Vs velocities of shallow soils at Fabriano

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Summary

Seismic velocity profiles have been obtained at selected sites of Fabriano, representative of the main geological lithotypes, and the mostly damaged by the September 26, 1997 earthquakes: Borgo, Regina Margherita gardens and Serraloggia.

FTAN analysis has been applied to Rayleigh waves, artificially generated, and the dispersion curves of group velocities have been inverted with the non-linear inversion Hedgehog method. Moreover, the phase velocities, determined by computing the synthetic dispersion curves corresponding to the solution sets of the inversion, have been compared with the SASW dispersion curve, and discrepancies have been found.

Shear wave velocities lower than 300 m/s have been measured at depths lower than 10 m and higher than 800 m/s in the Gessoso-Solfifera formation at Borgo. One-dimensional spectral amplifications have been computed and a correspondence has been found with the maximum peaks of some events recorded by SSN stations in October.

1. Introduction

The September 26, 1997 earthquake caused damage at two quarters of Fabriano: Borgo and Serraloggia (Fig. 1). In the framework of GNDT Umbria Marche special project, many velocimetric stations were installed in October 1997 and 250 drillings were performed [GNDT, 1999]. A detailed geological study and the stratigraphies of the drillings pointed out the presence of small valleys filled with eluvial-lacustrine deposits, mainly formed by gravels and coarse grained sands, as at Regina Margherita gardens, and peaty clays, as at Borgo and Serraloggia. In the historical centre these deposits cover the Gessoso-Solfifera formation, made by silty and marly clays, and the Schlier formation, formed by silty marls and marly-silty clays. Three test sites have been selected as representative of clayey (Borgo and Serraloggia) and gravelly (Regina Margherita gardens) soil carrings (Fig. 1).

Detailed profiles of shear wave velocities (Vs) with depth have been obtained by using Rayleigh surface waves recorded with vertical 4.5 Hz (70% damping) geophones in refraction seismic surveys, the source being a vertical impact on the ground of a 20 kg weight.

The signals have been analysed with FTAN method [Levshin *et al.*, 1992] to extract the group velocity dispersion curve of Rayleigh fundamental mode, and a non-linear inversion procedure, the Hedgehog method [Valyus *et al.*, 1968; Panza, 1981], has been utilized to obtain Vs models (see Appendix). The results obtained by using FTAN method have been compared to those provided by SASW method [Nazarian and Stokoe, 1985]. This comparison shows that SASW can lead to quite misleading results.

2. Vs measurements in clayey soil coverings

The most damaged quarters from the Colfiorito earthquakes in 1997 were Borgo and Serraloggia (Fig. 1). The two sites are both characterized by a clayey covering on the Gessoso-Solfifera formation, having a thickness of about 10 m.

2.1. Borgo structural local model

The Borgo quarter represents an urban developing area of Fabriano, where a house was seriously damaged. The drilling 2MS performed in the garden behind the damaged house, encountered a layer of silts and clays with a thickness of 14 m.

The seismic measurements were conducted in front of and behind the house. The signals, recorded at 24 and 48 m offsets (in front of the house) and 28 and 56 m (behind the house), have been analysed to obtain FTAN maps from which the group velocity dispersion curves of the fundamental mode have been obtained for each signal (Fig. 2).

Equivalent seismo-stratigraphic models, obtained with Hedgehog inversion, are quite similar in front of and behind the house (Fig. 3). Average Vs profiles with depth range from 110 m/s to 250 m/s, in front of the building, and from 90 m/s to

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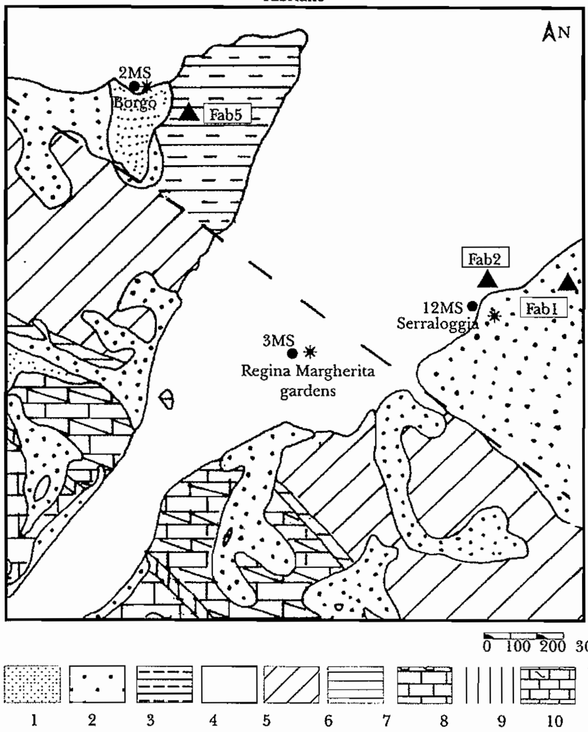


Fig. 1 – Geological sketch map of Fabriano and location of the investigated sites (✱) with location of drillings (•) [GNDT, 1999] and SSN velocimetric stations (▲). Legend: 1) Debris slide material; 2) Eluvial-colluvial deposits (thickness >10m); 3) Eluvial-colluvial deposits (thickness <10m); 4) Fluvial-lacustrine deposits; 5) Schlier formation; 6) Bisciaro formation; 7) Scaglia cinerea formation; 8) Scaglia variegata formation; 9) Scaglia rosata formation; 10) Fault.

Fig. 1 – Carta geologica di Fabriano e ubicazione dei siti di indagine (✱), dei sondaggi geognostici (•) e delle stazioni velocimetriche SSN (▲). Legenda: 1) Detrito di falda; 2) Depositi eluvio-colluviali (spessore >10m); 3) Depositi eluvio-colluviali (spessore <10m); 4) Depositi fluvio-lacustri; 5) Formazione Schlier; 6) Formazione Bisciaro; 7) Formazione scaglia cinerea; 8) Formazione scaglia variegata; 9) Formazione scaglia rosata; 10) Faglia.

350 m/s behind it. The layer below is obviously poorly resolved. These latter velocities are in good agreement with down-hole measurements at the 2MS drilling. The differences in the shallowest few metres can be easily explained in terms of morphological lateral variations of the soil covering the thickness of which is decreasing towards the hole. The down-hole test on the Gessoso-Solfifera formation has given Vs velocities of about 870 m/s.

The measuring of the phase velocity presents the uncertainty of the number of cycles of oscillation and can be fixed only by an a priori knowledge (see Appendix).

Phase velocities have been determined by computing the synthetic dispersion curves corre-

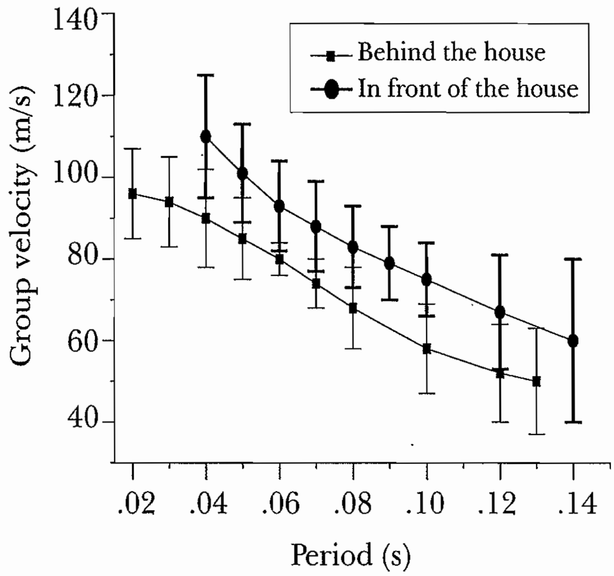


Fig. 2 – Average FTAN group velocity dispersion curves computed at Borgo, in front of and behind the damaged house.

Fig. 2 – Curve di dispersione medie delle velocità di gruppo FTAN calcolate a Borgo, davanti e dietro la casa danneggiata.

sponding to the solution set of the Hedgehog inversion of group velocities (Figs. 4a, b) and according to SASW method [NAZARIAN and STOKOE, 1985]. In the second case spectral analysis has been made with Matlab software and an unwrap function has been utilised to overcome the cycle numbering and to compute phase angles [NUNZIATA *et al.*, 1999]. The unwrapped phases usually present rapidly changing values when signals are noisy and/or contaminated by higher modes and this prevents to obtain significant phase velocities. As a result, the SASW phase velocities (Figs. 4a, b) jump by one or two integer phase cycles with respect to those computed from the Hedgehog solutions (Fig. 3) confirming that SASW is not a robust method.

2.2. *Serraloggia structural local model*

Serraloggia is located in the south-eastern part of the historic centre (Fig. 1). It is characterized by a covering of clayey soils, with a thickness of about 10 m, on the Gessoso-Solfifera formation, as indicated by the stratigraphy of the nearby drilling (Fig. 5).

The signals at 32 and 64 m offsets have been analysed with FTAN. The Hedgehog solutions obtained from the inversion of the average FTAN group velocity give a Vs profile for the uppermost 15 m (Fig. 5). The Vs velocities have values of 130-140 m/s in the shallowest 4 m (man-made ground and silty clay), of 210-250 m/s down to 9 m of depth (silty clay) and of 250-310 m/s down to 15 m (begin-

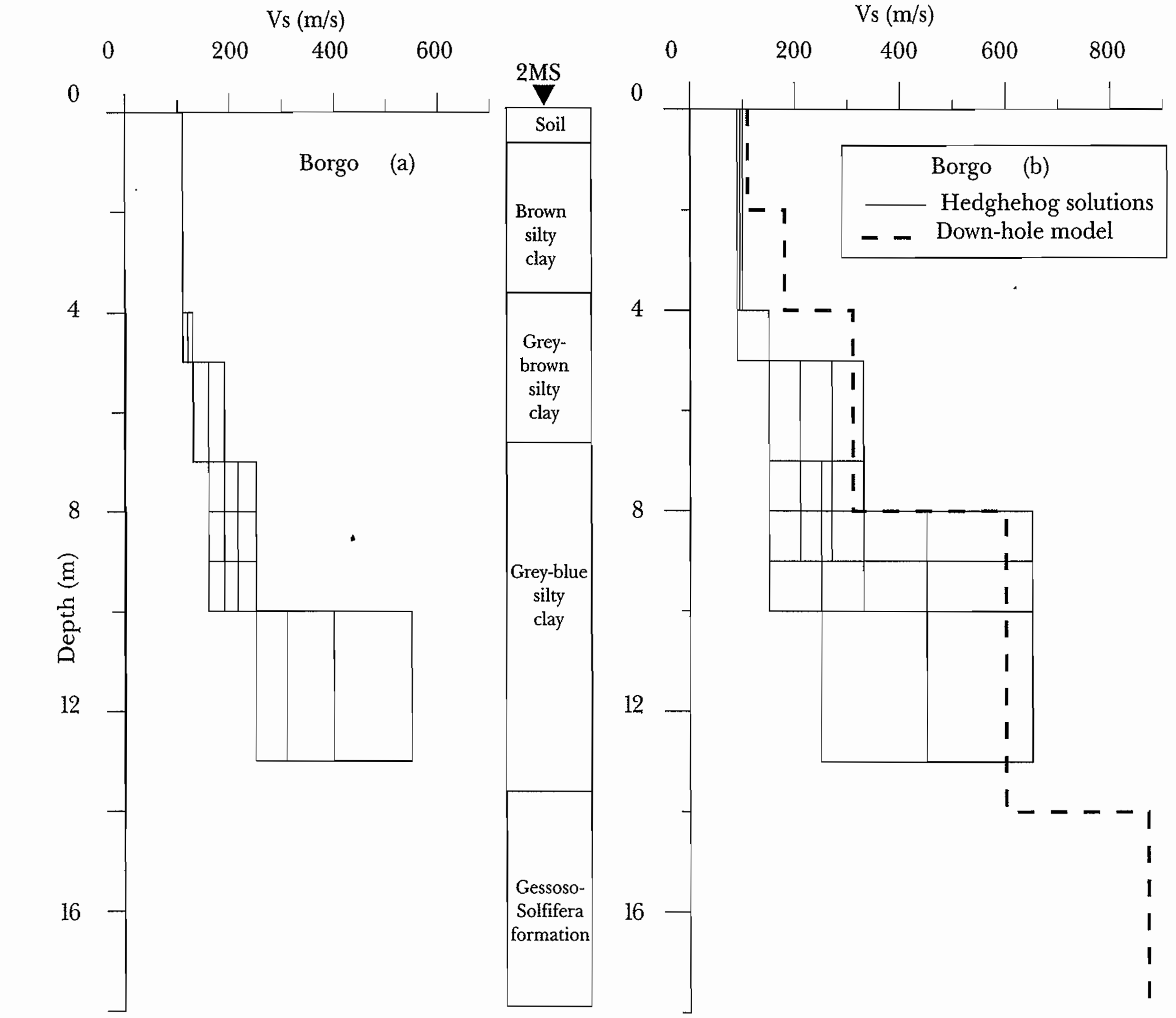


Fig. 3 – Comparison between Vs models (Hedgehog solutions) obtained at Borgo in front of (a) and behind (b) the damaged house and down-hole model at 2MS drilling (see Fig. 1 for location). The systematically higher velocities in the uppermost 5 m of the down-hole model (point model) with respect to the Hedgehog solution (average models) is a clear example of the limits of down-hole measurements.

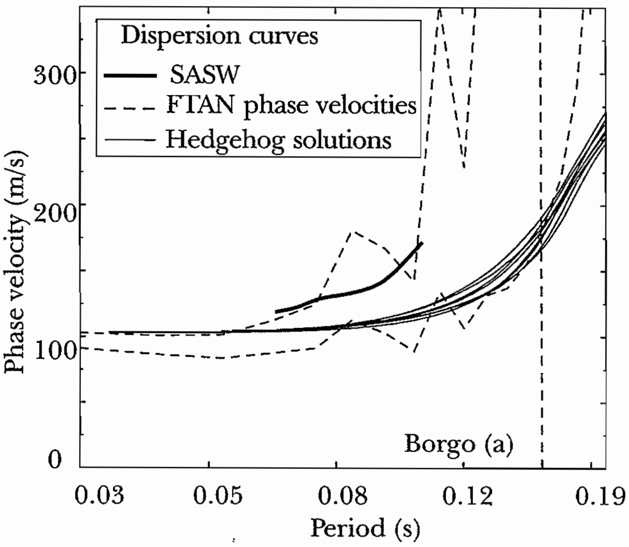
Fig. 3 – Confronto tra i modelli Vs (soluzioni Hedgehog) ottenuti a Borgo avanti (a) e dietro (b) la casa danneggiata e il modello down-hole *del sondaggio 2MS (vedi Fig. 1 per l'ubicazione). Le velocità sistematicamente più alte nei primi 5 m del modello* down-hole *(modello puntiforme) rispetto alle soluzioni Hedgehog (modelli medi) sono un chiaro esempio dei limiti delle misure* down-hole.

ning of Gessoso-Solfifera formation with abundant percentage of clay with respect to marl).

From 15 m to 25 m the presence of the standard Gessoso-Solfifera formation has been supposed and Vs velocity has been fixed at 870 m/s (from Borgo structural model).

3. Gravelly soil coverings at Regina Margherita gardens

Seismic measurements with forward and backward spreadings have been carried out in the southern part of the historic centre of Fabriano, at Regina Margherita gardens (Fig. 1). A stratigraphic sequence of the area, reconstructed from nearby drilling 3MS (Fig. 6b) shows an alluvial deposit (sandy gravel), 29 m thick, on the Schlier formation (silty marls and marly-silty clays). The signals recorded at 50, 52, 56 and 64 m offsets, with forward and backward spreadings, have been analysed according to FTAN method. The average group velocity dispersion curves obtained for the backward and forward spreadings (Fig. 6a) suggest the presence of some lateral heterogeneities only in the uppermost layers, since the two curves differ at the shortest period. The Hedgehog solutions show Vs values ranging on the average from 170 m/s (backward spreading) and 200 m/s (forward spreading) in the shallowest 6 m of depth, to 230-270 m/s down to 14 m of depth for both spreadings (Fig. 6b).



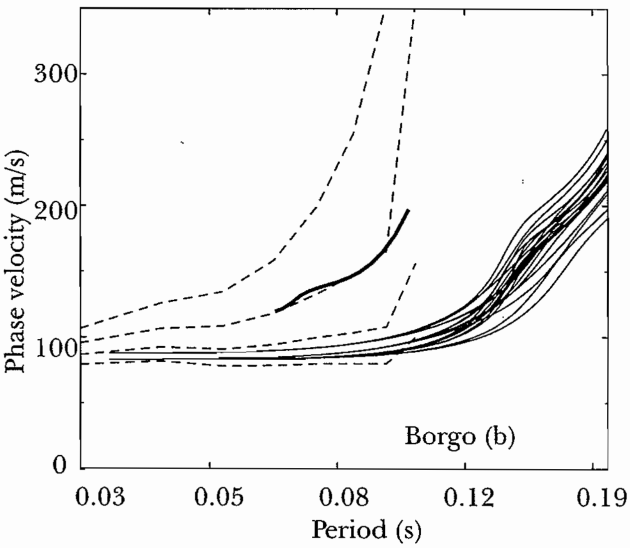


Fig. 4 – Borgo: Phase velocities computed from Hedgehog solutions (Fig. 3) and with SASW method (a) between signals at 24 and 48 m offsets in front of the damaged house and (b) between signals at 28 and 56 m offsets behind the damaged house. Phase velocities computed from the average dispersion curve of group Rayleigh velocities and corresponding to different phase cycles are also shown.
Fig. 4 – Borgo: Velocità di fase calcolate dalle soluzioni Hedgehog (Fig. 3) e con il metodo SASW (a) tra i segnali a 24m e 48m dalla sorgente davanti alla casa danneggiata e (b) tra i segnali a 28m e 56m dalla sorgente dietro la casa danneggiata. Sono anche mostrate le velocità di fase calcolate dalla curva di dispersione media delle velocità di gruppo Rayleigh e corrispondenti a differenti cicli di fase.

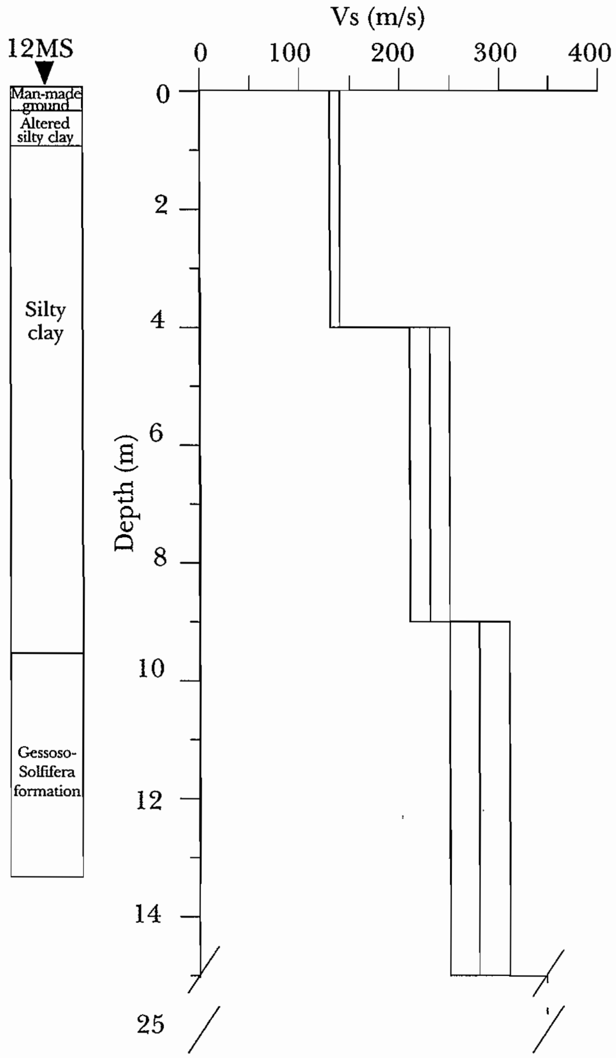


Fig. 5 – Vs models (Hedgehog solutions) obtained at Serraloggia (see Fig. 1 for location). The stratigraphic sequence (12MS) is representative of the investigated area.
Fig. 5 – Modelli Vs (soluzioni Hedgehog) ottenuti a Serraloggia (vedi Fig. 1 per l'ubicazione). La colonna stratigrafica (12MS) è rappresentativa dell'area investigata.

4. Spectral amplification

The amplification function of soil column has been computed at Borgo with respect to the Gessoso-Solfifera formation [SHAKE program, SCHNABEL *et al.*, 1972]. Different amplifications have been obtained for the Vs profiles taken from the down-hole model and the Hedgehog solutions, but we consider the latter more representative of the average seismo-stratigraphic pattern at the Borgo site. Moreover, the difference between in front of and behind the damaged house is not appreciable. A relative maximum peak amplification of about five at 4 Hz is obtained when using the average Hedgehog solution (Fig. 7).

Spectral amplifications have been computed at Serraloggia by assuming the seismic bedrock at 15 m and at 25 m for different Hedgehog solutions. By deepening the seismic bedrock, the first maximum peak moves from 4 Hz to 3 Hz (Fig. 8).

At Regina Margherita gardens, the amplification function has been computed for the Vs profiles taken from the average, forward and backward models, by considering as seismic bedrock

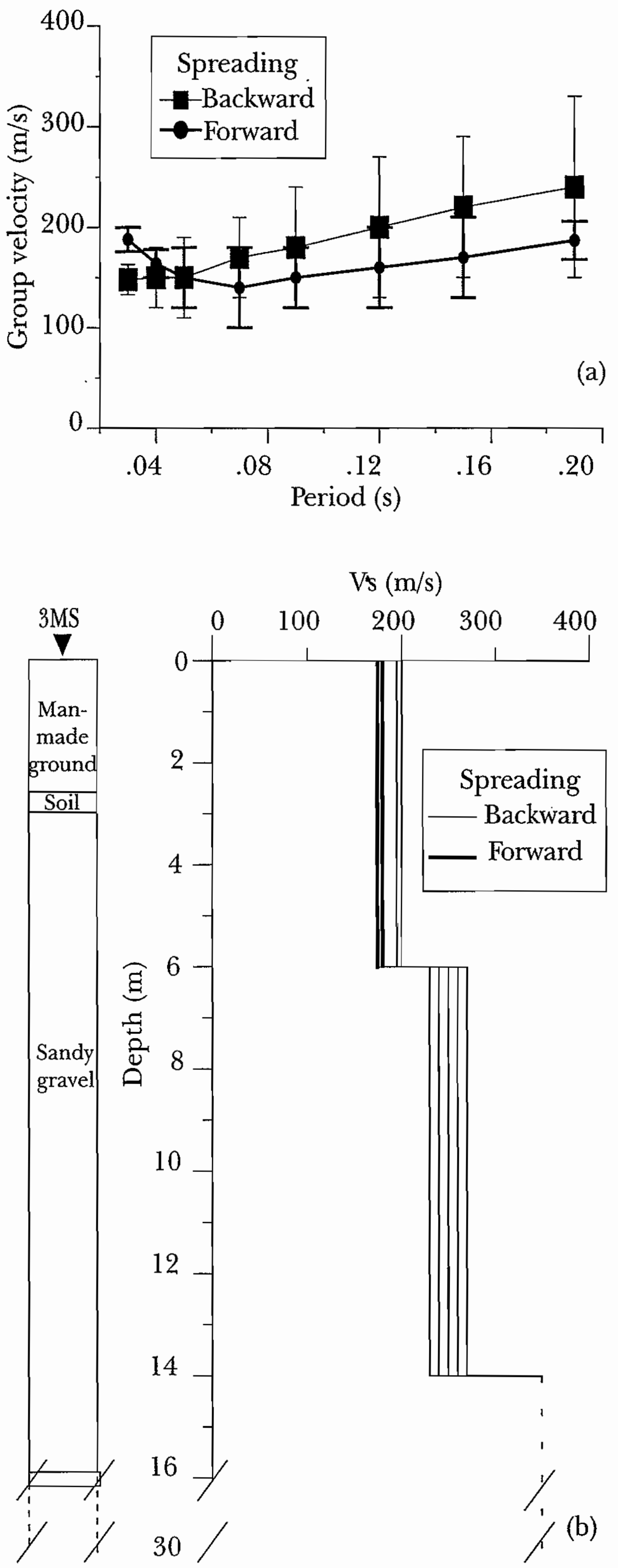


Fig. 6 – Regina Margherita gardens: (a) average FTAN group velocities along forward and backward spreadings and (b) inverted Vs models (Hedgehog solutions). The stratigraphic sequence (3MS) is representative of the investigated area.

Fig. 6 – Giardini Regina Margherita: (a) velocità di gruppo FTAN medie tra gli stendimenti diretti e coniugati e (b) modelli Vs invertiti (soluzioni Hedgehog). La colonna stratigrafica (3MS) è rappresentativa dell'area indagata.

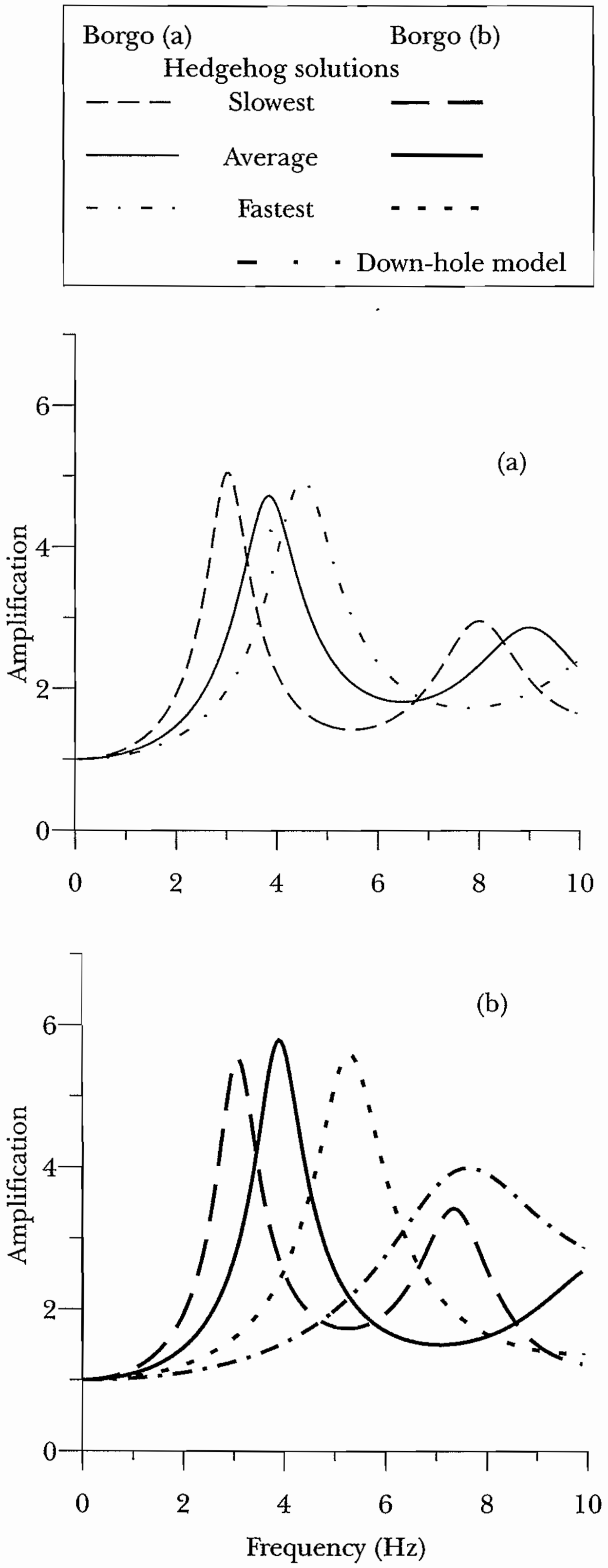


Fig. 7 – Spectral amplification computed with SHAKE program at Borgo for down-hole model and for slowest, average and fastest Hedgehog solutions, (a) in front of and (b) behind the damaged house.

Fig. 7 – Amplificazioni spettrali calcolate con il programma SHAKE a Borgo per il modello down-hole *e per le soluzioni Hedgehog minima, media e massima, (a) davanti e (b) dietro la casa danneggiata.*

the Schlier formation, at 30 m of depth (Fig. 6b). As shown in Fig. 9, a relative maximum peak of about 3 Hz characterizes the amplification function.

In the framework of GNDT "Umbria-Marche" project three velocimetric stations by SSN (Servizio Sismico Nazionale) have been recording on October 4-6, 1997 (Fig. 1) at Serraloggia (Fab1 and Fab2) and at Borgo (Fab5). They recorded a relatively strong event (M_L=4.6), about 40 km distant (Colfiorito seismogenic area) and 30 smaller events (M_L<4.0). Among these events, we have studied the strongest one (event 1, M_L=4.6), and the closest one (about 20 km of epicentral distance) (event 2, M_L=3.4). The recordings have been rotated, corrected for the instrument response and then computed derivatives to get acceleration time histories along the radial, transverse and vertical components. Very low maximum ground accelerations were obtained. Realistic modelling of the ground motion to be compared with the recorded events is the best way to evaluate the site amplification effects, and will be the subject of a forthcoming paper. In a preliminary step, our attention has been focused on trying to understand if the computed one-dimensional amplifications are compatible with recorded response spectra. In fact, the three stations were set on soil and there are no chances to get the observed amplifications. The horizontal normalized response spectra are very similar, and the frequencies of the relative maximum peaks of transverse components are in good agreement with those of the computed one-dimensional amplifications (Fig. 10). Even though this result must be considered only qualitative, it suggests that the medium between the recording stations, Fab1, Fab2 and Fab5, set on similar seismo-stratigraphic columns, is quite homogeneous.

5. Conclusions

Vs velocities have been measured at representative sites of Fabriano. In particular, clayey and gravelly soils have been investigated being the most widespread ones. Vs velocities lower than 300 m/s have been measured in the shallower 10 m of soil at the three studied sites, and higher than 800 m/s in the Gessoso-Solfifera formation at Borgo. The spectral amplifications computed for the one-dimensional inverted models show maximum peaks at 3-4 Hz, close to the

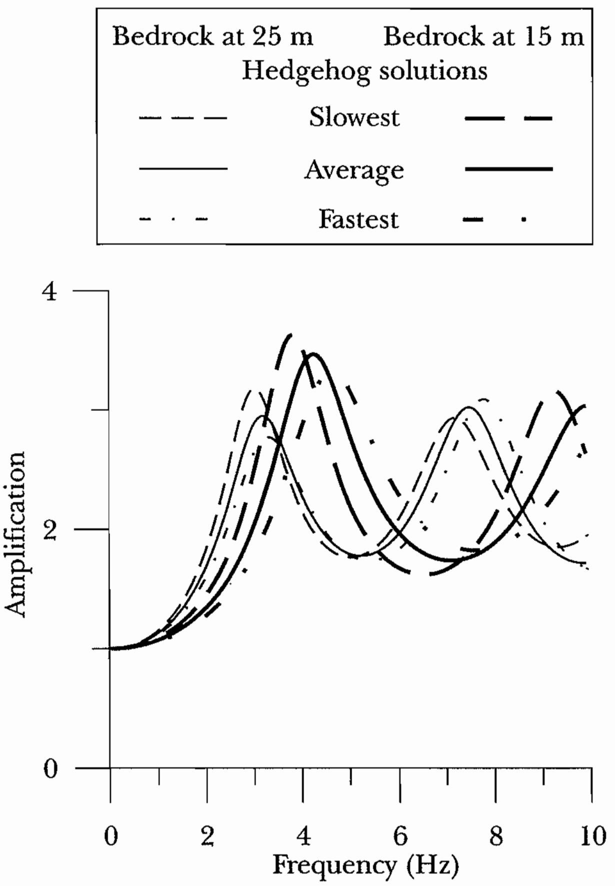


Fig. 8 – Spectral amplification computed with SHAKE program at Serraloggia for slowest, average and fastest Hedgehog solutions by assuming the basement at 15 m and 25 m.
Fig. 8 – Amplificazioni spettrali calcolate con il programma SHAKE a Serraloggia per le soluzioni Hedgehog minima, media e massima, assumendo il basamento a 15 m e 25 m.

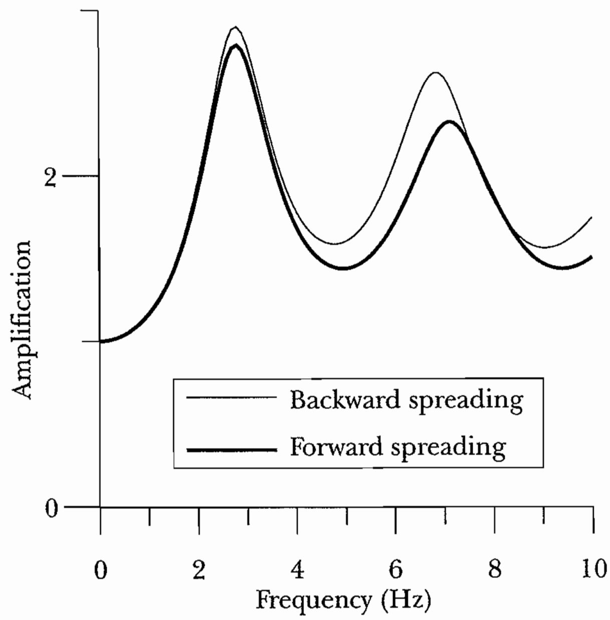


Fig. 9 – Spectral amplification computed with SHAKE program at Regina Margherita gardens for average Hedgehog solutions for forward and backward spreadings.
Fig. 9 – Amplificazioni spettrali calcolate con il programma SHAKE nei giardini Regina Margherita per le soluzioni Hedgehog medie tra gli stendimenti diretti e coniugati.

resonance frequency of existing buildings. On the other hand, the analysis of two events, the strongest and the closest ones, recorded at three velocimetric stations installed within few hundred metres from the investigated sites, has evidenced a maximum peak of the transverse response spectra in agreement with the one-dimensional spectral amplification. Such qualitative result suggests that significant site amplification effects occurred on September 26, as a consequence of stronger seismic events from the seismogenic Colfiorito area.

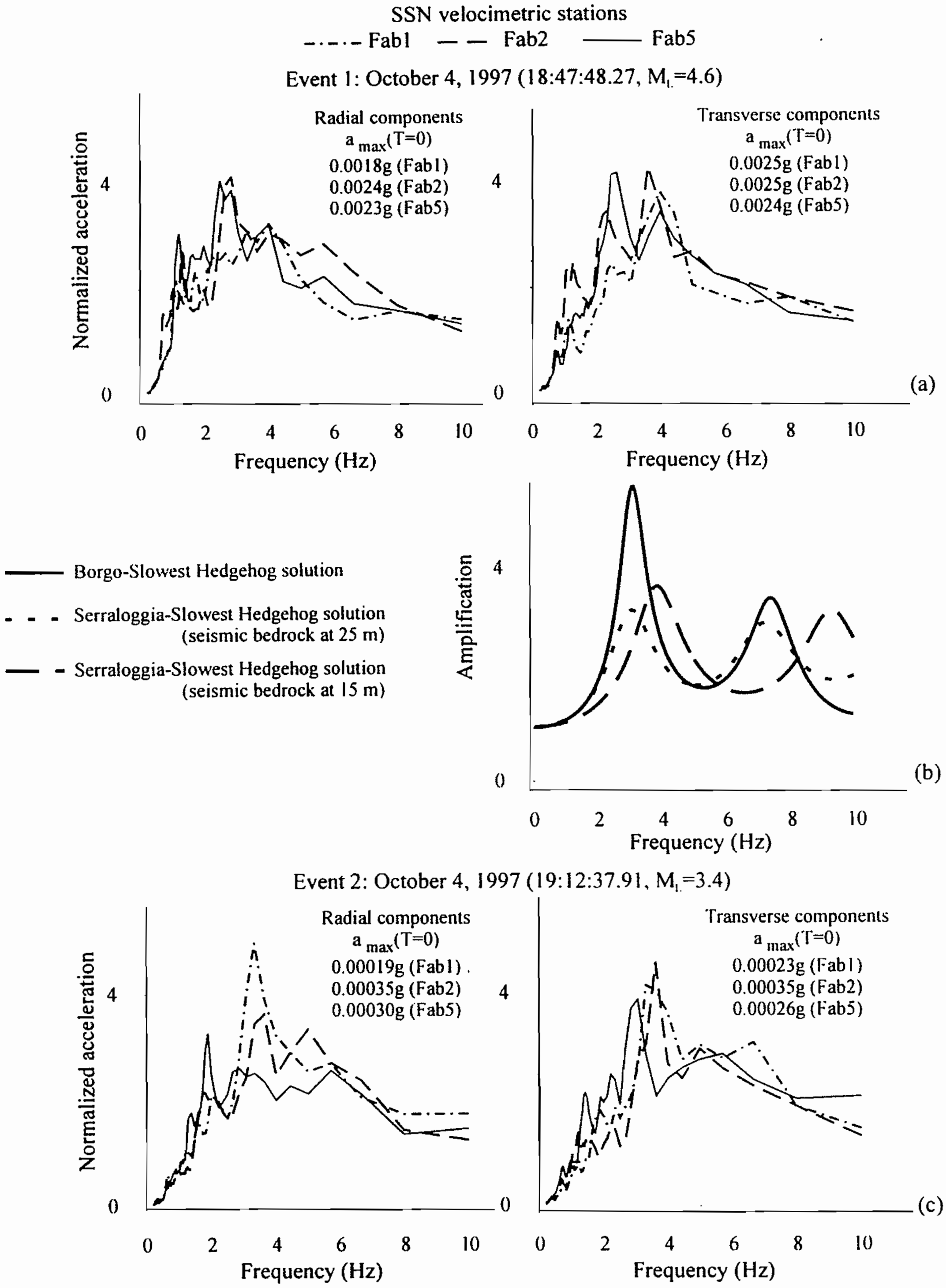


Fig. 10 – Normalized acceleration response spectra of radial and transverse components relative to events 1 and 2 (a, c) and soil column amplifications computed with SHAKE program at Borgo and Serraloggia for the slowest Hedgehog solution (b).
Fig. 10 – Spettri di risposta normalizzati delle accelerazioni radiali e trasversali relativi agli eventi 1 e 2 (a, c) e le amplificazioni della colonna di terreno calcolate con il programma SHAKE a Borgo e Serraloggia per la soluzione Hedgehog minima (b).

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Appendix

Given a seismogram the group and phase velocity can be defined as follows:

$$U(\omega) = x/[t_o + d\phi_H(\omega)/d\omega - d\phi(\omega)/d\omega] \quad (1)$$

$$c = x/\{t_o + [\phi_H(\omega) - \phi(\omega) \pm 2\pi N]/\omega\} \quad (2)$$

where x is the distance source receiver, t_o the difference between the origin time and the starting time of the analysed signal, ϕ_H and ϕ are respectively the phase of the recorded signal and the source apparent initial phase, at the frequency ω and N is an integer that can only be determined empirically. As a rule $\phi(\omega)$ is a weak function of ω, thus $d\phi(\omega)/d\omega$ can be considered negligeable for practical purposes; on the other side, expecially at short periods, the determination of N can be very problematic.

To eliminate the dependence of the phase velocity from the apparent initial phase of the source, $\phi(\omega)$, the so called two-station method can be applied; in such a case:

$$c = \delta x/[\delta t_o + (\delta\phi_H(\omega) \pm 2\pi\delta N)/\omega] \quad (3)$$

where the quantities δx, δt_o, $\delta\phi_H(\omega)$ and δN indicate the difference between the quantities appearing in (2) as measured at the two stations. For more details see e.g. PANZA [1976].

As a rule, the phase spectra present rapidly changing values and this prevents the good use of unwrapping methods to estimate phase jumps and, hence, the right number, N, of cycles. SASW method [NAZARIAN and STOKOE, 1985] is based on the measurement of the dispersion of surface phase velocities between two receivers, but it is not a robust method since the number of cycles in the phase spectrum cannot be always soundly determined. FTAN measures group velocities that are independent from N, and represents a significant improvement, due to LEVSHIN *et al.* [1972; 1992], of the multiple filter analysis originally developed by DZIEWONSKI *et al.* [1968]. FTAN can be applied to a single channel to measure group velocity even when there is higher modes contamination. A FTAN map is the image of a matrix whose columns are the energy values at a certain period and the rows are the energy values at a certain group velocity. Any dispersion curve can be inverted to determine the S-wave velocity profiles versus depth. A non-linear inversion is made with the Hedgehog method developed by VALYUS *et al.* [1968] and discussed in detail by PANZA [1981].

Velocità sismiche Vs delle formazioni affioranti a Fabriano

Sommario

Modelli sismo-stratigrafici sono stati ottenuti in alcuni siti di Fabriano, rappresentativi dei principali litotipi presenti e delle aree più danneggiate dal terremoto del 26 settembre 1997: Borgo, giardini Regina Margherita e Serraloggia. Le misure sismiche sono state effettuate nelle vicinanze di sondaggi geognostici, allestiti anche per prove down-hole. *La caratterizzazione sismica dei terreni è stata effettuata attraverso l'analisi delle onde superficiali di Rayleigh generate artificialmente con una massa battente di 20kg lungo stendimenti di sismica e rifrazione. Sono stati utilizzati geofoni verticali di 4.5 Hz e di 1Hz, per le distanze maggiori.*

Le misure sono state analizzate con le tecniche SASW e FTAN. Le curve di dispersione delle velocità di gruppo ottenute con il metodo FTAN sono state invertite con il metodo non lineare Hedgehog per ottenere i profili di velocità Vs con la profondità. Inoltre, le velocità di fase sono state calcolate per il set di soluzioni Hedgehog e messe a confronto con quelle ottenute con il metodo SASW. Sono state trovate discrepanze significative causate dall'erronea definizione del numero di cicli nello spettro di fase, nonostante l'uso di funzioni di unwrap.

Fabriano è morfologicamente caratterizzata dalla presenza di piccole valli colmate da depositi continentali di origine fluvio-lacustri nell'ambito delle quali si individuano una serie di terrazzi fluviali che testimoniano l'intensa attività erosiva e deposizionale dei corsi d'acqua superficiali. Questi depositi alluvionali sono costituiti prevalentemente da ghiaie e sabbie grossolane, in particolare per la zona giardini Regina Margherita, che lasciano il posto a coltri detritiche, legate a fenomeni di denudazione dei versanti, e ad argille torbose, come avviene nelle località di Borgo e Serraloggia. La copertura di depositi fluvio-lacustri poggia su un substrato prevalentemente rappresentato dalla formazione Gessoso-Solfifera (argille marnoso - siltose scure a volte bituminose e marne argillose diatomitiche). Velocità sismiche di taglio minori di 300 m/s sono state misurate a profondità inferiori a 10m nei terreni argillosi e ghiaiosi e maggiori di 800 m/s nella formazione Gessoso-Solfifera a Borgo. Inoltre, sono state calcolate le amplificazioni spettrali unidimensionali della copertura dei terreni incoerenti che sono risultate in buon accordo con gli spettri di risposta della componente trasversale di eventi registrati in ottobre 1997 nei pressi dei siti di indagine. Questo risultato qualitativo suggerisce che i danni subiti da Fabriano per il terremoto di Colfiorito del 26 marzo 1997 siano da attribuire ad effetti di amplificazione locale.