Site effect zonation of the Fabriano municipality

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Summary

In the framework of the Umbria Marche microzonation project, we prepare a first generation site effect zonation of the urban area of Fabriano by means of the analyses of seismometric recordings of aftershocks and seismic noise as well as of geological and geotechnical data collected in the area by different institutions. Velocimetric data have been employed to perform the basic elaboration aimed to the construction of the site effects map. In particular, we examine the incidence angles of P waves to obtain a qualitative appraisal of the rigidity of the deposits under the stations and Nakamura's ratios to prepare a map of the fundamental period of the deposits in the investigated area. Both analyses show a fairly good congruity with geological and lithological information available. Then spectral ratios, which represent our leading estimate of site effects, are analysed in detail. We find relevant amplifications, up to around 7, in zones "Borgo" and "Serraloggia – Spina", the latter is also characterised by considerable variability of expected ground motion as evidenced by the difference in the spectral ratios between stations located at distances less than 200 m. Consequently, considering these elements, we propose a subdivision of the area under examination into five zones distinguished by an overall homogeneous seismic behaviour. For each zone we also estimate the expected amplification in terms of acceleration response spectrum and Housner Intensity. The obtained results, being strongly based on weak motion recordings, should be considered valid only for small deformations. However, by means of geotechnical data available for a borehole, we obtain a preliminary appraisal of the expected entity of soil non linearity potential in one zone. The results show that when PGA in the zone with no amplification is equal to the expected value for a return period of 475 years, amplification of response spectrum for short periods is reduced by a factor of 1.5 with respect to the linear case. For greater periods reduction is negligible.

1. Introduction

In the framework of a microzonation work, the site response evaluation represents a basic step towards the definition of the seismic actions recommended for the area under investigation. As a matter of fact, site effects have been definitively recognised to play a significant role in the characterisation of earthquake ground motion as evidenced both by accelerometric recordings and by damage pattern experienced in many recent and past earthquakes and, in particular, during the Umbria-Marche September-October 1997 sequence. For instance, as pointed out by TENTO *et al.* [1998] a M_S 5.5 event of this sequence was recorded by three accelerometric stations with practically the same epicentral distance and back azimuth. The corresponding peak ground accelerations were 0.14, 0.05, 0.03 g , respectively. Moreover, CAPOTORTI *et al.* [1997] observed a damage corresponding to a Macroseismic Intensity of IX MCS in Cesi (Umbria) and of VII MCS in the nearby village of Cesi Villa situated at about 0.5 *Km*.

In this work site effects in Fabriano village are accounted for by means of the analyses of seismometric recordings of aftershocks and seismic noise as well as of the geological and geotechnical data collected in the area by different institutions in the framework of the Umbria Marche microzonation project [MARCELLINI *et al.*, this issue]. Our results consist in a first generation site effect zonation of the urban area of Fabriano and they also point out the present limitations of this work and consequent investigations that should be performed to improve the quality and reliability of the proposed map.

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2. Velocimetric data acquisition and analysis

In the period October-November 1997 a seismometric temporary network was installed in the urban area of Fabriano to record aftershocks with the specific aim of site effect assessment. A detailed description of the deployment of the array, data acquisition and processing is contained in DE FRANCO *et al.*[2000] whereas FRANCESCHINA [2000] fully describes the obtained database of the selected events and noise samples. In this paragraph we briefly recall the main points concerning the seismometric data used in this study.

The array was deployed at 21 sites (see Fig. 1) mainly on the fluvio-lacustrine deposits that characterise the geology of the area investigated except for two stations that were installed on the outcrops of the Umbro-Marchigiana series (SS1 and SS5) to be taken as reference sites for the analyses. In 10 addi-

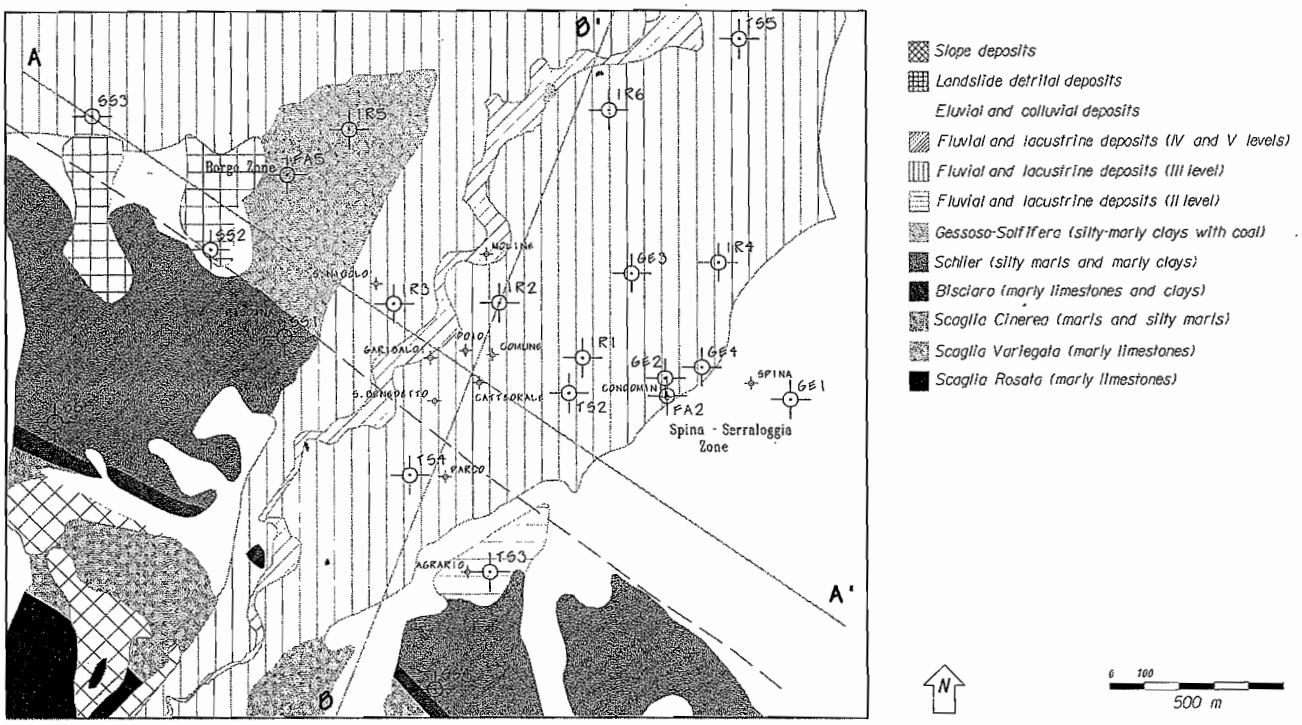

Fig. 1 – Geological map of Fabriano [PARRONI *et al.*, this issue] with location of the stations installed to record aftershocks. Extended names refer to sites where only seismic noise recordings have been collected. Also the 2MS and 9MS drilling sites are indicated. The river Giano flow approximately corresponds to fluvial and lacustrine deposits of IV and V levels.
Fig. 1 – Mappa geologica di Fabriano [PARRONI et al., *this issue] con la localizzazione delle stazioni installate per la registrazione delle repliche. I nomi estesi si riferiscono a siti dove sono state raccolte solo registrazioni di rumore sismico. Vengono indicati anche i siti dei sondaggi 2MS ed 9MS. Il corso del fiume Giano corrisponde approssimativamente ai depositi fluviali e lacustri del IV e V livello.*

tional sites samples of seismic noise were also collected in order to apply the Nakamura's technique. The employed equipment, owned and managed by the different groups that participated in the fieldwork, was not uniform: data loggers were Lennartz Mars-lite, Lennartz Mars88-FD and RefTek 72A-07/HD TERRAPROBE. Sensors were Mark L4C-3D 1*Hz*, Mark L22-3D 2*Hz* and Lennartz LE-3D 0.2 *Hz*. A 24-bit PRAXS data logger equipped with Lennartz 3D-Lite 1*Hz* recorded noise at the 10 additional sites.

About 1500 seismometric 3D recordings corresponding to 114 seismic events (70 events per site on the average) have been collected. For the experimental evaluation of the site effects, the best recorded 40 events occurred in the period 4-14 November 1997 and 30 events occurred in the period 4-6 October 1997 have been selected. Magnitude of these events ranges from M_L 2.1 to 4.6, their hypocentral distance is between 25 to 40 *Km* and their back azimuth, with respect to the centre of the array, is between 170 to 220 degrees. Because of the different kind of sensors we needed to operate a deconvolution for the instrumental response and, to obtain a homogeneous set of records, all data have been high pass filtered at 0.6 *Hz*.

The data evidence a remarkable variability of site effects in the area investigated. For instance, the acceleration response spectra, 5% damping, of a M_L 4.5 earthquake, generated at about 55 *Km*, show a variability as high as 4 for PGA, 6.5 for T=0.1 *s* and 3.5 for T=0.5 *s*. This fact confirms that a microzonation study is appropriate for this area. Velocimetric data have been employed to perform the basic elaboration aimed to the construction of the site effects map. In particular, we examine the incidence angles of P waves to obtain a qualitative appraisal of the deposit rigidity under the recording stations. Then spectral ratios and Nakamura ratios are analysed in detail. The former represent our leading estimate of site effects, the latter are utilised to arrange a map of the fundamental period of the deposits in the investigated area.

Recordings of station SS4 are not deemed completely reliable, therefore we present its results without commenting and using them.

2.1. Incidence Angles

The analysis of the incidence angle of P waves allows a qualitative evaluation of the ratio between Vp of the shallow deposits, where most of the stations are installed and Vp of a reference site. This technique is based on the assumption that the lithology under any examined station should be composed by horizontal and homogeneous layers over-

laying a common bedrock where a plane P wave is impinging. A straightforward application of Snell's law to any couple of stations allows the estimation of the ratio between Vp of the respective shallowest layers.

$$RVp = \frac{\sin(\theta_i)}{\sin(\theta_r)}$$

where θ_i and θ_r are the incidence angle at station i and at the reference station respectively. The incidence angle is evaluated by means of a polarisation analysis of P wave first arrival based on a single value decomposition of a 0.5 *s* window of the 3D recording. This technique, which is described in LANZA *et al.* [1993], has been applied to 8 simultaneously well recorded events in 19 stations. For such events we do not have any recordings for stations FA2 and FA5 which are consequently excluded from this analysis. Station SS5 showed the largest incidence angle and therefore it has been chosen as reference ($\theta_r = \theta_{SS5}$). Tab. I reports the results of these analyses in terms of geometric mean of the computed values of *RVp* ($\underline{RVp}$) and the corresponding boundaries of $\pm$ 1σ interval, assuming a lognormal distribution.

The obtained results are not directly usable with the purpose to esteem Vp since they can be remarkably dependent on the hypotheses previously reported, besides, a Vs assessment would be certainly more meaningful with respect to site effects evaluation. Yet, from a qualitative point of view, these results can be usefully correlated to the geology of the area.

Following the results of Tab. I, we can group our observations as follows:

Stations SS5 and SS1, installed on Schlier outcropping, show the largest incidence angles: their $\underline{RVp}$ values imply a P wave velocity up to 5 times greater than that on some stations installed on fluvio-lacustrine deposits. Therefore these results support their choice as reference sites.

Stations GE1, GE2, GE4 are installed on the fluvio-lacustrine and elluvial-coluvial deposits in the Eastern part of Fabriano (zone "Serraloggia"). They show quite low values of $\underline{RVp}$.

Stations installed in the historical centre of Fabriano (IR3, GE3, IR4, IR2, IR1, and TS2) exhibit $\underline{RVp}$ values comparable to or greater than those found in zone Serraloggia.

Stations installed at North and South with respect to the historical centre (TS5, IR6, TS4 and TS3) show larger $\underline{RVp}$ values compared to those of the historical centre.

The zone to West of the historical centre, zone "Borgo", appears heterogeneous, in fact here every station (SS3, IR5, SS2) is installed on a different formation and shows a different value of $\underline{RVp}$. Particularly, IR5, that is installed on the outcrop of the Gessosa-Solfifera formation, gives the lowest value of $\underline{RVp}$. This fact suggests a considerable superficial alteration that is also confirmed by borehole 9MS [PARRONI *et al.*, this issue].

2.2. *Nakamura's ratios*

Since the first time that Nakamura's technique was reported in the western literature [FINN, 1991] and immediately after tested and applied by LERMO *and* CHAVEZ-GARCIA [1993] there has been a more and more increasing number of its applications. This technique is based on a spectral ratio between the horizontal and vertical components of a recording of seismic noise whose main characteristic is its remarkable stability in various acquisition conditions.

In a recent state of the art paper, BARD [1999] claims that Nakamura ratio, whatever be its theoretical background, does point out the fundamental

Tab. I – Mean *RVp* (see text) and $\pm 1\sigma$ interval, computed with the traces of 8 simultaneously recorded events.
Tab. I – Media di RVp e intervallo corrispondente a $\pm 1\sigma$, calcolati con le tracce di 8 eventi registrati simultaneamente.

Station	RVp	$\underline{RVp} - 1\sigma$	$\underline{RVp} + 1\sigma$	Station	RVp	$\underline{RVp} - 1\sigma$	$\underline{RVp} + 1\sigma$
SS3	0.23	0.12	0.45	TS2	0.21	0.13	0.36
IR5	0.17	0.09	0.32	GE4	0.23	0.16	0.33
SS2	0.42	0.37	0.49	GE1	0.22	0.16	0.30
TS5	0.62	0.55	0.70	GE2	0.22	0.13	0.36
IR6	0.24	0.13	0.43	TS4	0.35	0.23	0.52
IR3	0.37	0.27	0.51	TS3	0.41	0.32	0.53
GE3	0.23	0.11	0.49	SS4	0.57	0.46	0.69
IR4	0.19	0.11	0.31	SS1	0.85	0.78	0.93
IR2	0.26	0.15	0.47	SS5	1.00	1.00	1.00
IR1	0.25	0.13	0.47				

period of soft soil but, in general, cannot provide the complete true site amplification function for incident S waves. Comparison between earthquake spectral ratios and Nakamura ratios in Fabriano area confirms the above statements, as can be seen in Fig. 7. Therefore in this work we prepare a map of the fundamental period of the deposits, T_0, that is the period corresponding to the peak in Nakamura's ratio. For the sake of homogeneity with the site where we have only seismic noise recording, we use Nakamura ratio even where spectral ratios would be available. As described in DE FRANCO *et al* [2000], using 10 minutes of "almost stationary" seismic noise recording, Nakamura ratio is estimated as the geometric mean of about 60 horizontal to vertical spectral ratios computed on overlapping time windows of 20 *s*. Each time window is tapered for 2 *s* at the beginning and at the end and then the computed spectrum is smoothed by means of a triangular window with a half width of 0.5 *Hz*. As an example, Fig. 2 reports Nakamura ratios for some stations along SS1-GE1 section; in the figure it is also showed the variation of the estimated T_0 along the same section.

T_0 values read on Nakamura ratios of about 30 sites have been used as input to an interpolation procedure constrained to assume $T_0 = 0$ *s* for the outcrops of the formations of the Umbro – Marchigiana series. The obtained map, reported in Fig. 3, appears to be in a quite good agreement with the geological interpretations reported in PARRONI *et al.* [*this issue*]. In particular, both the geologic section B-B', that crosses the fluvio-lacustrine deposits from SSW to NNE, and the geologic section A-A' (NW to SE) show an increase of the depth of such deposits, up to almost 30 *m*, in correspondence with the historical centre. Continuing toward North the depth decreases. This description is well reflected in the T_0 map that, in the area of the historical centre, shows values greater than 0.5 *s*. In such an area the T_0 map is well constrained because of the presence of numerous observations. Because of the lack of observation points, isoperiod lines do not have the tendency to close towards East where, on the contrary, the deposit thickness tends to decrease. It should be noted however that, even in the simplest approximation given by a 1D single layer model, T_0 depends both on the thickness as well as on V_S. The latter, given the relevant heterogeneity of the deposits in Fabriano, especially in the zone Serraloggia – Spina, is expected to be quite variable. To the West of the outcrop of the Gessosa- Solfifera formation, T_0 tends to increase reaching values greater than 0.4 *s*. However, the shortage of points of observation in this area does not allow obtaining a conclusive description. T_0 of the stations installed directly on the outcrop of the Gessosa- Solfifera formation varies between 0.2 and 0.3 *s* confirming the presence of superficial alteration already found by sur-

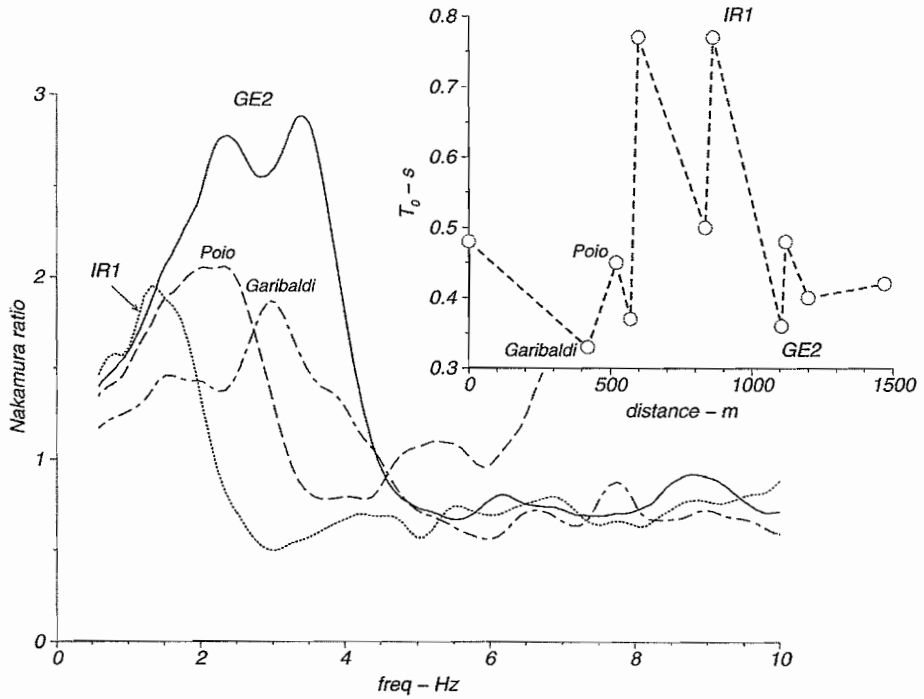

Fig. 2 – Nakamura ratios at some stations situated along the SS1-GE1 section. In the inside panel: T_0 variation along the same section.

Fig. 2 – Rapporti di Nakamura per alcune stazioni situate lungo la sezione da SS1 a GE1. Nel pannello interno: variazione di T_0 lungo la stessa sezione.

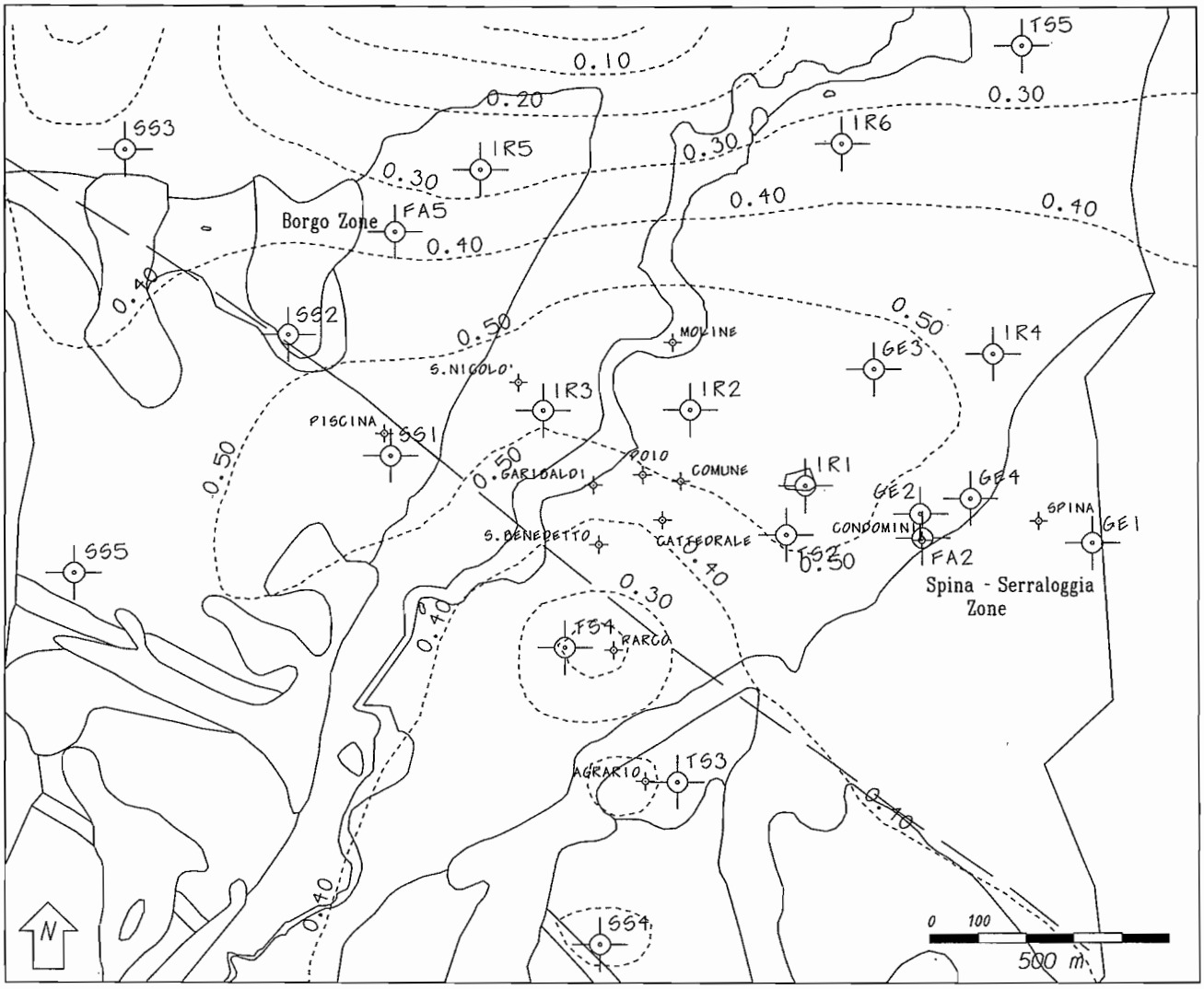

Fig. 3 – Map of the fundamental period of the sediments (T_0), as derived from Nakamura ratios.
Fig. 3 – Mappa del periodo proprio dei depositi (T_0), ricavato dai rapporti di Nakamura.

vey 9MS [PARRONI *et al.*, this issue] and by the analysis of incidence angles.

Given the good congruity found between geologic and seismic information, the presented map of T_0 should be considered rather reliable especially in the area of the historical centre. For the other areas, information presently at disposal only allows to draw a preliminary map. That means that additional ambient noise recording would be needed.

2.3. Spectral ratios

In order to provide reliable and stable seismic response evaluations, spectral ratio technique is presently largely employed [FIELD and JACOB, 1995]. In this work we also use such a technique: an example of the obtained results is shown in Fig. 4. In this figure we show the 95 % confidence interval of the expected spectral ratio together with the interval corresponding to $\pm$ 1σ when a lognormal distribution is assumed. It can be observed that spectral ratios are quite stable, being their variability limited inside a factor 1.5; moreover the number of the recordings used seems definitely enough since it allows to achieve an error of the expected value around a factor of 1.15. For spectral ratio computation we select a time window starting 0.5 *s* before the S arrival time with total duration varying from 8 to 20 *s* from one event to the other and from one station to the other, depending on the level of signal to noise ratio. Before computing the Fourier transform we choose the minimum duration for the couple of stations involved in the successive spectral ratio. Data are also tapered for 0.5 *s* at the beginning of the time window and for 2.5 *s* at the end. Spectra are then smoothed by means of a triangular window with a half width of 0.5 *Hz*.

Spectral ratio technique is based on the selection of a site supposed without any site amplification and where recorded seismic signal would correspond to the bedrock motion. Practically this situa-

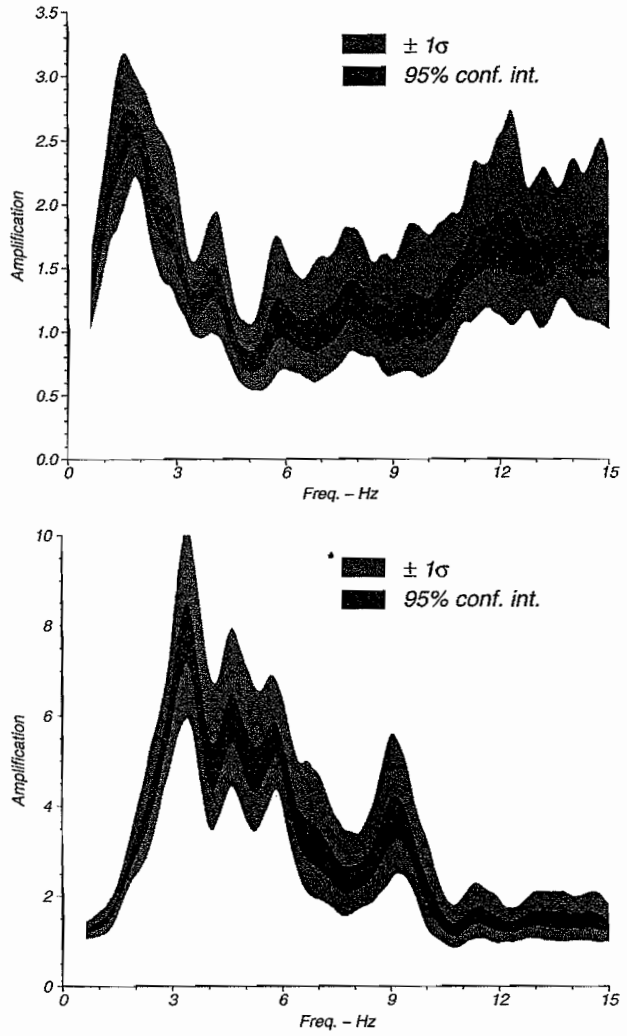

Fig. 4 – 95% confidence interval and ±1σ interval of the N-S component IR1/SS5 spectral ratio (upper panel) and N-S component SS3/SS5 spectral ratio (lower panel).
Fig. 4 – Intervallo di confidenza del 95% e intervallo corrispondente a ± 1σ della componente N-S del rapporto spettrale fra IR1 e SS5 (pannello superiore) e fra SS3 e SS5 (pannello inferiore).

tion can be problematic to be met because both superficial weathering and topography can cause, for particular frequencies, amplifications or deamplifications of the seismic waves, even for stations installed on particularly competent formations. Then, the computed spectral ratios can be contaminated by such perturbations and therefore they cannot fully reflect the local geologic structure. In Fabriano, as described in DE FRANCO *et al.* [2000] two stations were installed on the outcrops of the Umbro-Marchigiana series, SS5 and SS1 (the station SS4 in following analyses is not considered because of some problems occurred during its operation). Both SS1 and SS5 stations, from a geologic point of view as well as from the analyses of incidence angles, seem to have the characteristics of reference sites. In Fig. 5 it seems that SS1 should be a better reference

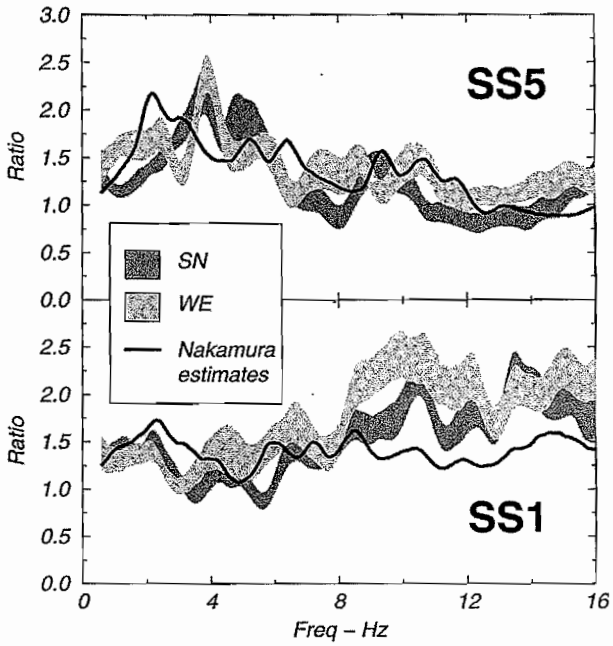

Fig. 5 – 95% confidence interval of receiver function and Nakamura ratio of stations SS1 (dark areas) and SS5 (light areas).
Fig. 5 – Limite di confidenza del 95% della funzione ricevitore e rapporto di Nakamura delle stazioni SS1 (aree scure) ed SS5 (aree chiare).

station than SS5 since its receiver function and the Nakamura's ratio are almost flat and closer to unity with respect to the other station. Besides, the spectral ratio between the two stations shows that ground motion in SS5 is amplified with respect to SS1 (see Fig. 7).

One more remark reported in DE FRANCO *et al.* [2000] concerns the general homogeneity between the spectral ratios of the two horizontal components. To verify this aspect in detail, we compute spectral ratios of the rotated components in longitudinal and transversal direction with respect to the axis of river Giano valley (Fig. 1). The results, reported in Fig. 6 for some stations, do not seem to evidence remarkable differences between such horizontal components. However, because of the narrow interval of back azimuth of the recorded events, it has not been possible to verify the stability of the results in comparison to the direction of the origin of the seismic waves. This last fact represents one of present limitations of our analyses, in fact to the East of Fabriano is located a particularly active seismogenic zone to which is associated the earthquake that in 1741 produced the largest Macroseismic Intensity (IX MCS) ever experienced in Fabriano [CASTELLI and MONACHESI, this issue].

In the following analyses we therefore choose to use the spectral ratios averaged on the two horizontal components. Fig. 7 reports the spectral ratios referred both to SS1 and SS5. We give more weight to

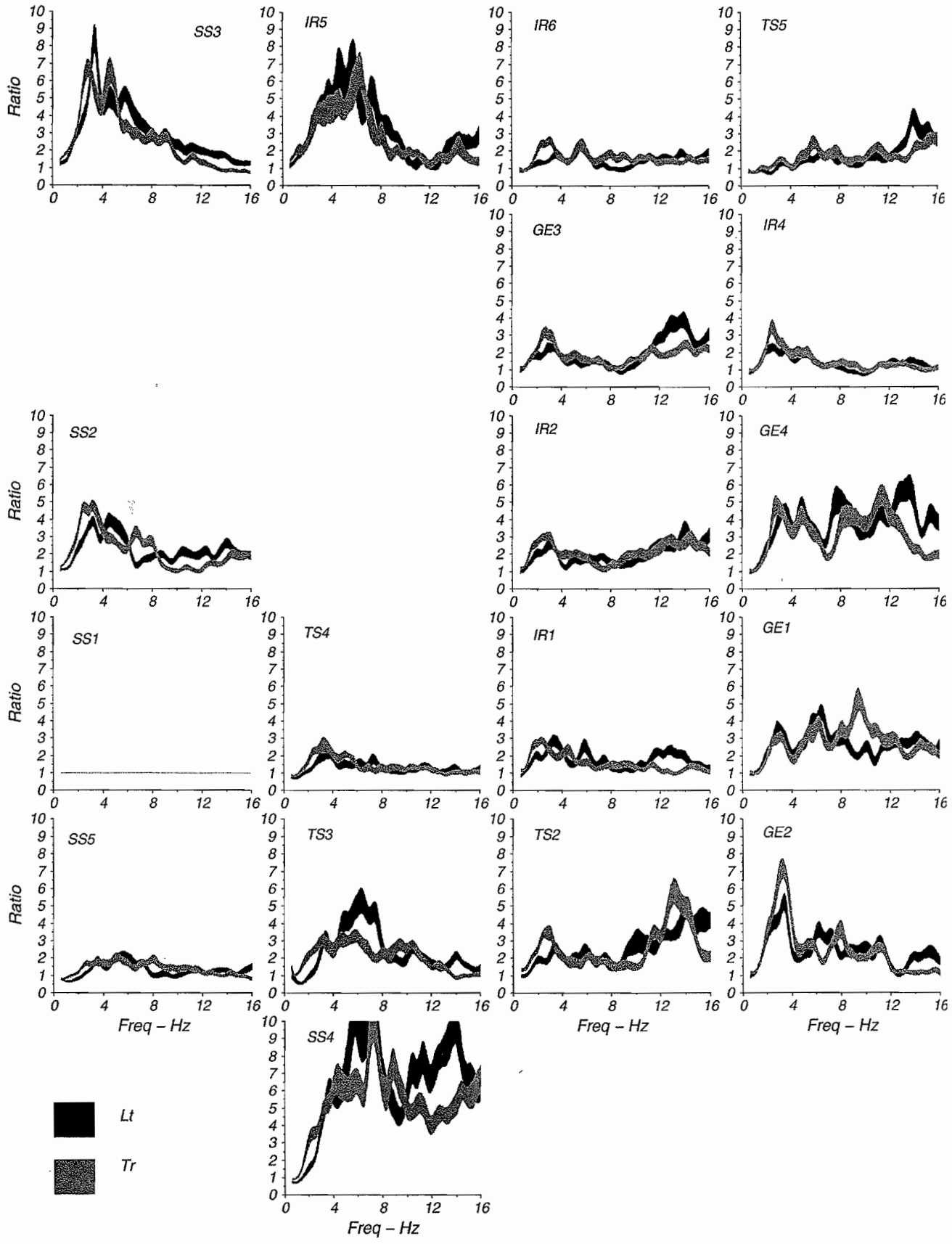

Fig. 6 – Horizontal components spectral ratios with respect to the SS1 station. Recorded horizontal components have been longitudinally (Lt) and transversally (Tr) rotated respect to the river Giano valley.

Fig. 6 – Rapporti spettrali delle componenti orizzontali rispetto alla stazione SS1. Le componenti orizzontali registrate, sono state ruotate longitudinalmente (Lt) e trasversalmente (Tr) rispetto alla valle del fiume Giano.

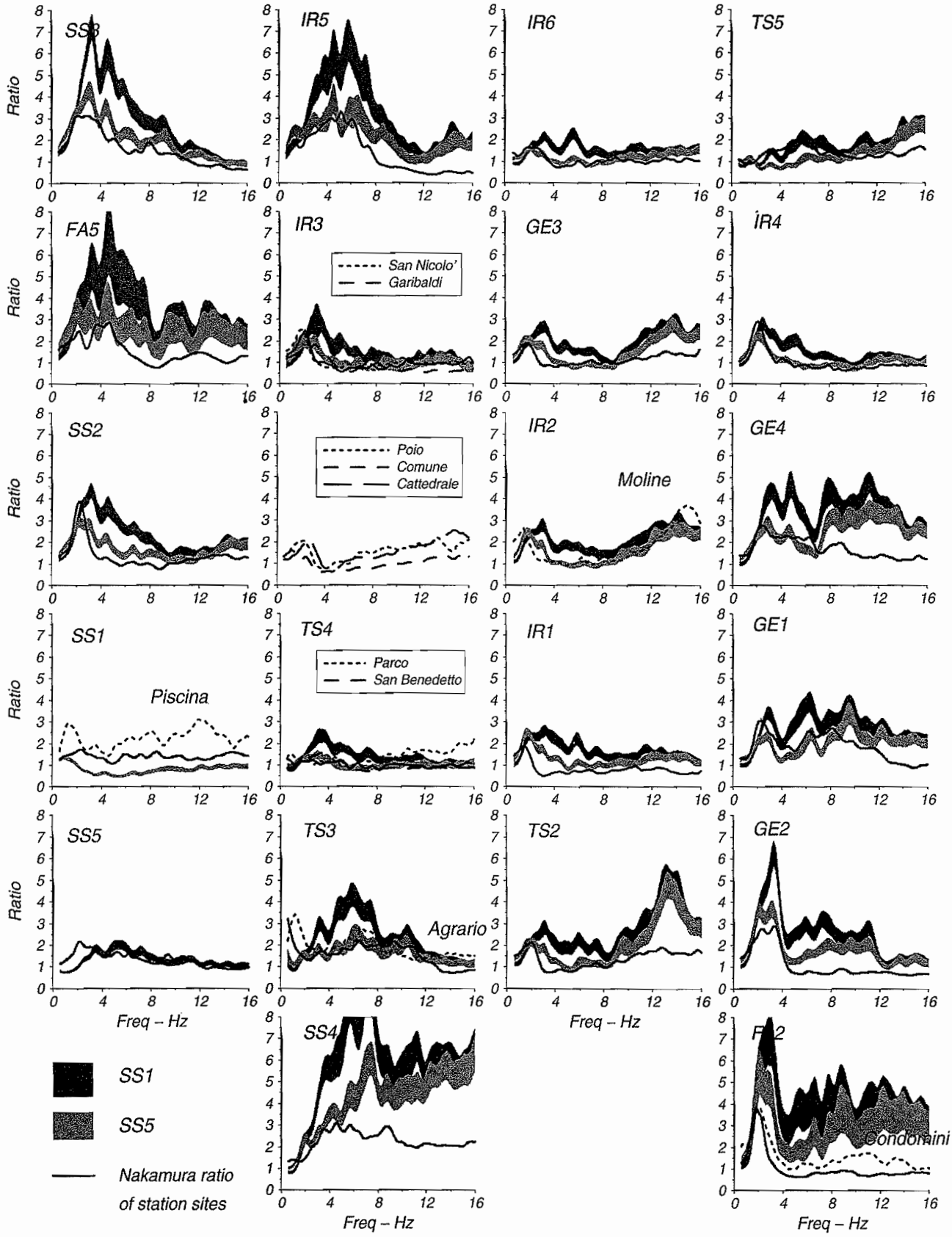

Fig. 7 – 95% confidence interval of the spectral ratios with respect to stations SS1 (dark areas) and SS5 (light areas). Continuos lines refer to Nakamura' ratios at station sites. Dashed lines refer to the additional sites where ambient noise was recorded.
Fig. 7 – Limite di confidenza del 95% dei rapporti spettrali rispetto alle stazioni SS1 (aree scure) ed SS5 (aree chiare). Le linee continue si riferiscono ai rapporti di Nakamura dei siti stazione. Le linee tratteggiate si riferiscono agli ulteriori siti dove è stato registrato rumore ambiente.

the former because of the reasons explained above and because they generally show a higher amplification level. Following the results of Fig. 7, we can observe:

- Stations SS3, SS2, FA5 and IR5, located in zone Borgo, present analogous characteristics despite they are installed on three different lithotypes. In particular, spectral ratios are wide band with amplifications greater than 2.5 in the interval between 2 and 8 *Hz*. Station SS2 shows minor amplification but the spectral ratio shape is similar to that of the others three stations.
- Stations IR3, IR2, IR1, TS2, GE3 and IR4 evidence an amplification peak, whose level is between 2.5 and 3, for frequencies between 2 and 3 *Hz*. This feature is typical for these stations that are installed in quite wide area and that can be distant each other up to about 1 *Km* (for instance IR4 and IR3).
- Spectral ratios referred to SS1 of stations TS4 and IR6 are similar to the preceding ones but they show negligible amplification when SS5 is taken as reference. Also the station TS5 does not present any relevant amplification in comparison to SS5 whereas with respect to SS1 there is a peak of limited value (of about 2) around 6 *Hz*.
- Station TS3, located on II order fluvio lacustrine deposits, shows an amplification of about 4 around 6 *Hz*.
- Stations GE2 and FA2 show a considerable amplification, up to around 6, in the interval between 2 to 4 *Hz*. These stations are installed at a distance less than 100 *m*.
- Stations GE4 and GE1 display a lower amplification than the preceding ones but in a wider interval of frequency, approximately between 2 and 12 *Hz*. It should be noted the remarkable variability between spectral ratios of stations GE2-FA2 and that of GE4 at a distance shorter than 200 *m*.

This analysis describes the main characteristics of the computed spectral ratios but their interpretation is presently not yet complete. For example, it has been observed that SS3 shows a greater amplification for higher frequencies in comparison to the stations of the historical centre. These stations have the same substratum constituted by Gessosa-Solfifera formation though the spectral ratios are referred to stations lying on the Schlier outcrop. For the sake of simplicity, if we refer to 1D models, these observations would imply that in the zone around SS3, both V_S and the fluvio lacustrine deposit thickness are rather lower than those relative to the stations in the historical centre. Alternatively it is possible to explain such observations assuming, in the two zones, different V_S and thickness of Gessosa Solfifera formation that consequently could not be assimilated to the seismic bedrock for this case. Thus, a definitive understanding of site effects in Fabriano area will be possible with the availability of more information on the dynamic properties of the deposits. Besides, for some zones the number of observation points are not enough. To get a sufficiently uniform areal coverage, at least ten additional station sites would be needed.

3. Zonation

In the preceding paragraphs we have described the available elements for the evaluation of site effects. A possibility to assemble such information would be the productions of some amplification maps derived by spectral ratios and arranged for some intervals of frequency, as been done, for instance, by HARTZELL *et al.* [1998]. We choose not to follow this option because the quantity and the areal distribution of spectral ratios are not sufficient and because we consider more useful a map that characterise the examined area in terms of zones with overall homogeneous seismic behaviour. Therefore we operate the following subdivision of the area under examination that, being strongly based on aftershock recordings, should be considered valid only in range of small deformations. However a brief account of soil non linearity issue is reported in the next paragraph.

Referring to Fig. 8 we identify these zones:

zone 0

Zone with amplification 1. Such zone is limited by the geologic boundaries of the Schlier and Bisciaro formations and includes the stations SS1 and SS5. Such formations can be considered as seismic bedrock on the base of geological evidences, receiver functions and Nakamura ratios. Besides, the highest P wave incidence angles are observed in this zone.

zone 1

This zone, which approximately corresponds to zone "Borgo", comprises three different kinds of lithotypes. It is characterised by the spectral ratios of the stations SS3, SS2, IR5 and FA5 which show the highest amplification experienced in the investigated area attaining values greater than 2.5 in a wide frequency band, from 2 to 8 *Hz*. In this zone the incidence angles are relatively different, for instance, IR5, which shows the lower value, is installed on the outcrops of Gessosa Solfifera. T_0 map and a geologic survey also confirm the presence of superficial alterations for such a formation. Zone 1 is limited at South by the border of zone 0. To East, on the base of the available data, the border cannot be well determined and therefore we make it coincide to the limit of the outcrop of the Gessosa Solfifera formation.

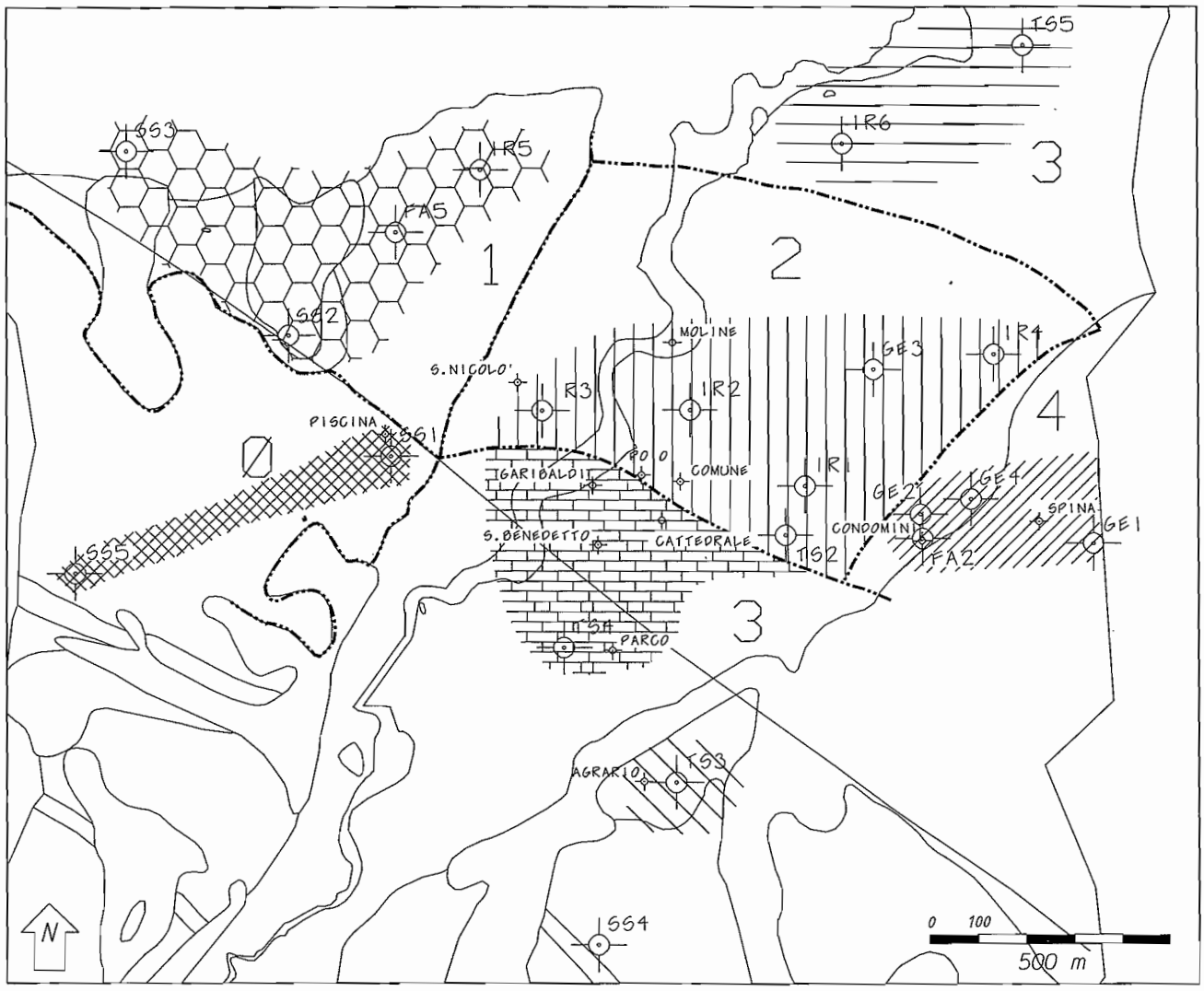

Fig. 8 – Zonation of site effects in Fabriano.
Fig. 8 – Zonazione degli effetti di sito in Fabriano.

zone 2

This zone approximately encompasses the Fabriano historical centre. It is characterised by spectral ratios of the stations IR3, IR2, IR1, TS2, GE3 and IR4, with an amplification peak around 3 between 2 and 3 *Hz*. In this zone the incidence angle is comparable or greater than in zone 4. Areas around sites IR6 and TS4 have not been included in this zone for the reason reported in spectral ratios paragraph and because T_0 map denotes a remarkable increase of the fundamental period value in proximity of the historical centre. Consequently we choose to make use of isoline 0.5 *s* furnished by such a map to draw the Southern and Eastern limit of this zone 2.

zone 3

This zone includes the stations TS4, TS3 at South and IR6, TS5 at North. Spectral ratios of TS4 and IR6 have similar characteristics compared to those of the zone 2, whereas TS5 does not exhibit any particular amplification and ground motion at TS3 should be amplified at higher frequencies. Incidence angles are in general higher than those of the zone 2. The motivation to distinguish this zone from zone 2 has been previously reported. Besides, the shortage of stations in the Northern part of this zone does not allow to demarcate a reliable limit with zone 2.

zone 4

This zone corresponds to "Serraloggia – Spina" and is characterised by spectral ratios of stations GE2, GE4, FA2 and GE1. Relevant amplifications are expected: up to 6 in the interval between 2 and 4 *Hz* (GE2-FA2) and a little lower but over a wider frequency range for GE4 and GE1. A relevant feature of this zone is the considerable variability of the expected ground motion as evidenced by the difference in the spectral ratios between GE2-FA2 and GE4 located at less than 200 meters. Incidence angles are the lowest in the Fabriano area. It is possible to de-

limit such zone only to East at the boundary with zone 2 on the base of T_0 map.

In order to assemble the zonation map of site effects in a way more directly usable for application, we characterise every zone in terms of amplification of acceleration response spectrum with 5 % damping (*SAR*) and of amplification of the Housner intensity (*SIR*). In this work we compute the Housner intensity, which is the integral of pseudo velocity response spectrum with damping 5 %, for periods between 0.1 and 0.5 *s*, as suggested by PERGALANI *et al.* [1999]. As reported in SAFAK[1997], response spectra ratio can be dependent on the spectral content of ground motion. Therefore, being our results intended for strong ground motion, we cannot directly compute *SAR* or *SIR* from aftershock recordings. We have then adopted a three step procedure:

1) FRANCESCHINA *et al.* [*this issue*] assessed the seismic hazard for Fabriano in terms of uniform hazard acceleration response spectrum for 475 year return period referred to the site category "rock". Lithotypes with good mechanical properties and average V_S in the shallowest 20 *m* greater than 800 *m/s* belong to such a category. This situation can be associated to zone 0.
2) The input motion used for site effect analyses consisted in some real accelerograms, selected from the Italian accelerometric data bank, whose opportunely scaled response spectra were similar to the hazard spectrum. The accelerograms of the Italian accelerometric data bank were appropriately scaled in both acceleration and time scale to make them conform as much as possible to the target spectrum. Time scaling was constrained to be between ± 20 %. Ten modified accelerograms, which showed the most pronounced similarity to the target spectrum, were then selected for the analyses [TENTO, 1999].
3) The spectral ratios described previously can be considered as empirical transfer functions between the seismic motion of zone 0 and that of the other recording stations. They are then used to perform the convolution of the selected accelerogram following the procedure used in TENTO *et al.* [1998] which does not correctly reconstruct any synthetic accelerogram but, rather, it attains an approximate evaluation of response spectra values.

As regard to point 2), it should be noted that the shape of uniform probability response spectra depends on the frequency of occurrence of small events relative to large events (Gutemberg-Richter *b* value) [MARCELLINI, 1995], therefore in principle, such spectra could not be directly related to any time history and their shapes may be different from those of events expected to occur with a comparable return period. Nevertheless we deem this procedure suited for our aim which only consists in obtaining some time histories which enable us to estimate how such uniform probability response spectra would be amplified by site effects.

The obtained results in terms of *SAR* and considering SS1 as reference station, are reported in Fig. 9. In the same figure, for the available cases we display the estimations of the fundamental period of the building near to or containing the recording station [CALVANO and MONACHESI, 1998]. From this figure it can be observed that in some cases the fundamental period of buildings is next to the period of the maximum of *SAR*, in such cases the vibrations of the building could have altered the seismic recordings. However, apart from the case of TS3, for each zone the shape of *SAR* is generally common to all stations suggesting therefore a good reliability of the results. Unfortunately, the effect of building vibrations on seismic recordings is still a remarkable problem of difficult quantification in site effect studies in urban areas. Similarly, Tab. II reports the values of *SIR* calculated for every station.

SAR and *SIR* values give a quantitative description of site effects for the proposed zones. A clear difference between zone 1 and 4 with respect to zone 0 can be observed, whereas for zones 2 and 3 the amplifications are of smaller entity and quite similar between them.

Tab. II – Housner Intensity Ratio estimations (*SIR*).
Tab. II – Stime del rapporto di intensità di Housner (SIR).

Zone 0		Zone 1		Zone 2		Zone 3		Zone 4	
Station	SIR	Station	SIR	Station	SIR	Station	SIR	Station	SIR
SR5	1.5	FA5	4.5	GE3	2.0	TS4	1.8	FA2	4.8
		IR5	4.3	IR1	2.2	TS3	2.7	GE1	2.8
		SS2	3.4	IR2	2.1	IR6	1.8	GE2	3.8
		SS3	4.9	IR3	2.1	TS5	1.3	GE4	3.5
				IR4	2.1				
				TS2	2.2				

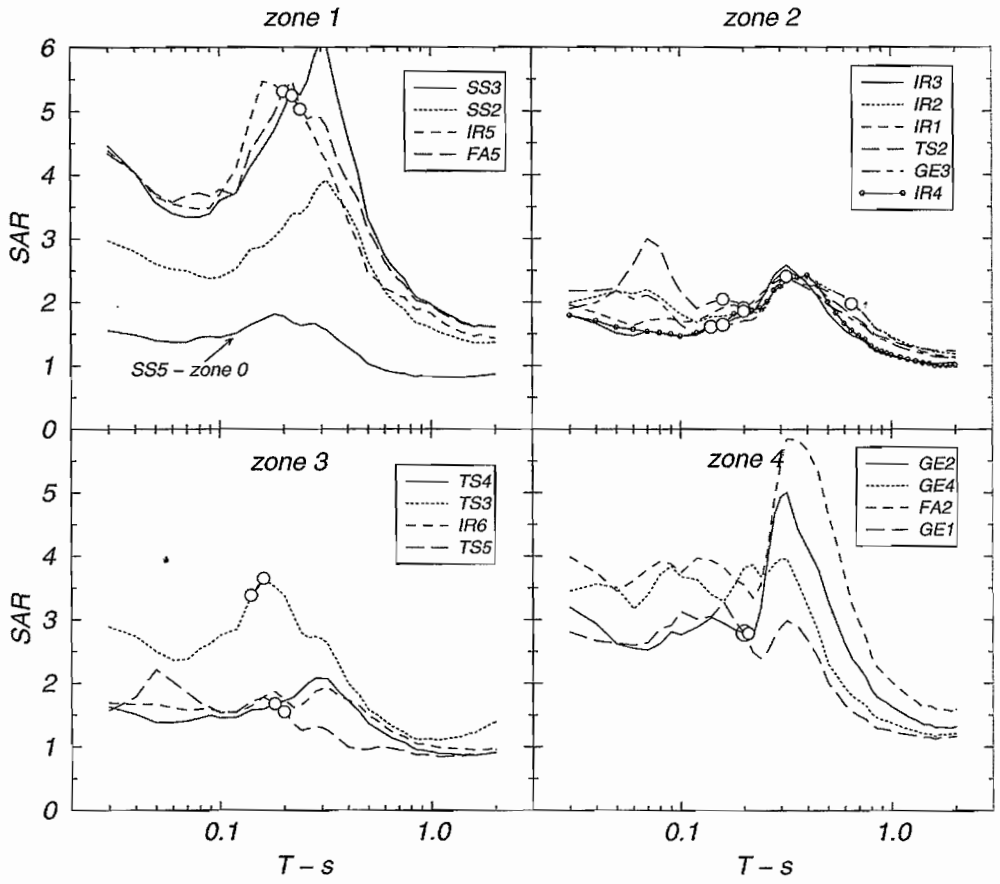

Fig. 9 – Acceleration Response Spectra Ratio (5% damping) (*SAR*). Circles indicate the estimation of fundamental period of the buildings located near the recording stations.
Fig. 9 – Amplificazione dello spettro di risposta di accelerazione al 5% di smorzamento (SAR). I cerchi indicano la stima del periodo proprio degli edifici vicini alle stazioni di registrazione.

4. Soil non linearity

The results shown in the last paragraph have been obtained using the spectral ratios calculated with recordings of low magnitude events. Such results refer, therefore, to a linear behaviour of the various lithotypes under seismic loading. A complete evaluation of site effects should also include an assessment of *SAR* variation with respect to the amplitude of input motion.

In the framework of the geothecnical investigations executed in Fabriano, some undisturbed soil samples have been tested in laboratory in order to assess their dynamic properties [CRESPELLANI *et al.*, 2000]. In particular for borehole 2MS, CRESPELLANI *et al.* [this issue] obtained the relationships between G/G_0 and damping with respect to the amplitude of shear strain. Besides, for the same site a Vs profile is available. Borehole 2MS is located in zone 1 in landslide detrital deposits at 400 *m* from stations IR5 and SS3, at 240 *m* from SS2 and at 200 *m* from SS2 (see Fig. 1). Information provided by this borehole can be synthesised as follows.

- First 6 *m* of landslide detrital constituted by silty clay with Vs of 150 *m/s*.
- From 6 to 15 *m* of elluvial deposit constituted by clayey silt with Vs of 270 *m/s*. At 6.5 *m* the undisturbed sample has been taken for laboratory test.
- At a depth of 15 *m* the Gessosa Solfifera formation is encountered. It is composed by bituminous marls with Vs of 520 *m/s*. The borehole reaches the depth of 24 *m*.

Given the distance of borehole 2MS from the recording stations, a direct comparison between the computed transfer function and spectral ratios would not be meaningful. We then apply the same procedure described before to obtain *SAR* for site 2MS. In this case instead of using a spectral ratio, we employ the linear transfer function for vertical incidence of S waves computed with the available Vs profile data. We arbitrarily add a layer of 30 *m* with Vs of 800 *m/s* to such profile, to account for the extension of the Gessosa Solfifera formation up to the seismic bedrock whose Vs value is assumed as 1400 *m/s*.

If we want to compare the obtained *SAR* with those derived from spectral ratios of the stations of zone 1, we will have to take into account that the latter are computed with respect to a station of zone 0

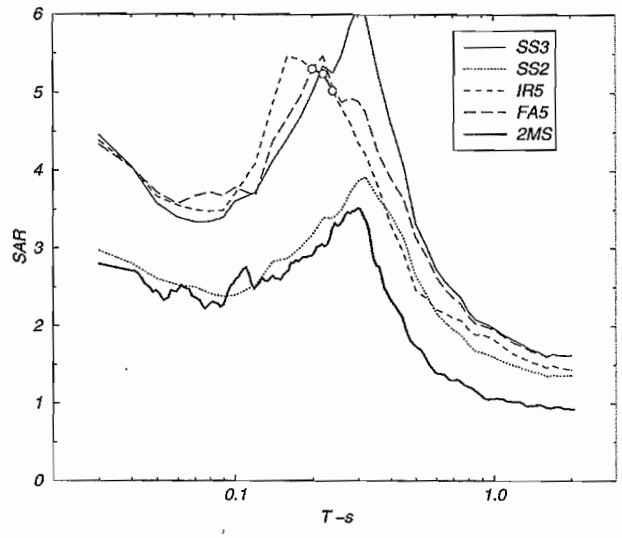

Fig. 10 – Acceleration Response Spectra Ratio (5% damping) (*SAR*). Comparison between the *SAR* of the stations of zone 1 and the *SAR* evaluated at the 2MS drilling site – linear case.

Fig. 10 – Amplificazione dello spettro di risposta di accelerazione al 5% di smorzamento (SAR). Confronto fra il SAR delle stazioni della zona 1 e il SAR valutato nel sito del sondaggio 2MS – caso lineare.

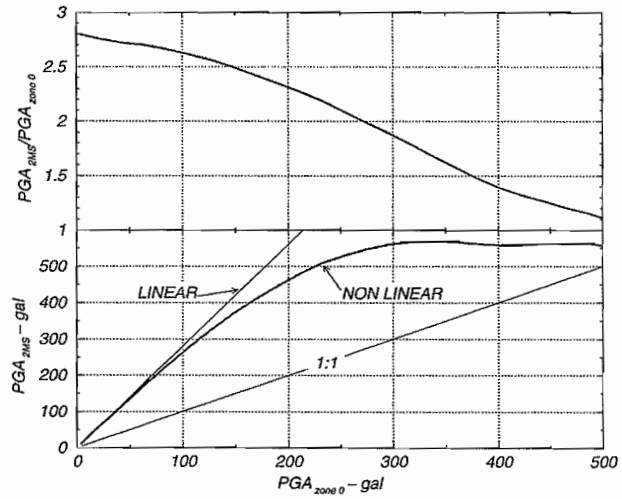

Fig. 11 – Upper panel: amplification of PGA at site 2MS with respect to PGA_{zone0}. Lower panel: PGA at site 2MS vs. PGA_{zone0}.

Fig. 11 – Pannello superiore: amplificazione di PGA al sito 2MS rispetto a PGA_{zona0}. Pannello inferiore: PGA al sito 2MS in funzione di PGA_{zona0}.

with a probable presence of superficial alteration. To account for this fact, on the base of some simulations the motion in zone 0 is supposed to be amplified by a factor of 1.25 in comparison with the imposed motion at the bedrock of 2MS profile. The accordingly modified *SAR* of 2MS site, displayed in Fig. 10, appears to be compatible with those derived from spectral ratios of the stations of zone 1. This fact allows us to consider the following qualitative assessment of the significance of soil non linearity of 2MS site as representative of zone 1. Therefore we used the linear equivalent procedure as implemented in the code SHAKE [SCHNABEL *et al.*, 1972] to model the seismic response of 2MS site. We use the curves of G/G_0 and damping versus shear strain found by CRESPELLANI *et al.* [this issue] for layers up to 15 *m* of depth, then, for the Gessosa Solfifera formation, those reported in SEED and IDRISS [1970] for soil type "rock". We perform a series of computations using the opportunely scaled input accelerograms. In Fig. 11 we show PGA amplification with respect to PGA amplitude in zone 0. Such a figure represents a first evaluation of non linearity of 2MS, in fact we observe a reduction of the amplification up to 20 % for PGA(zone 0) smaller than 200 *gal*. Then the non linear effect is more significant causing a 50 % reduction of the amplification when PGA(zone 0) reaches 400 *gal*. It should be noted that when PGA(zone 0) attains the expected value for a return period of 475 years, that is 250 *gal* [FRANCESCHINA *et al.*, this issue], the amplification reduction is around 25 %. In the lower panel of the same figure we observe the saturation of the output PGA for PGA(zone 0) greater than 300 *gal*.

In Fig. 12 some *SAR* are plotted for different values of PGA(zone 0). We observe a remarkable change in the *SAR* shapes: the maximum spectral amplification ranges from 3.5 at T = 0.30 *s* in the linear case up to 2.2 at T = 0.44 *s* for PGA(zone 0) of 420 *gal*. When PGA(zone 0) is 250 *gal* we get a maximum spectral amplification of 3.1 for T = 0.33*s*.

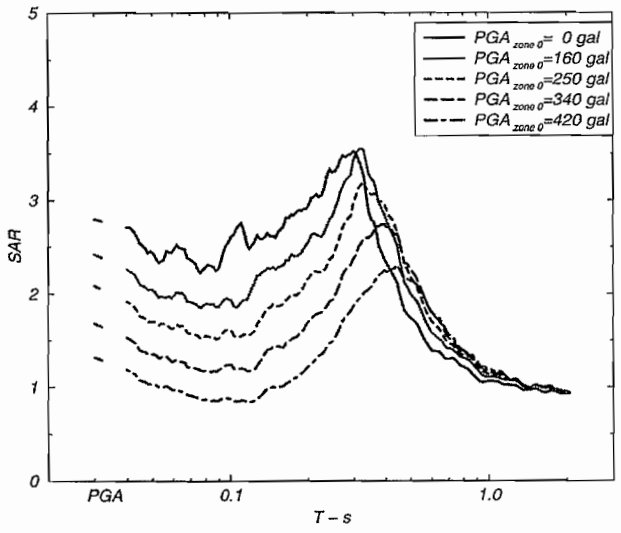

Fig. 12 – *SAR* estimations of site 2MS for different values of PGA_{zone0}, obtained by considering the non-linearity evaluated by results of 2MS drilling.

Fig. 12 – Stime di SAR del sito 2MS per diversi valori di PGA_{zona0}, ottenute considerando la non linearità valutata mediante i risultati del sondaggio 2MS.

This brief analysis, whose main limit is the use of a linear equivalent model which is valid for deformations lower than those reached in the cases of the most energetic input accelerograms, provides a first appraisal of the expected entity of the effect of soil non linearity in zone 1.

In particular our results show:

- Even for high values of PGA(zone 0) there still exists a PGA amplification.
- The linear model constitutes an upper bound of the amplification level for periods smaller than 0.3 *s*. In this range it can overestimate as much as 2.5 times for the examined cases. For greater periods the difference in negligible.
- In the case of PGA(zone 0) equal to 250 *gal* the overestimation of the linear model for short periods is around a factor of 1.5.

5. Conclusions

In this work we evaluate site effects in the urban area of Fabriano and present a first site effect zonation map that will be a basic reference for the proposed seismic microzonation map and related recommendations. Our analyses are based on the seismometric recordings of aftershocks and seismic noise as well as on the geological and geotechnical data available for the area under investigation.

In the first step of the work, velocimetric data have been used for the analysis of incidence angles of P wave first arrival. We obtain a qualitative appraisal of the rigidity of the deposits on which the seismometric stations are installed. The results appear congruent with the information on superficial geology. Then, by means of Nakamura's ratios, we prepared a map of the fundamental period of the deposits and we found a good agreement with the information furnished by the geologic cross sections drawn along the investigated area. Finally spectral ratios have traced a quantitative illustration of seismic amplifications. These elements have been synthesised in a zonation map that identifies five zones with homogeneous behaviour from the point of view of the seismic amplifications.

In order to assemble such zonation map of site effects in a way directly usable for application, we compute for every station the amplification of the acceleration response spectrum with 5 % damping and the amplification of the Housner intensity by using the spectral ratios as empirical transfer functions. These results imply a linear behaviour of soil under seismic loading. Therefore, by means of geothecnical data available for a borehole, we obtain a first appraisal of the expected entity of the effect of soil non linearity in zone 1. Our results show that when PGA in the zone with no amplification is equal to the expected value for a return period of 475 years, the amplification of the response spectrum for short periods is reduced of a factor of 1.5 with respect to the linear case. For greater periods the reduction is negligible.

The performed analyses have also pointed out the principal limits of the present work. For instance the areal coverage furnished by the seismological stations is sufficiently homogeneous only in some zones. Additional measurements of urban noise and the installation of some temporary seismological stations in new sites would uniformly complete the analyses throughout the investigated area.

Acknowledgements

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Zonazione degli effetti di sito del comune di Fabriano

Sommario

Nell'ambito del Progetto Microzonazione Sismica Umbria Marche è stata preparata una prima zonazione degli effetti di sito dell'area urbana di Fabriano utilizzando le registrazioni sismometriche sia di aftershock *sia di rumore sismico e le informazioni geologiche e geotecniche raccolte nell'area dalle diverse istituzioni partecipanti. I dati velocimentrici sono utilizzati per effettuare le elaborazioni di base volte alla definizione di una mappa di zonazione degli effetti di sito. In particolare è stata eseguita un'analisi degli angoli di incidenza delle onde P, per ottenere una indicazione qualitativa della rigidità dei depositi su cui sono installate le stazioni, e dei rapporti di Nakamura per ottenere la mappa del periodo proprio dei depositi nell'area in esame. Entrambe le analisi evidenziano una buona congruità con le informazioni geologiche e litologiche. Successivamente sono stati analizzati in dettaglio i rapporti spettrali che costituiscono la nostra stima principale degli effetti di sito. Amplificazioni consistenti, fino a 7, sono presenti nelle zone "Borgo" e "Serraloggia – Spina", quest'ultima è anche caratterizzata da una considerevole variabilità del moto sismico evidenziata dalla differenza dei rapporti spettrali di stazioni installate a meno di 200 m. Sulla base di questi elementi, si è quindi operata una suddivisione dell'area indagata in cinque zone a comportamento omogeneo dal punto di vista delle amplificazioni sismiche. Per ogni zona è stata inoltre stimata l'amplificazione dello spettro di risposta in accelerazione e dell'Intensità di Housner. I risultati ottenuti, essendo basati su registrazioni di moto debole, sono validi solo nel campo delle piccole deformazioni. Tuttavia, utilizzando i dati geotecnici disponibili per un sondaggio, si è ottenuta una valutazione dell'entità degli effetti non lineari riferibili a una delle zone individuate. I risultati mostrano che quando la PGA nell'area senza amplificazione raggiunge il valore corrispondente a un periodo di ritorno di 475 anni, l'amplificazione dello spettro di risposta per bassi periodi è ridotta di un fattore 1.5 rispetto al caso lineare. Per periodi superiori la riduzione è trascurabile.*