\omega_p$  is always minor than 5 Hz. In conclusion, the peak amplitudes are presented for similar frequencies to the ones own of soil, when this is intermediate or soft. However, rock sites seem permeable at a bigger frequency range of movement

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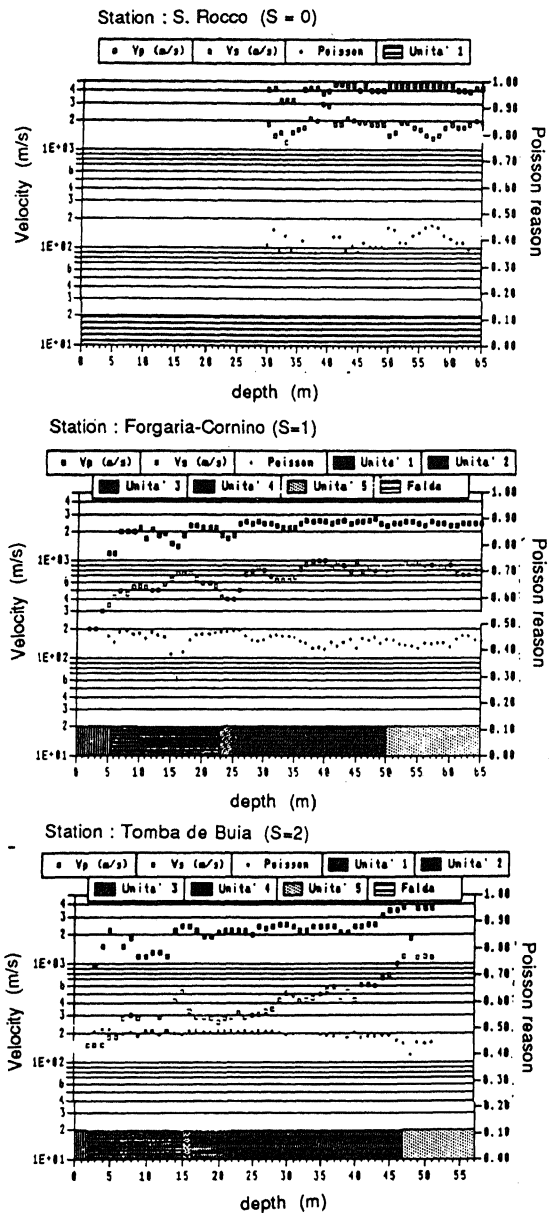


Figure 5. Velocities profile for 3 locations over different classes of soil : rock, intermediate and soft.

## 6. ONGOING RESEARCH

Last trends in prediction of ground motion are aimed at estimating the same probability of exceedence for response spectrum across the whole range of frequencies of engineering interest. As result of this process, an Uniform Hazard Spectrum (U.H.S) may be derived. Benito and Lopez-Arroyo (1991) recently proposed a methodology to obtain a first estimate of the U.H.S in areas where strong motion data are not available

The final aim of the present work is to apply Benito and Lopez-Arroyo methodology to an Italian area, where strong motion data are available, in order to compare the results and value the reliability of the method based on macroseismic data. With this purpose, a seismic hazard research is being carried out in two sites selected in Northeastern Italy: Forgaria and S.Rocco. The macroseismic data used are those reported in the Italian National Catalogue of earthquakes (Postpisch, 1985) and the sources considered for carrying on the hazard calculations are part of a recent seismotectonic zonation of Italy (Scandone, personal. com.) with same modification according to Slejko and Viezzoli (1984)

Two disjoined analysis are performed for sources at distance less than 50 Km from the site and for sources between 50 and 300 Km, in order to obtain for each class an intensity value which, converted in acceleration, can be used to define a point of the U.H.S. The results of this part of the study will be compared with the ones obtained by using the attenuation laws estimated in the present paper.

#### 7. DISCUSSION AND CONCLUSIONS

The estimation of the spectral ground motion models which present good agreement with the observations from Friuli and Campano-Lucano earthquakes, has been carried out from records in rock sites. For this class of soil, we have found that attenuation laws according to the expression:

$\ln GM = c_1 + c_2 M_1 + c_3 \ln (R+R_0) + c_4 (R+R_0)$   
constitute a reliable representation of the spectral parameters within the frequency range: [0.1-25 Hz] for PSA and [0.1-10 Hz] for PSV. This fact could be interpreted as an evidence of the linear behaviour of hard soils, since no term representing local effect is introduced in the equation.

A different behaviour is found for softer soils, where the previous equation predicts the movement only for low frequencies, similar to the natural one of these types of soils. For higher frequencies the effect doesn't seem linear and the prediction of ground motion becomes more complicated. Although the records have been previously classified attending the type of soil, the need for including a term in the model, reflecting explicitly the local amplification out of the quoted range is noted. How could be estimated this term is an open question. In our opinion, the effect for one determined frequency may depend on the natural one of soil as well as the predominant frequency of incident radiation on the bed rock.

A future research will carry out comparisons of records in rock and soft soil, with similar characteristics about magnitude and distance. It will aim to get information about the possible transference of spectral models in rock sites in order to find the correspondent models in softer soils.

Finally, relationships between predominant period of movement, magnitude, distance and natural period of site have been analyzed. The evidence of that the last one is the more critical parameter in the frequency associated at the maximum Fourier amplitude, is the main result of this part of the study.

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