Seismic characterization of shallow soils at Nocera Umbra, for seismic response analysis

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Summary

Seismo-stratigraphic models of shear wave velocities have been obtained at representative geological sites of Nocera Umbra, that is: the historical centre for scaglia formations; the cemetery, for eluvial and alluvial soils; Bagni, for travertine deposit; Isola and Le Molina, for debris fan material, alluvial soils and silty and marly formation. The signals, recorded along seismic refraction spreadings, have been analysed by FTAN and Hedgehog methods. A very good agreement has been found with down-hole measurements in nearby drillings.

Moreover, the October 6 and 14, 1997 earthquakes, recorded at two ENEL-SSN accelerometric stations, Nocera set on alluvial deposits investigated in this paper, and Biscontini on marly calcareous rock, have been studied. It turns out that the observed response spectra have a very good match with those computed with standard 1D approach (SHAKE program), by using the lowest velocity profile among the Hedgehog solutions.

1. Introduction

Nocera Umbra has been severely damaged by the 1997 seismic sequence started with the September 26 events, the first at 2:33 (M_L=5.6) and the second one at 11:40 (M_L=5.8), with the epicenters about 3-4km far from the town. Structural damage was suffered by the historical centre and the villages of Bagni, Isola and Le Molina, corresponding to VIII and IX degree of Intensity on the MCS scale. In the framework of the GNDT (Gruppo Nazionale Difesa Terremoti) activities, seismic measurements have been done at Nocera Umbra to characterize the main lithotypes and to estimate the site amplification effects.

Seismo-stratigraphic models have been obtained at representative geological sites of Nocera Umbra by the non-linear inversion of dispersion curves of Rayleigh wave fundamental mode, generated by the vertical impact of a 20 kg weight on the ground and by bullets of gunpowder (5-6 gr) fired into the ground. Vertical geophones have been used with 4.5 Hz and 1 Hz resonant frequency, damping 70%, for the shorter and the larger distances, respectively.

Down-hole measurements have also been carried out. Velocity profiles were deduced using the data analysis method of Mok [1987] based on the application of discrete inverse theory to overdetermined problems. Using measured P and S wave arrival times as input data, the velocity profile is determined through an iterative process. The initial guess is obtained with the assumption of straight ray paths, and the calculations then continue according to Snell's refraction law. The iterative process stops when the sum of the squared differences between the new velocities and the previous velocities is within ± 0.3 $(m/s)^2$. The historical centre, the cemetery, Isola, Le Molina, and Bagni have been investigated (Fig. 1).

The signals, recorded along seismic refraction spreadings, have been analysed by FTAN method. FTAN method [Levshin et al., 1992] is based on the frequency-time bidimensional analysis of the signal and it is able to separate the different oscillation modes starting from the whole seismic trace. By the introduction of the "floating point filtering", the selection of a mode is easier. The analysis is bidimensional, because the dispersion curve is a function of two variables: travel time and frequency. It is possible to give an interpretation of a signal by dispersion curves of different modes and by representing instantaneous spectral amplitudes as a function of period and group velocity. Along the same seismic spreading, various signals have been generated, in order to obtain, by FTAN analysis, various measurements of group velocity dispersion. At each selected period, the mean velocity of the various results on the same path has been calculated and, to be conservative, the error is fixed equal to the double of the standard deviation. A non-linear method is used in the inversion to obtain the earth structure [Valyus et al., 1968; Panza, 1981]. The structural model, which is unknown, is characterized by a set of parameters and its determination is obtained by assigning numerical values

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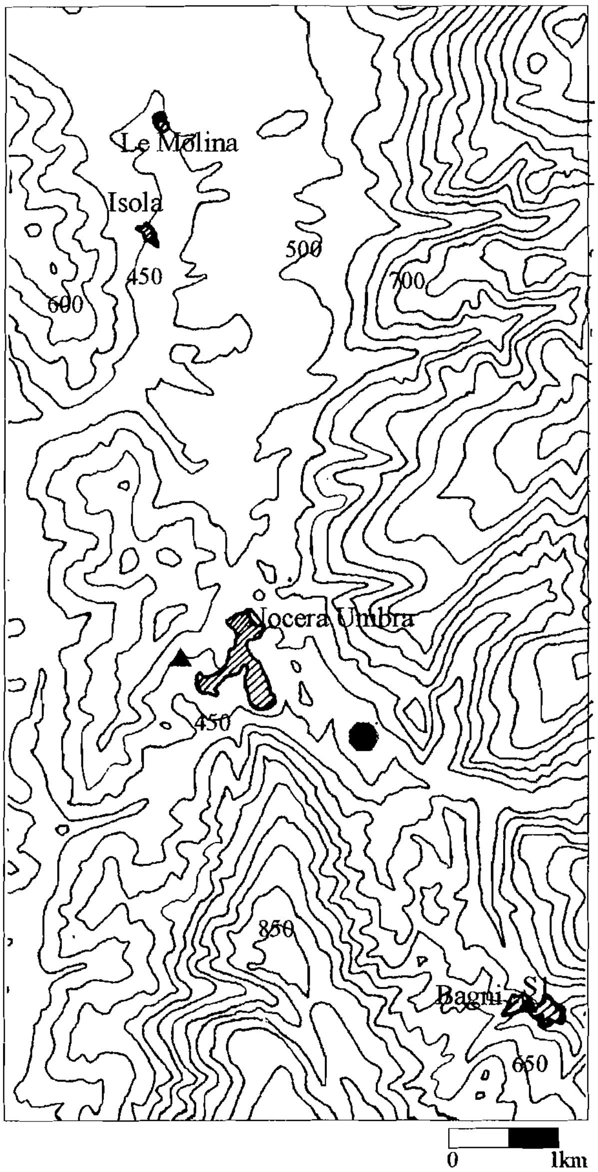


Fig. 1 – Location of investigated sites of Nocera Umbra and Biscontini (●) and Nocera (▲) ENEL-SSN accelerometric stations.

Fig. 1 – Ubicazione dei siti di indagine di Nocera Umbra e delle stazioni accelerometriche ENEL-SSN di Biscontini (●) e Nocera (▲).

to the parameters, which are defined in a range of possible values. For every earth model the differences between theoretical and observed values are calculated. The solutions of the problem are the sets of models, for which the differences between theoretical and observed values are smaller than the experimental errors.

2. Geological setting

The geological setting of Nocera Umbra is characterized by the Umbria-Marche sequence, from the scaglia rossa up to the silty and marly formation. In the north, at Isola and Le Molina, and at the cemetery (Figs. 2a-b), this sequence is covered by recent eluvial-lacustrine sediments. In particular, at the cemetery, an old landslide has been reactivated by the September 1997 earthquakes. The scaglia rossa formation represents the skeleton of the ancient settlement (Fig. 2a), whereas the western and eastern slopes of the Nocera Umbra hill are filled with debris slide material and man-made ground with a thickness greater than 10 m. Huge thicknesses of man-made ground were often used as reinforcement of the ancient walls, as in the case of the arcades in the historical centre (S6 in Fig.2a).

Isola and Le Molina villages are located along the valley of the Caldognola stream, and are characterized by terraced eluvial and recent alluvial deposits covering the silty and marly formation (Fig. 2b). The thickness of this covering is of about 10 m and includes the man-made ground and debris flow material. Instead Bagni (Fig. 1) is a singularity as it is characterized by the presence of travertine deposit on scaglia variegata and scaglia rossa formations.

3. Seismic measurements

Seismic measurements have been carried out nearby and in drillings performed by GNDT [1999] in order to define the elastic properties of the main lithotypes present at Nocera Umbra. In the following, the results are presented for each site.

3.1. Historical centre

Different types of scaglia formation (rossa, variegata and cinerea) are present inside the historical centre of Nocera Umbra (Fig. 2a). Scaglia rossa formation has been investigated at the Caprera square (S8 drilling) and close to the ancient walls, in S. Martino street (S10 drilling in Fig. 2a), under a covering of man-made ground consisting of heterogeneous gross pieces and clayey material. FTAN measurements have been carried out at Caprera square and down-hole tests have been made in S6 drilling (Fig. 2a). Vs values of 190-230 m/s have been obtained for the man-made ground at Caprera square (Fig. 3) with the Hedgehog method, in very good agreement with down-hole measurements at S6 drilling. The shallower, altered scaglia rossa formation is characterized by Vs of 390-490 m/s, at the Caprera square, and of 440-480 m/s, at the S6 site (Fig. 3). Shear wave velocities of scaglia rossa formation have been measured at Caprera square and have values of 600 m/s down to 12 m of depth (Fig. 3). The Vp

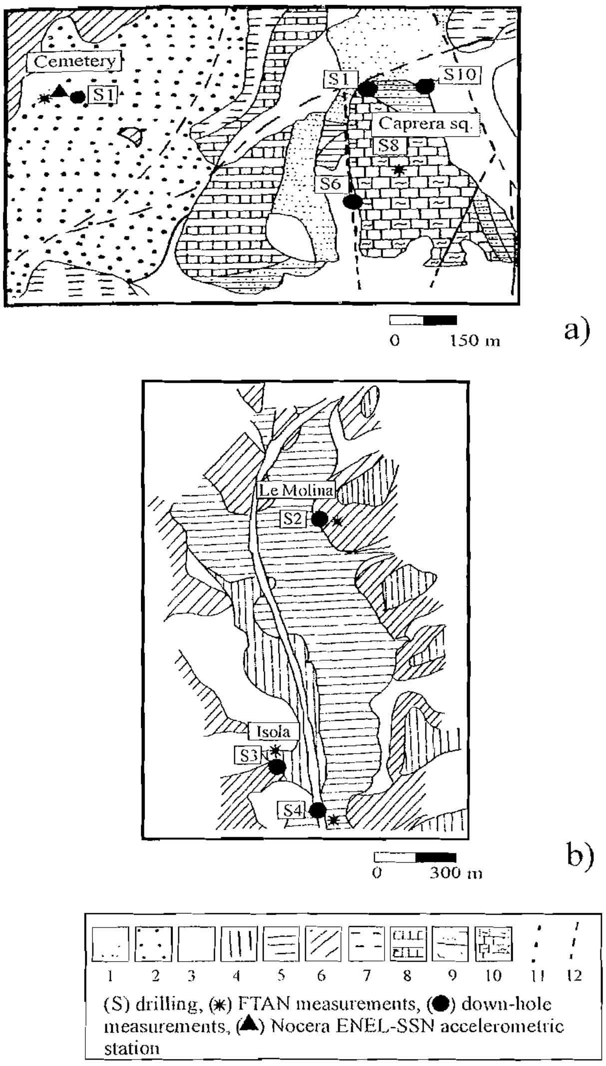


Fig. 2 – Geological sketch map of historical centre (a) and Isola and Le Molina (b) of Nocera Umbra with the location of drillings (GNDT, 1999). Legend: 1) Man-made ground; 2) Eluvial deposits; 3) Slope debris material; 4) Present and recent alluvial deposits; 5) Terraced alluvial deposits; 6) Sandy and marly formation; 7) Bisciaro formation; 8) Scaglia cinerea formation; 9) Scaglia variegata formation; 10) Scaglia rossa formation; 11) Fault 12) Hypothesized fault.

Fig. 2 – Carta geologica del centro storico (a) e dei borghi Isola e Le Molina (b) di Nocera Umbra con l'ubicazione dei sondaggi geognostici (GNDT, 1999). Legenda: 1) Materiale di riporto; 2) Depositi eluviali; 3) Detrito di falda; 4) Depositi alluvionali recenti ed attuali; 5) Depositi alluvionali terrazzati; 6) Formazione marnosa-arenacea; 7) Formazione del Bisciaro; 8) Formazione della scaglia cinerea; 9) Formazione della scaglia variegata; 10) Formazione della scaglia rossa; 11) Faglia; 12) Faglia ipotizzata.

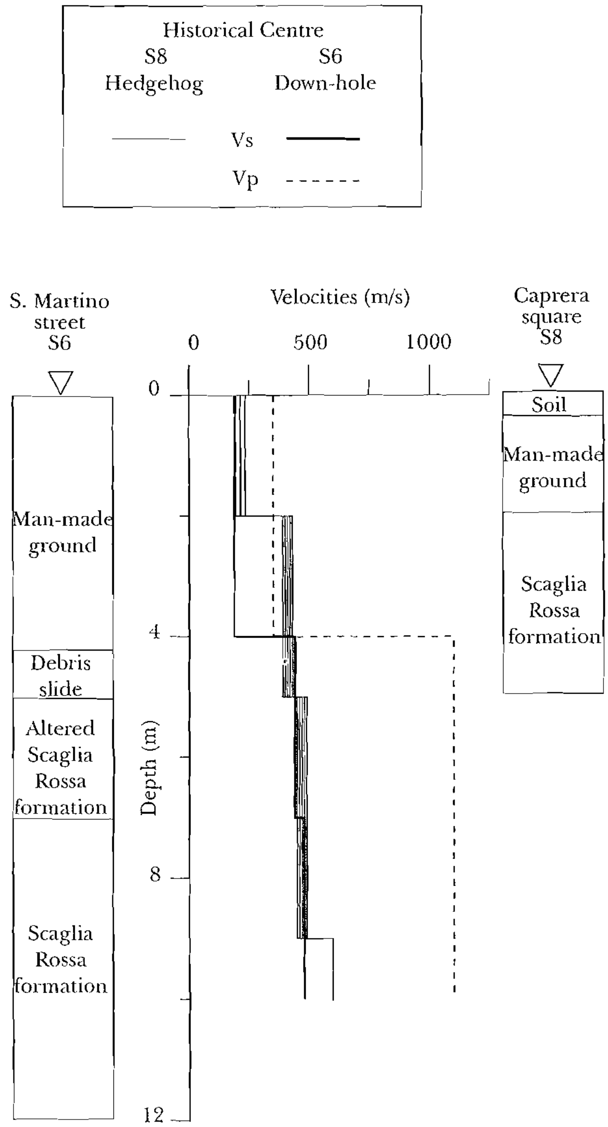


Fig. 3 – Scaglia rossa formation: comparison between down-hole velocity models at S6 drilling (Fig. 2a for location) and Hedgehog models obtained at Caprera square close to S8 drilling (Fig. 2a for location).

Fig. 3 – Formazione della scaglia rossa: confronto tra i modelli di velocità down-hole *nel sondaggio S6 e i modelli Hedgehog ottenuti a Piazza Caprera nei pressi del sondaggio S8 (vedi Fig. 2a per l'ubicazione).*

down-hole measurements vary from 350 m/s, in the shallower 4 m of man-made ground to 1100 m/s in the altered part of the scaglia rossa formation (Fig. 3).

The S. Filippo arcades (S1 drilling in Fig. 2a) are on man-made ground and debris slide material, and then on the scaglia variegata formation. Vp and Vs values have been measured in the man-made ground and the altered part of scaglia variegata formation, and they are respectively 420 m/s-190 m/s and 1650 m/s 640 m/s. (Fig. 4). The scaglia variegata formation has been tested in S10 drilling (Fig. 2a), in Delle Mura street. Values of 800 m/s and 1700 m/s have been obtained for Vs and Vp velocities, respectively (Fig. 4), from 11 to 17 m of depth. At shallower depths measurements could not be made because of the bad cased drilling.

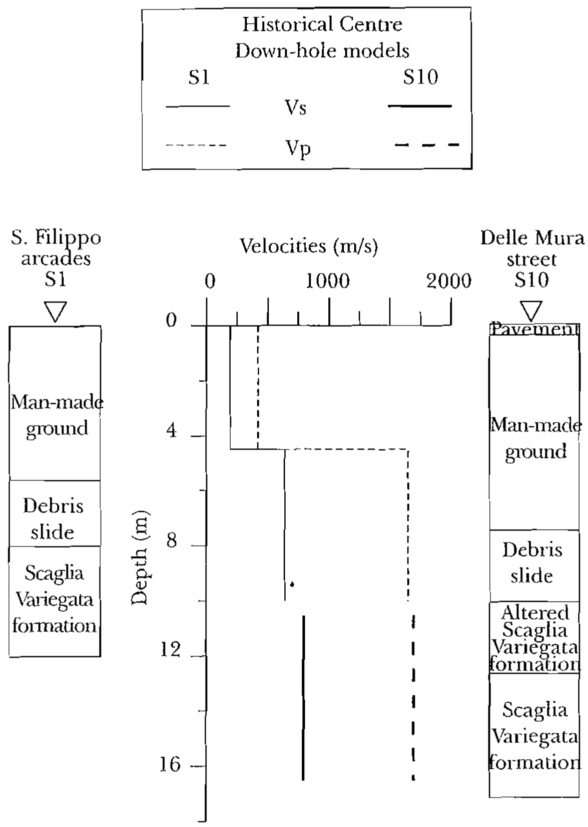


Fig. 4 – Scaglia variegata formation: down-hole velocity models obtained at S. Filippo arcades (S1 drilling located in the Fig. 2a) and Delle Mura street (S10 drilling located in the Fig. 2a).
Fig. 4 – Formazione della scaglia variegata: modelli di velocità down-hole *ottenuti sotto il porticato S. Filippo (sondaggio S1 ubicato in Fig. 2a) e in via Delle Mura (sondaggio S10 ubicato in Fig. 2a).*

3.2. Cemetery

FTAN measurements have been made a few metres far from the down hole, towards the cemetery, to define Vs velocities of eluvial and alluvial soils. Forward and backward spreadings have been aligned across the seismic station installed by ENEL-SSN. By inverting the average dispersion curve of group velocity with Hedgehog method, it has been possible to investigate down to 10 m of depth. The obtained earth models are characterized by a first layer, 2 m thick, with Vs values of 120–200 m/s, and by a second layer, 5 m thick, with increasing velocities from 200 m/s to 450 m/s, the layer below is obviously poorly resolved (Fig. 5).

Down-hole measurements in S1 drilling have tested the marl formation. In particular, Vs ranges between 590 m/s (5-9 m of depth) and 670 m/s down to 13 m, and Vp ranges between 1040 and 1280 m/s, in the same layers (Fig. 5).

3.3. Bagni

Earth models have been obtained with Hedgehog method and they are characterized by a first layer of altered travertine deposit with Vs of 180-300 m/s, a second layer of travertine deposit with Vs of 310-370 m/s, and a third layer of travertine deposit and altered scaglia variegata formation with Vs of 460-520 m/s (Fig. 6).

3.4. Le Molina and Isola

Down-hole tests have been done at Le Molina (S2 drilling in Fig. 2b) down to 10 m from the surface (Fig. 7). The Vp model consists of 2 layers: the first one of dense silty clay, 1.64 m thick, has a Vp of 520 m/s, the second one has a Vp of 910 m/s down to 10 m, in the silty and marly formation. The Vs model is formed by 3 layers with velocities of 170 m/s, down to 3 m in the silty clay, of 270 m/s, from 3 to 6 m in the silty and marly formation, and of 420 m/s, from 6 to 10 m in the silty and marly formation (Fig. 7).

The physical properties of the shallower 10 m of subsoil have been inverted from the dispersion curve measured with FTAN analysis. The ratio between P and S velocities and the width of the homogeneous layers has been fixed from the stratigraphy studies and the down-hole test, while S wave velocities have been inverted. The first layer, 3 m thick, has Vs values of 190-220 m/s, the second one, 3 m thick, has an S wave velocity of 250-310 m/s, and the third one, 4 m thick, of 350 and 400 m/s (Fig. 7). Hedgehog solutions are in very good agreement with the down-hole Vs model (Fig. 7).

Seismic surveys have been carried out on eluvial and alluvial deposits at the village of Isola, while down-hole tests have been made at the basis of these deposits, about 10 m lower.

Hedgehog solutions consist of 3 layers with variable thickness and Vs velocities from 160 to 450 m/s. At 9.64 m of depth they include the down-hole model, which seems a very credible measurement of the alluvial deposit thickness (Fig. 8).

Down-hole measurements have been made in S4 drilling (Fig. 2b), close to the Railway Bridge. Two seismic layers have been obtained from the inversion of P and S wave travel times. The first one has a Vp of 340 m/s and Vs of 160 m/s down to 6 m, the second layer, consisting of eluvial and silty and marly formation, has a Vp velocity of 1450 m/s, indicating the water level, and Vs of 345 m/s from 6 to 13 m from surface (Fig. 9).

Seismic spreadings have also been made and Hedgehog solutions have been obtained starting from the stratigraphy of the drilling and assuming the Vp/Vs ratio from the down-hole investigation. The resulting model has two layers: the first layer

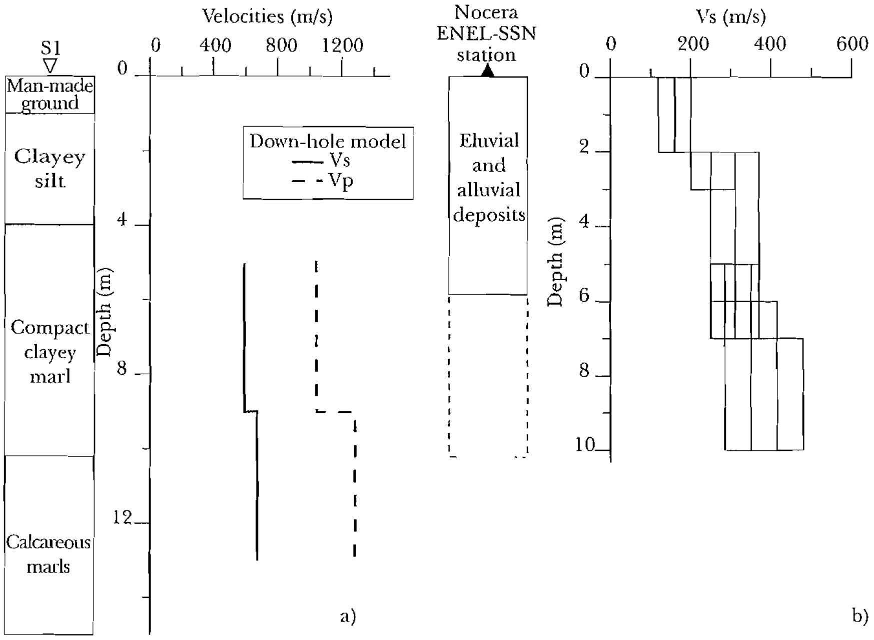
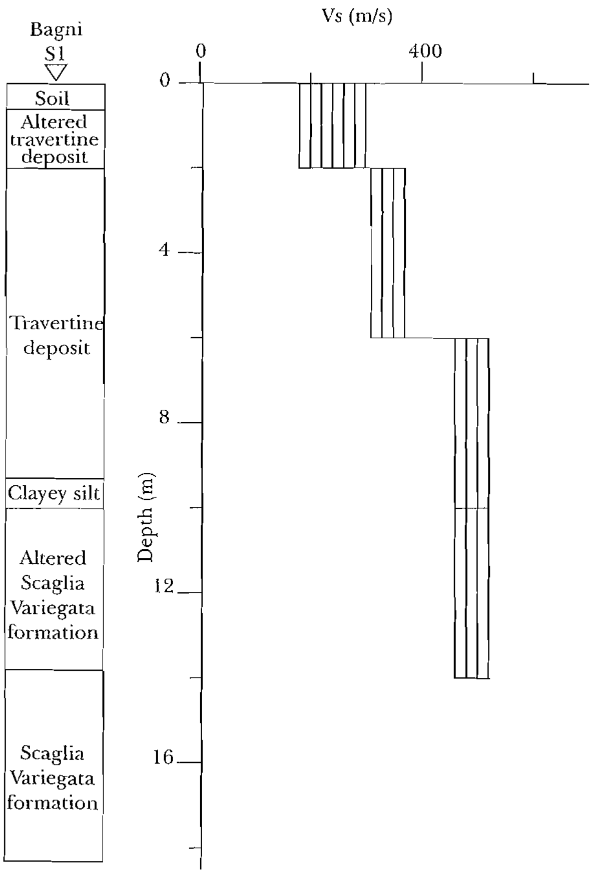


Fig. 5 – Cemetery: comparison beteen down-hole velocity models (a) obtained at S1 drilling (see Fig. 2a for location), and Hedgehog models (b) obtained across the Nocera ENEL-SSN accelerometric station.
Fig. 5 – Cimitero: confronto tra i modelli di velocità down-hole *(a) nel sondaggio S1 (vedi Fig. 2a per l'ubicazione) e i modelli Hedgehog (b) ottenuti lungo un profilo attraverso la stazione accelerometrica ENEL-SSN di Nocera.*



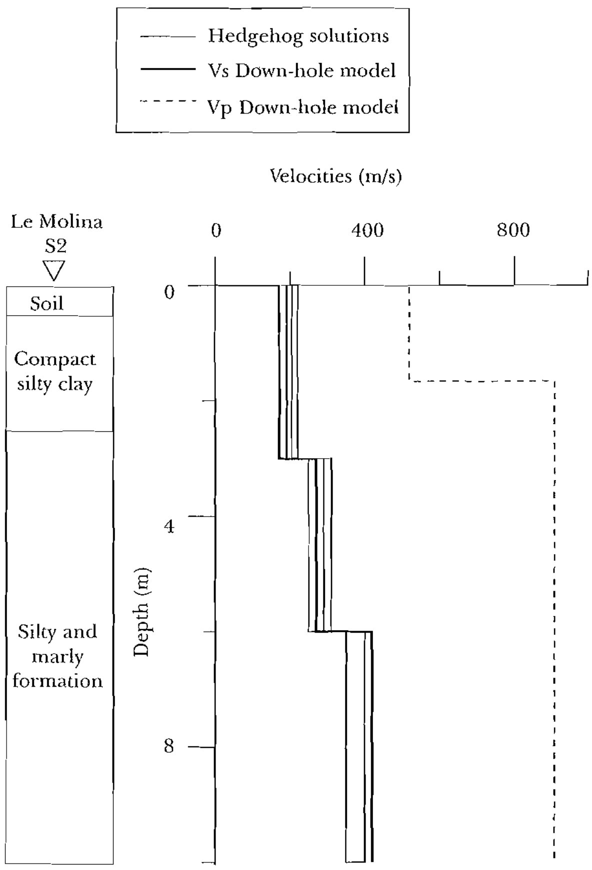


Fig. 6 – Bagni: Hedgehog solutions inverted from FTAN measurements nearby the S1 drilling (see Fig. 1 for location).
Fig. 6 – Bagni: soluzioni Hedgehog delle misure FTAN effettuate lungo uno stendimento attraverso il sondaggio S1 (vedi Fig. 1 per l'ubicazione).

Fig. 7 – Le Molina: comparison between Hedgehog solutions obtained nearby the S2 drilling (see Fig. 2b for location) and down-hole models relative to the S2 drilling.
Fig. 7 – Le Molina: confronto tra le soluzioni Hedgehog ottenute nei pressi del sondaggio S2 (vedi Fig. 2b per l'ubicazione) e i modelli di velocità down-hole *relativi al sondaggio S2.*

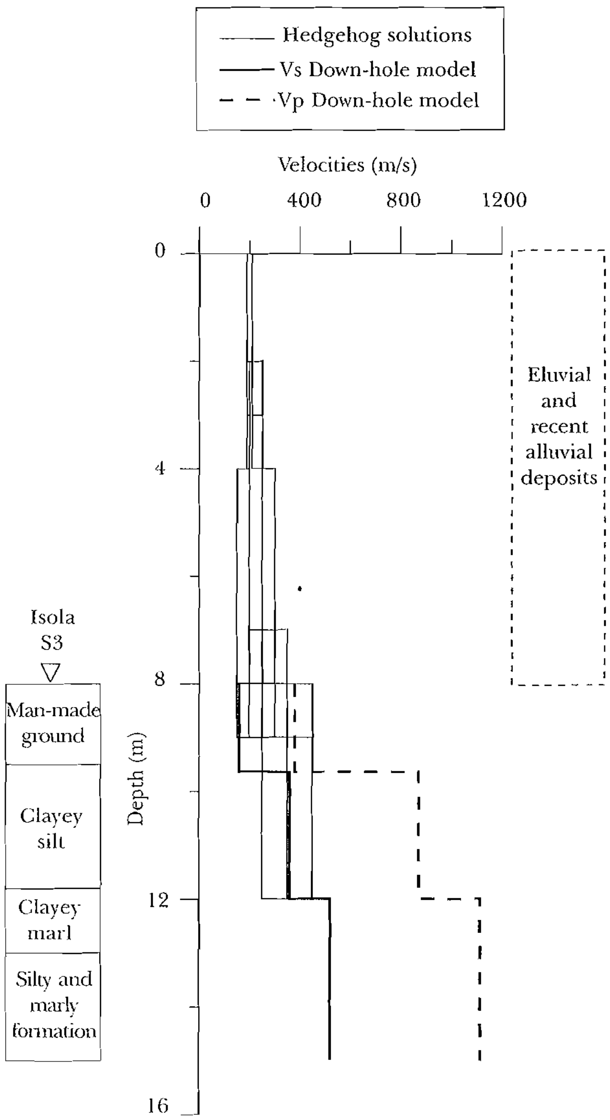


Fig. 8 – Isola: comparison between *down-hole* models obtained at S3 drilling (see Fig. 2b for location) at the basis of alluvial deposits. Hedgehog solutions have been obtained on alluvial deposits. The thickness of eluvial and recent alluvial deposits is hypothesized from the Vs velocity comparison.

Fig. 8 – Isola: confronto tra i modelli di velocità down-hole *del sondaggio S3 (vedi Fig. 2b per l'ubicazione) alla base dei depositi alluvionali. Le soluzioni Hedgehog sono state ottenute per i depositi alluvionali. Lo spessore dei depositi eluviali e alluvionali recenti è ipotizzato in base al confronto delle velocità Vs.*

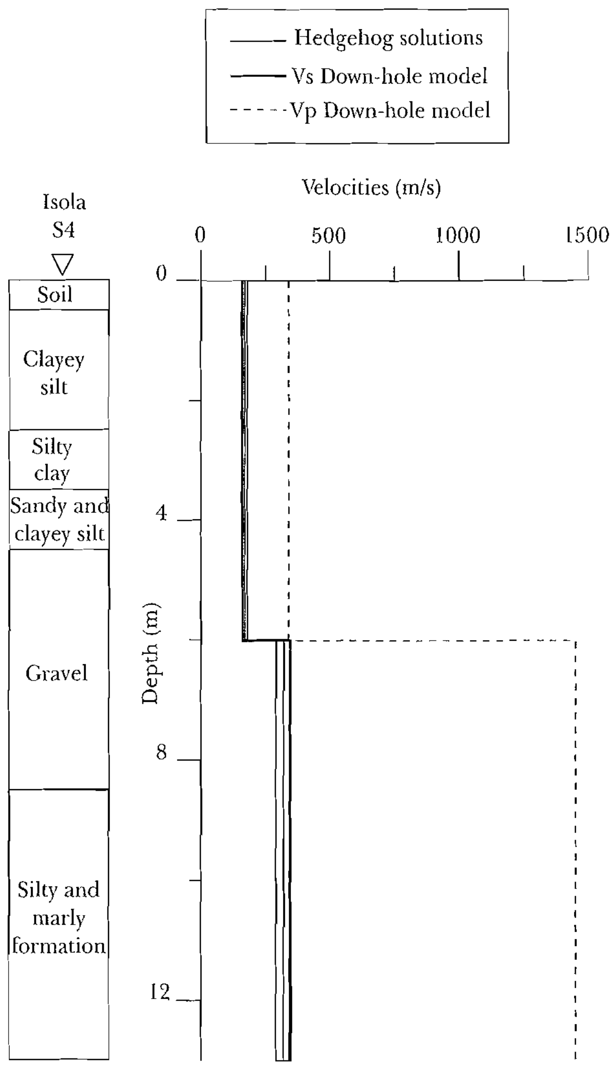


Fig. 9 – Isola: comparison between Hedgehog and down-hole velocity models at S4 drilling (see Fig. 2b for location).

Fig. 9 – Isola: confronto tra i modelli di velocità Hedgehog e down-hole *ottenuti nel sondaggio S4 (vedi Fig. 2b per l'ubicazione).*

has a shear wave velocity between 200 and 220 m/s and the second one has a Vs between 340 and 430 m/s. As it can be seen in Fig. 9, a very good agreement exists with the down-hole model (Fig. 9).

4. Seismic response

The October 6[th] and 14[th], 1997 earthquakes were recorded at two ENEL-SSN accelerometric stations. In Nocera a station was installed, close to the S1 drilling (Fig. 2a), on soft soils, and Biscontini station (see Fig. 1 for location) was installed on marly calcareous rock (Bisciaro formation). We have studied the October events recorded at the two stations to evaluate the amplification effect of Nocera station. In this paper we present a preliminary one-dimensional study of the effect of the measured Vs profile at the Cemetery on the Biscontini accelerogram, and make a comparison with the Nocera accelerogram. The accelerograms have been rotated to get the radial and transverse components of the ground motion. Computed response spectra have been computed at S1 site by assigning the lowest velocity profile among the Hedgehog solutions and by assuming as input the acceleration time histories recorded at Biscontini station. A standard one-dimensional approach [SHAKE program, SCHNABEL et al., 1972] has

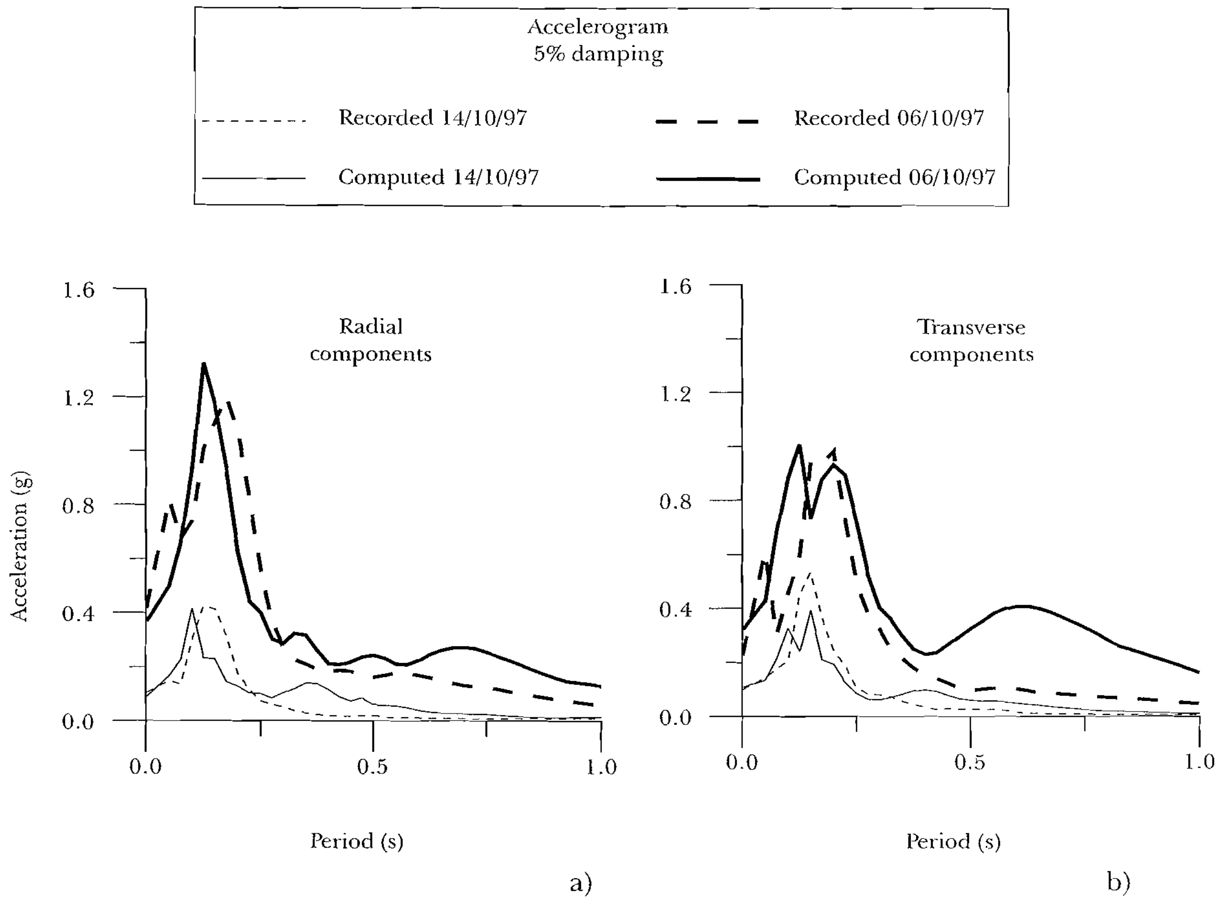


Fig. 10 – Response spectra of radial (a) and transverse (b) components of computed and recorded accelerograms of the October 6 and 14, 1997 events at Nocera ENEL-SSN accelerometric station (see Fig. 2a for location).
Fig. 10 – Confronto tra gli spettri di risposta delle componenti radiale (a) e transversale (b) degli accelerogrammi calcolati e osservati degli eventi del 6 e 14 ottobre 1997 nella stazione accelerometrica ENEL-SSN di Nocera (vedi Fig. 2a per l'ubicazione).

been used by attributing to the eluvial and alluvial deposits the variation of G/Gmax and D/Dmin with shear strain measured with resonant column [GNDT-SSN, 1999] on a clay sample from S4 drilling at Isola (Fig. 9). As it can be seen from Fig. 10, a good match has been obtained between recorded and computed response spectra, and this suggests that, even in a qualitative way, the amplification effect at S1 station can be explained as a site effect.

Conclusions

The main lithotypes of Nocera Umbra have been seismically defined. Eluvial and alluvial deposits have velocity values typical of incoherent soils and thicknesses ranging between 10 m, at Nocera accelerometric station and Isola (S3 drilling) and a few metres at Isola (S4 drilling) and Le Molina. The travertine deposit is locally present at the village of Bagni and can be considered a soft rock for depths greater than 6m, since it is characterized by Vs velocities of about 500 m/s. The same is true for the silty marly formation investigated at Isola and Le Molina, but at greater depths (12 m). Scaglia formations have been investigated at the historical centre of Nocera Umbra and result to be good rocks. In particular, the scaglia variegata formation is the most rigid with Vs of 800 m/s at 11 m of depth.

The 1D computation of the radial and transverse components of October 6 and 14, 1997 accelerograms at Nocera station, taking into account the lowest velocity model obtained with FTAN and Hedgehog methods and using the recordings of Biscontini (on rock) properly scaled, fits well the recorded accelerations. This suggests that the amplification observed at Nocera station can be simply explained as a site effect.

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Caratterizzazione sismica dei terreni superficiali di Nocera Umbra al fine della risposta sismica locale

Sommario

Profili dettagliati delle velocità sismiche di taglio Vs con la profondità sono stati ottenuti con misure in foro down-hole *e attraverso lo studio della dispersione delle velocità di gruppo delle onde di Rayleigh generate artificialmente lungo stendimenti di sismica a rifrazione utilizzando geofoni verticali a 4.5 ed 1Hz. Le curve di dispersione delle velocità di gruppo, ottenute con il metodo FTAN* (Frequency-Time Analysis)*, sono state invertite con il metodo non lineare Hedgehog per ottenere i modelli di velocità Vs. Un buon accordo è stato trovato tra i profili di Vs così ottenuti e le misure* down-hole *nei sondaggi ubicati lungo gli stendimenti. Le misure sismiche sono state effettuate in siti rappresentativi dell'assetto geologico di Nocera Umbra, nei pressi di sondaggi geognostici allestiti anche per le prove in foro. I siti scelti per le indagini sono il centro storico, la zona del cimitero, la frazione di Bagni e gli abitati di Isola e Le Molina.*

Nel territorio di Nocera Umbra affiorano le formazioni della serie umbro-marchigiana, dalla scaglia rossa alla marnoso-arenacea. Le formazioni delle scaglie sono state investigate nel centro storico di Nocera Umbra e risultano delle buone rocce. In particolare, la formazione della scaglia variegata è caratterizzata da velocità Vs di 800 m/s a 11 m di profondità. Sia il deposito di travertino, presente a Bagni, sia la formazione marnoso-arenacea, investigata a Isola e Le Molina, hanno velocità Vs tipiche di una roccia tenera (Vs=500 m/s) a profondità maggiori rispettivamente di 6 m e 12 m. I depositi eluvio-alluvionali, i detriti di versante e il materiale di riporto sono predominanti nella parte settentrionale della città (abitati di Isola e Le Molina) e presentano valori di velocità tipici di terreni incoerenti. La zona del cimitero, dove è stata installata la stazione accelerometrica ENEL-SSN, è caratterizzata dalla formazione marnoso-arenacea con copertura di materiale eluvio-lacustre e detritico.

In seguito al terremoto del 26/09/97 due stazioni accelerometriche ENEL-SSN sono state installate a Nocera Umbra (cimitero) e a Biscontini, rispettivamente su terreno soffice e su roccia (formazione del Bisciaro). Al fine di valutare l'amplificazione di sito nella zona del cimitero, gli accelerogrammi degli eventi del 6-14/10/97 sono stati corretti per la risposta strumentale e ruotati per ottenere le componenti radiali e trasversali. Gli spettri di risposta 1D (programma SHAKE) calcolati nella stazione accelerometrica di Nocera, assumendo il profilo delle velocità minime tra tutte le soluzioni Hedgehog, e l'accelerogramma registrato a Biscontini come input sismico, sono in buon accordo con quelli registrati. Questo risultato suggerisce che l'amplificazione osservata a Nocera può essere spiegata come effetto di sito.