Pure appl. geophys. 161 (2004) 1285–1300
0033 – 4553/04/061285 – 16
DOI 10.1007/s00024-003-2492-z

Pure and Applied Geophysics

Seismic Characterization of Neapolitan Soils

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Abstract—Detailed shear-wave velocity profiles versus depth have been obtained in typical lithostratigraphies of Napoli. FTAN and hedgehog methods have been applied to Rayleigh surface waves recorded in refraction seismic surveys. The comparison with literature measurements shows good agreement with nearby down- and cross-hole tests.

The pumiceous and lapilli content, and the different welding and alteration degree of the Neapolitan pyroclastic soils cause a strong scattering of the shear wave velocities (V_S) from bore-hole measurements, even for the same formation. Surface measurements, based on FTAN-hedgehog methods, determine average V_S along travel paths of about 100 m, give results that are comparable with down- and cross-hole velocity profiles, and have the additional advantage of being less scattered, and thus more representative of average properties than bore-hole measurements. The results of surface measurements should be preferred in the computation of realistic seismograms and are particularly suitable in urban areas, as they are not destructive and need just one receiver.

Key words: Napoli, pyroclastic materials, shear wave velocities, inversion.

1. Introduction

Napoli is located within the Campi Flegrei (CF), an active volcanic area, and is delimited on the eastern border by Somma-Vesuvius active volcano (Fig. 1). The CF area is a structural depression interpreted as a calderic system characterized by many Quaternary vents (ROSI and SBRANA, 1987; ORSI *et al.*, 1996). The subsoil structure of the CF caldera consists of incoherent volcanic products with different characteristics. Besides the alteration processes undergone after deposition, this is due to the differences of the primary magma composition, the mechanisms and environment of setting. As a consequence of these processes, the deposits are arranged in complex structural settings with vertical and lateral inhomogeneities, overlying a tufaceous formation.

The seismic hazard of Napoli is controlled both by Apennines tectonic earthquakes and by Vesuvius seismic activity. The last Apennines earthquake, November 23rd

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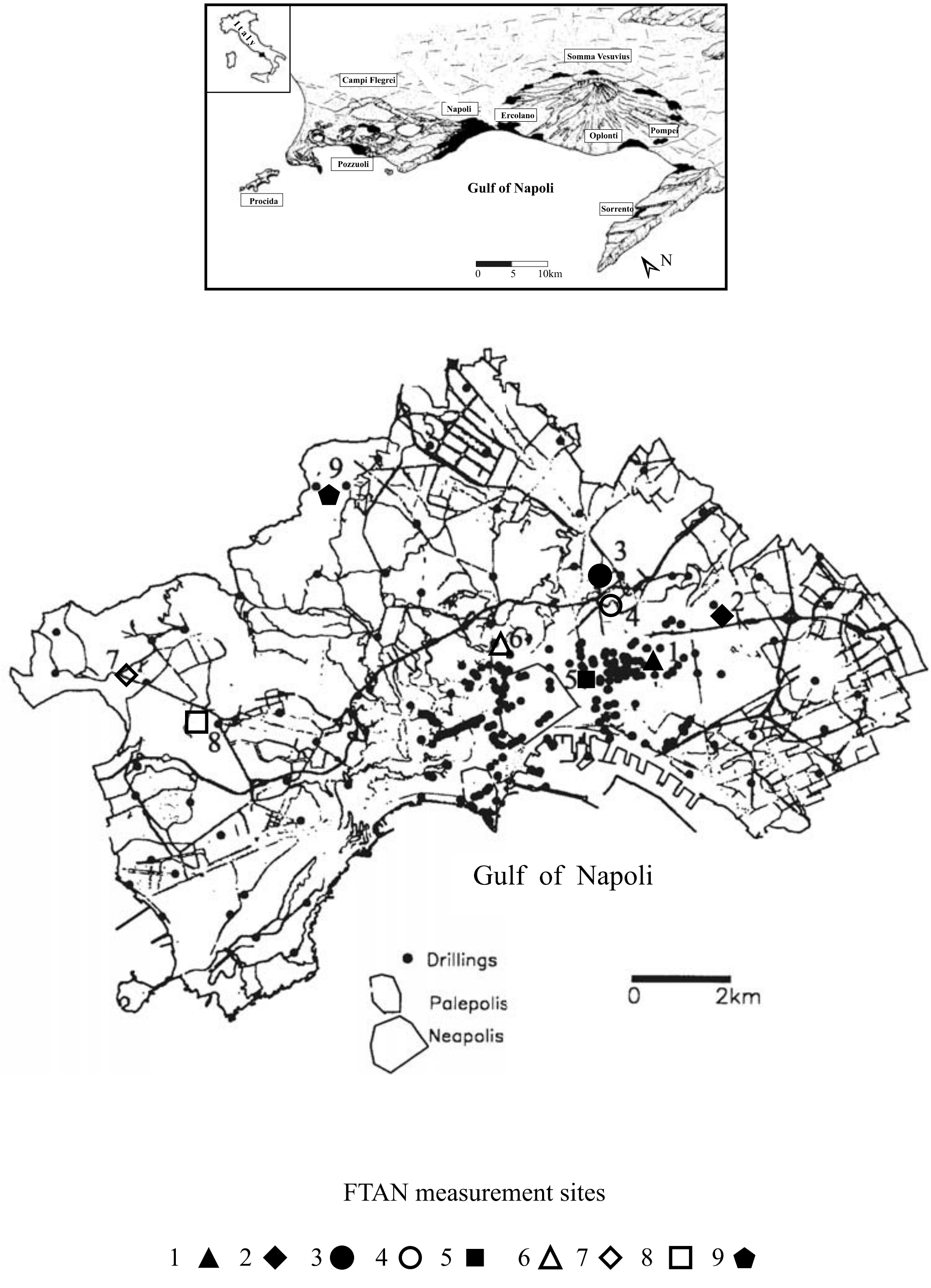

Figure 1
Location (top) and map of the urban area of Napoli with the location of collected drillings and FTAN measurement sites. The ancient Greek Palepolis and Neapolis are also shown.

1980, ($M_s = 6.9$) caused extensive damage corresponding to an intensity of VII-VIII on MCS (Mercalli-Cancani-Sieberg) scale. Even more damage is expected from the earthquakes connected to the volcanic activity of the Somma-Vesuvius complex, as testified by historical chronicles (ALFANO and FRIEDLANDER, 1929).

In this context, the definition of the shear wave velocities (V_S) of volcanic soils and rocks is fundamental for the evaluation of the site amplification effects in different stratigraphic conditions. Moreover, a better knowledge of the shear dynamic properties of the lithotypes and their variations associated with different deposition conditions may help in the stratigraphic modelling of seismic measurements.

The aim of this paper is twofold: the first one defines the ranges of V_S of the Neapolitan pyroclastic soils and rocks, based upon literature and original seismic measurements, and the second one defines V_S profiles in a highly urbanized city with a rich historical building heritage like Napoli, from the inversion of Rayleigh wave group velocities.

2. Geological Setting

Napoli is located on volcaniclastic soils and rocks (various types of tuffs) erupted by the Campi Flegrei (CF) volcanoes, and secondly by Vesuvius. The original material that forms the tuffs and the volcanic soils is in general the same, with the volcaniclastic rocks resulting from the hardening of the volcaniclastic soils by post depositional hydrothermal alteration. Such hardening is not homogeneous, thus intermediate facies may exist from lithoid (compact tuff) to incoherent (pozzolana), through welded incoherent facies (welded pozzolana). Beside the intense volcanic activity, Napoli has suffered extensively due to the influence of meteoric and marine agents, and the anthropic action of morphological modeling for urban settlement. In fact, the ancient Napoli, Palepolis and later Neapolis, in the middle of the city, was founded by Greek settlers, and was a tuff hill, separated from the neighbouring lands by several rivers and limited by the sea in the south (Fig. 1). Subsequently, the presence of so many rivers generated deep hollows filled with alluvial materials and bricks derived from the urban settlement. The sea receded and streets were built along the coastline. Numerous «vacua» of a different nature cross the Neapolitan underground. They include, besides present and ancient sewer systems and tunnels, tuff quarries, pits to extract the pumiceous lapilli and pozzolana, the canalisation of the ancient (Greek and Roman) aqueducts.

The volcanological study of the products of different explosive vents in the CF area (SCARPATI *et al.*, 1993; ORSI *et al.*, 1996), and the stratigraphic sequences from bore-holes (Fig. 1) (AA.VV., 1967; VINALE, 1988; COMUNE DI NAPOLI, 1994) have been very useful in reconstructing the volcanological and structural setting of the Neapolitan urban area. It results that below a cover of man-made ground material 10 m thick the most widespread pyroclastic products belong to the Neapolitan

Yellow Tuff (NYT) eruption (12,000 years old) and more recent volcanic activity (< 12,000 years old) of different CF eruptive centers (Fig. 2). The oldest product, that is the Campanian Ignimbrite tuff (33,000 years old), is sporadically present. Marine sands are present along the coast and organic materials are encountered locally. At last, Vesuvius tuff and ashes have been found in the eastern area of Napoli. The lithoid tuff horizon is, on average, 10–30 m deep, but deepens to more than 100 m in the western area and to more than 40 m in the southeastern area of Napoli (Fig. 3).

Laboratory measurements of geotechnical properties of several specimens, extracted from drillings and quarries (AA.VV., 1967; VINALE, 1988; COMUNE DI NAPOLI, 1994; NUNZIATA *et al.*, 1999a), show that the CF soil generally ranges from

LEGEND
(MG) Man-made ground; (ES) Eluvial sands;
(PMS) Present marine sands; (RMS) Recent marine sands;
(FLD) Fluvial-lacustrine deposits; (VA) Vesuvius ashes;
(RPD) Recent pyroclastic deposits; (VT) Vesuvius tuff (soil facies);
(NYTs) Neapolitan Yellow Tuff (soil facies);
(NYT) Neapolitan Yellow Tuff (lithoid facies);
(CI) Campanian Ignimbrite

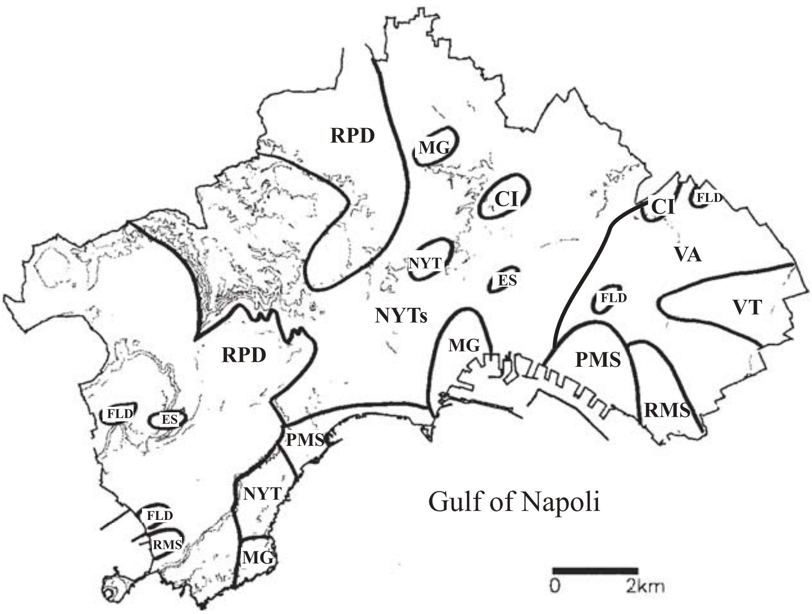

Figure 2
Volcanological map of Napoli at 10 m of depth from ground surface, placed on the topographic sketch map.

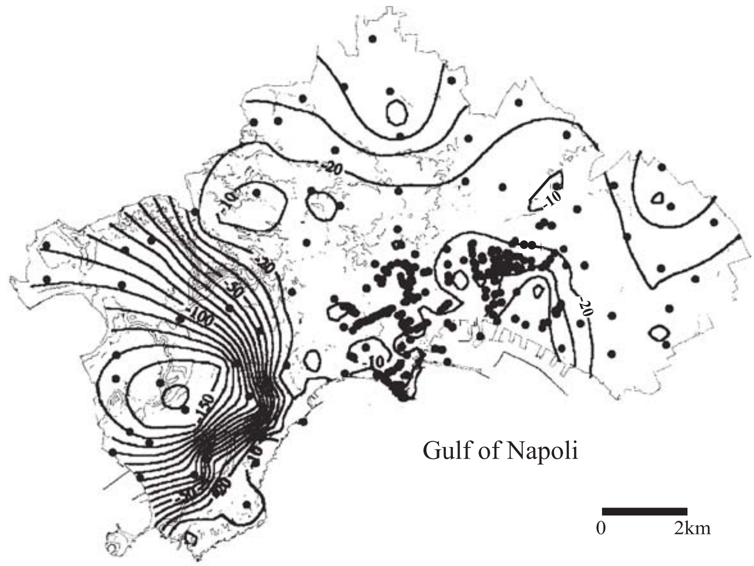

Figure 3
Map of isobaths of the lithoid tuff horizon in meters from ground surface (dots represent the drillings).

silty sand to sandy silt. The coarser deposits correspond to the pumiceous layers of the younger pyroclastic products. The unit weight of the soil solids (γ_s) ranges 17.5 ÷ 27.0 kN/m^3 and the natural unit weights (γ_n) vary between 9.4 and 21.7 kN/m^3. The shear resistance values ($\varphi°$) vary in the 18° ÷ 64° range, the porosity is between 30 and 90% and the water content varies between 6.5 and 62.3% (Table 1).

3. Shear wave Velocities of Neapolitan Soils and Rocks

The V_S of different deposits, determined in borehole, cross- and down- (Vinale, 1988; Comune di Napoli, 1994) tests, have been collected. To define the ranges of variability for the Neapolitan soils and rocks, all V_S measurements have been analysed with the framework of the volcanological and geotechnical stratigraphies. A preliminary study of the V_S of NYT and of younger pyroclastic deposits of Campi Flegrei-Neapolitan area has been conducted, based on the comparative analysis of field and laboratory measurements by Nunziata *et al.* (1999a). Wide ranges of variations have been shown. They are the consequence of the profound differences of the physical properties and textural conditions that can be present even in the same formation. An additional important influencing factor is represented by the different hardening degree, due to the diagenetic process.

Down-hole (DH) and cross-hole (CH) measurements are point measurements, therefore average values of V_S, over some one hundred meters, are more suitable for any evaluation of seismic site amplification effects. With such aim, within the

Table 1

Geotechnical properties of the Neapolitan lithotypes

Lithotype	γ_s (kNm^{-3})	γ_n (kNm^{-3})	n (%)	$\varphi°$	W%
Eluvial deposit	23.0–25.8	11.0–20.7	34–66	32–41	18.8–53.7
Present marine sands	24.0–26.8	16.5–20.8	33–50	29–42	13.5–37.4
Recent marine sands	22.9–25.7	15.7–18.8	35–54	26–40	19.3–50.8
Fluvial-lacustre deposits	17.5–26.6	10.0–20.7	34–90	32–41	18.8–61.3
Vesuvius ashes	21.0–27.0	10.0–20.0	37–86	26–39	19.1–60.2
Recent pyroclastic deposits	23.5–26.3	13.5–14.5	40–64	21–45	9.9–62.3
NYT (soil facies)	22.1–26.0	10.6–18.6	38–64	18–41	6.5–47.5
NYT (lithoid facies)	22.3–24.5	9.4–15.3	38–58	no data	no data
Vesuvius tuff (soil facies)	20.5–26.8	11.0–20.3	30–41	36–64	18.1–50.8
Vesuvius tuff (lithoid facies)	24.7–26.3	16.0–17.6	44–54	30	26.9–41.3
Campanian Ignimbrite	23.3–26.9	11.0–21.7	no data	30–41	no data

γ_s = unit weight of the soil solids; γ_n = natural unit weights; n = porosity; $\varphi°$ = shear resistance values; W = content of water.

framework of the UNESCO-IUGS-IGCP project "Realistic Modelling of Seismic Input for Megacities and Large Urban Areas", detailed V_S velocity profiles with depth have been obtained in representative lithostratigraphic sites of Napoli by using Rayleigh waves recorded in refraction seismic surveys. The source was the vertical impact of a 20 Kg weight on the ground, the receivers were 1 Hz and 4.5 Hz vertical geophones (70% damping) and the source-receiver distance variable between 50 and 150 m. Group velocities of surface waves have been measured employing the FTAN method on single channels (LEVSHIN *et al.*, 1992). A nonlinear inversion, hedgehog method (VALYUS *et al.*, 1968; PANZA, 1981), of the group velocity dispersion curves defines the V_S distribution with depth. The average dispersion curves of the fundamental mode of Rayleigh wave group velocities typically fall in the 0.02 to 0.3 s period range.

Such an approach produces results well in agreement with DH and CH tests (NUNZIATA *et al.*, 1999b; NUNZIATA *et al.*, 2001a, b) and is substantially more reliable than the SASW method (NAZARIAN and STOKOE, 1985), often employed in engineering problems and based on phase velocity measurements.

In the following, the sets of V_S profiles obtained with hedgehog inversion are compared with bore-hole measurements given in literature, for the different formations and then, site by site, with the closest DH or CH velocity profile with depth. In such a way we improve our knowledge of the shear dynamic parameters of the Neapolitan pyroclastic products, and we test the possibilities offered by FTAN against bore-hole measurements, that are considered the most efficient by engineers.

3.1 Recent Pyroclastic Products

Volcanic products erupted by different vents of the CF area after the NYT tuff eruption (< 12,000 y) are mainly concentrated on the western side of Napoli and, to a lesser degree, on the northern side (Fig. 2). These deposits are represented by a proximal facies of pyroclastic-flow and -surge, in the CF caldera, and outside by distal fallout products (ORSI *et al.*, 1996). They are present as soil facies and are characterized by V_S velocities ranging between 80 m/s and more than 600 m/s (Fig. 4). FTAN measurements have been carried out at five sites (measurements at sites 7 and 8 are from GAROFALO, 2000) and they fall in the range defined by DH and CH tests (COMUNE DI NAPOLI, 1994), however they are always lower than 400 m/s, even at greater depths.

3.2 NYT Deposit

The NYT deposit is the most extensively present in Napoli, and consists of both lithoid (tuff) and soil (pozzolana) facies. The V_S of NYT pozzolana are strongly scattered, roughly between 100 m/s and 650 m/s (Fig. 5). The velocity range defined by the hedgehog nonlinear inversion is less scattered, between 150 m/s and 400 m/s.

Shear wave velocities of the NYT tuff range from about 300 m/s up to 1300 m/s (Fig. 5), and a continuity seems to exist between the velocity values of NYT pozzolana and tuff which may be interpreted as evidence of their origin. In fact, the NYT formation is the result of hardening processes due to hydrothermal alteration of the *pozzolana* deposit (DE' GENNARO *et al.*, 1983). The different degrees of these hardening processes have, as a consequence, a wide welding range of the volcanic products with strong variations of the physical properties, and consequently a wide range of V_S values. The wide range of tuff V_S can also be explained in terms of the different textural conditions, as the NYT tuff is present in facies with different

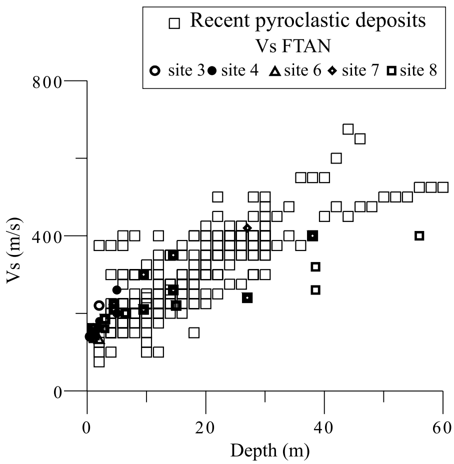

Figure 4

V_S velocities of recent pyroclastic deposits. Symbols indicate down- and cross-hole tests (COMUNE DI NAPOLI, 1994), and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements at sites located in Figure 1.

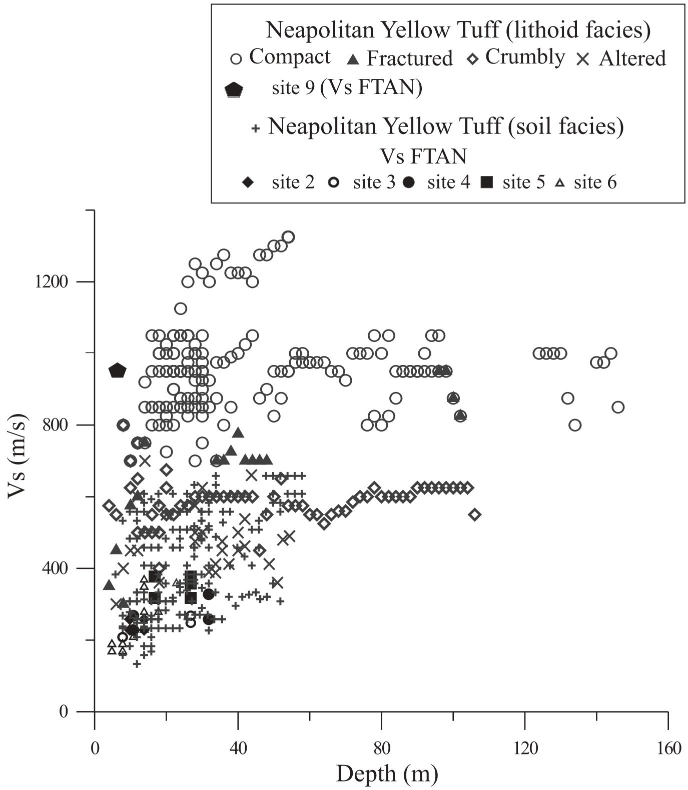

Figure 5
V_S velocities of Neapolitan Yellow Tuff, both soil and lithoid facies. Symbols indicate down- and cross-hole tests (Vinale, 1988; Comune di Napoli, 1994), and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements at sites located in Figure 1.

degrees of lithification, porosity, and percentage of the pumiceous and/or lithic elements. The lowest values of V_S can be assigned to altered tuff which is always present in the shallower part of the tufaceous formation a few meters thick, and especially at the borders or where such bodies taper. Probably even at great depths (100 m), V_S velocities of altered tuff are similar to those of welded pozzolana. Altered NYT tuffs have wide ranges of V_S, from 300 m/s to 700 m/s (Fig. 5). Vacuous tuffs are characterized by the presence of pumiceous elements, and show a variability of V_S between 500 m/s and 650 m/s. The V_S of fractured NYT tuff increase with depth, nonetheless it is reasonable to think that fractures are already closed at 20 m of depth, since values higher than 700 m/s have been measured at those depths (Fig. 5). In compact NYT tuff V_S velocities higher than 700 m/s have been measured and FTAN experiments carried out in a NYT quarry have led to the definition of a V_S of about 950 m/s.

3.3 Vesuvius Products

Vesuvius tuffs and ashes are widespread in the eastern area. Ashes are characterized by V_S velocities in the range 100–450 m/s and such a wide range can be justified by the variable content of pumiceous and lithic elements (Fig. 6). Instead, hedgehog solutions show a narrow range between 150 m/s and 200 m/s.

Vesuvius tuff was erupted similarly in time as NYT tuff. Soil facies, pozzolana, is characterized by V_S ranging 300–600 m/s; lithoid facies, tuff, has V_S values between 650 m/s and 1100 m/s (Fig. 6). The transition V_S value of about 600 m/s from pozzolana to tuff facies is clearly evident. Physical characteristics of Vesuvius deposits are similar to those of NYT deposits and, consequently, the scattering of V_S measurements can be explained, also for these products, in terms of the different percentage of the pumiceous and/or lithic elements, and of welding process and alteration.

3.4 Campanian Ignimbrite Deposit

The oldest products include Campanian Ignimbrite (CI) deposit (33,000 years old), made by gross scoriae in a cinerite matrix. The variability can be clearly associated with the prevalence of scoriae on the cinerite matrix and/or the alteration of cinerite matrix, as it happens, for example, at the borders of the deposit. DH and CH measurements are

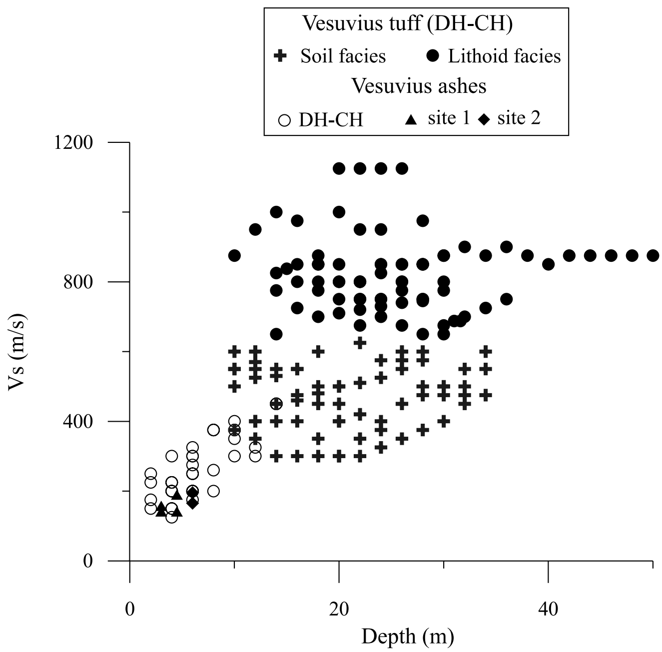

Figure 6
V_S velocities of Vesuvius ashes and tuff, both soil and lithoid facies. Symbols indicate down- and cross-hole tests (VINALE, 1988; COMUNE DI NAPOLI, 1994), and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements at sites located in Figure 1.

few, and give V_S velocities of 600–700 m/s (Fig. 7). The velocity range defined by the hedgehog nonlinear inversion obtained at two sites is characterized by V_S values of 250–450 m/s, typical of NYT (Fig. 5) and Vesuvius pozzolana (Fig. 6).

3.5 Sandy Deposits

The analysis of the lithostratigraphies has shown the presence of recent and present coastal sands along the coastline, and of eluvial and fluvial-lacustrine deposits with peat layers. In the western area the deposits are mainly constituted by the recent coastal sands and, to a minor extent, by the eluvial products made by reworked volcanic deposits. By contrast, in the eastern sector the outcropping deposits are formed by the ashy and sandy products, mainly of volcanic origin, reworked in marshy environment as testified by the presence of the peat layers (Fig. 2). These products are considered separately because they suffered different sedimentation processes, even though they have similar grain-size characteristics. As a consequence of the sedimentation environment and of the alteration processes, V_S are widely scattered and, on average, V_S of the eluvial and fluvial-lacustrine products are lower than those of the coastal sandy deposits (Figs. 8a–b). Regardless, it would seem that both eluvial and marine sands improve their mechanical behaviour with depth, reaching, at depths greater than 60 m, an average value for V_S of approximately 600 m/s.

4. Hedgehog and DH-CH Velocity Models

In order to test the V_S profiles versus depth obtained from the nonlinear inversion of Rayleigh wave group velocities, a comparison has been performed between FTAN-hedgehog V_S models and nearby DH and CH tests (Fig. 9).

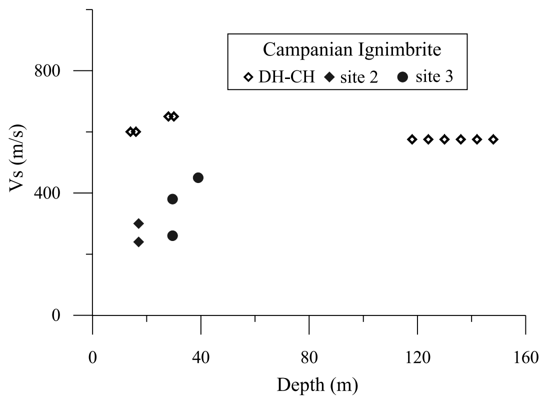

Figure 7
V_S velocities of Campanian Ignimbrite deposit. Symbols indicate down- and cross-hole tests (COMUNE DI NAPOLI, 1994), and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements at sites located in Figure 1.

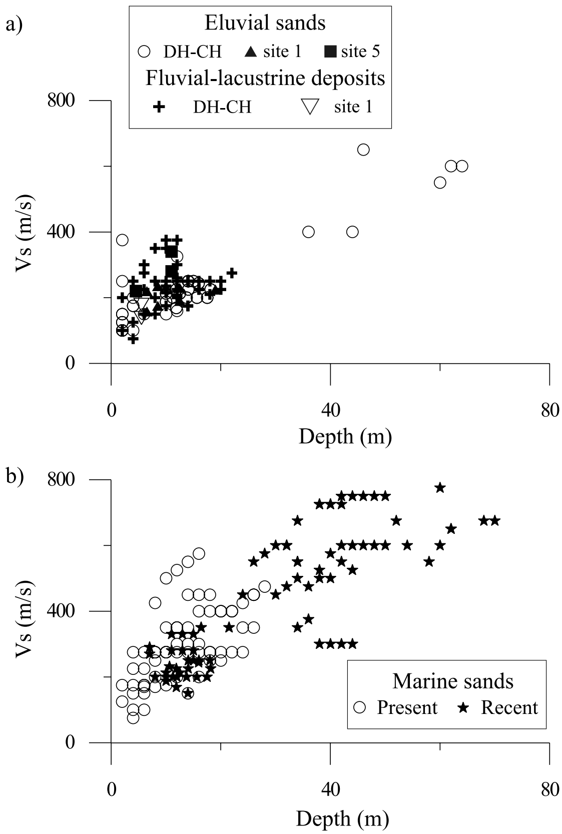

Figure 8

V_S velocities of sands. a) Eluvial sands and fluvial lacustrine deposits; b) Present and recent marine sands. Symbols indicate down- and cross-hole tests (VINALE, 1988; COMUNE DI NAPOLI, 1994), and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements at sites located in Figure 1.

Site 1 (Fig. 1 and Fig. 9) is located in the eastern sector of Napoli, about 400 m far from the nearest S20 cross-hole test. The subsoil is characterized by eluvial sands and Vesuvius ashes, with peat levels. Even if lateral inhomogeneities have been found in the area, mostly regarding the peat layer, good agreement exists between hedgehog solutions and cross-hole V_S profiles, in particular for the solution with a velocity inversion at 10 m of depth, surely to be attributed to the presence of the peat layer.

Site 2 (Fig. 1 and Fig. 9) is some meters from the building that collapsed during the last earthquake in 1980 ($M_s = 6.9$). The stratigraphy is characterized by Vesuvius ashes, NYT pozzolana and CI deposit. The agreement of the velocity range defined by the hedgehog nonlinear inversion with the DH test in the S67 drilling, located along the FTAN seismic spreading, is quite good for the uppermost 10 m. Below 10 m of depth, probably due to a bad borehole casing or to the presence of large scoriae or lavic lapilli, there is a large discrepancy.

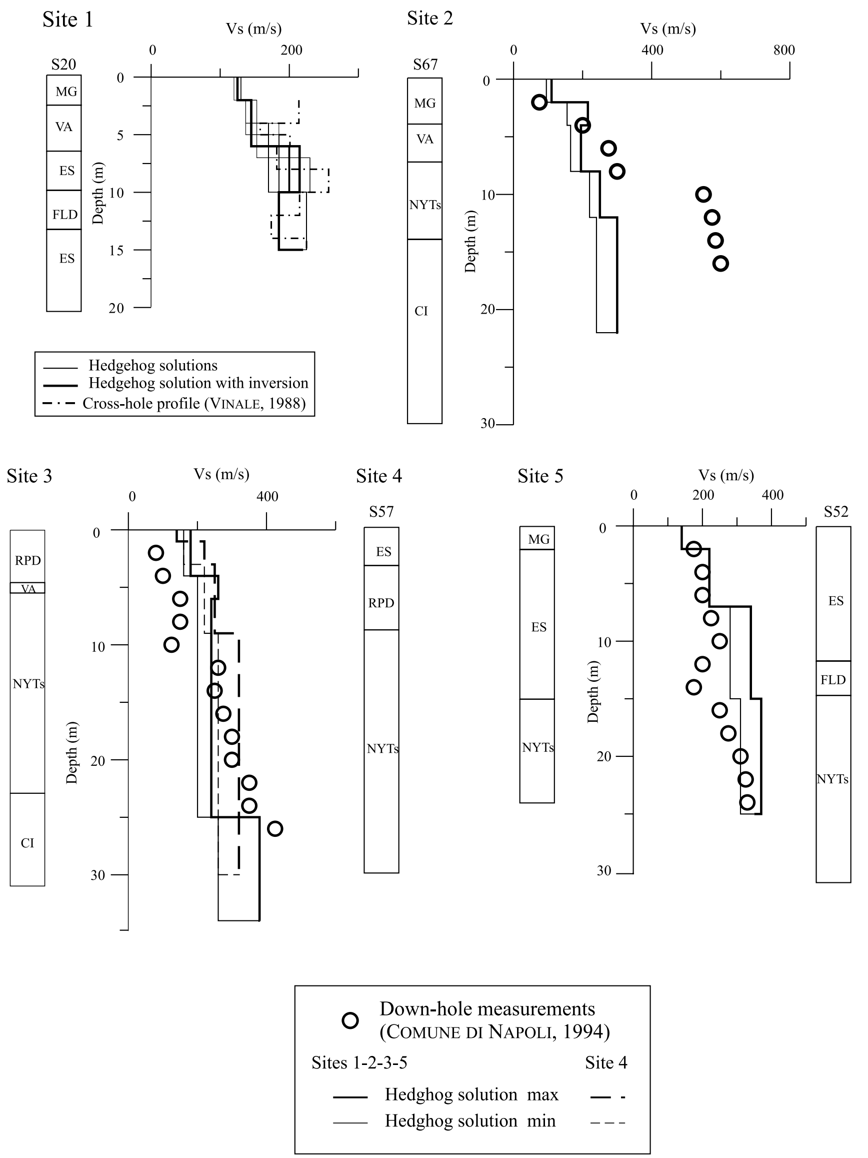

Figure 9
Comparison between down- and cross-hole V_S measurements and the velocity range defined by the hedgehog nonlinear inversion of FTAN measurements obtained at sites located in Figure 1.

Sites 3 and 4 (Fig. 1 and Fig. 9) are 400 m apart and 200 m and 400 m respectively from the drilling S57. The stratigraphy is mainly represented by NYT pozzolana and, at site 3, by CI deposit at depths greater than 20 m. Some discrepancy between the hedgehog velocity range and DH V_S profiles can be observed at depths

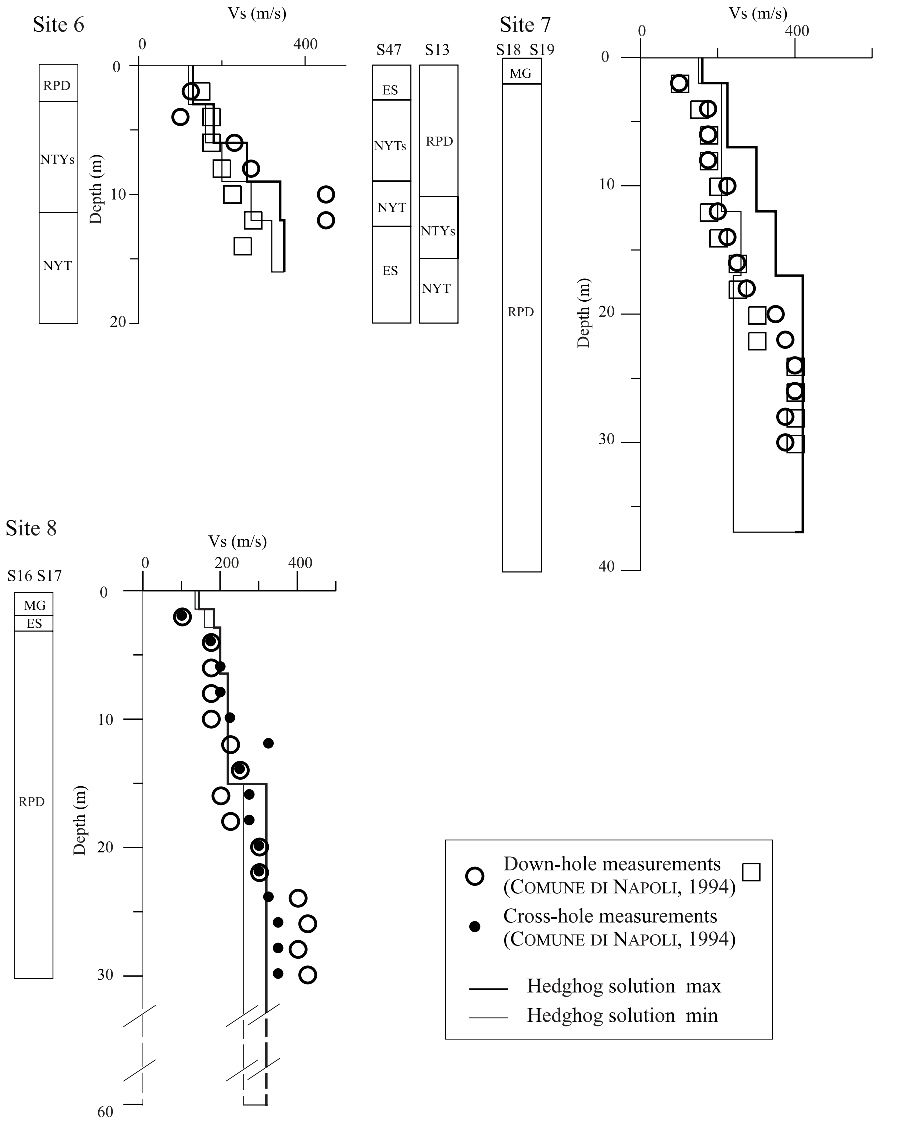

Figure 9
(Contd.)

lower than 10 m, however in the NYT pozzolana there is practically overlap between DH and the corresponding V_S measurements at site 4. Moreover, the hedgehog models obtained at the two sites differ by about 50 m/s, meaning that the NYT pozzolana horizon has the same characteristics.

Site 5 (Fig. 1 and Fig. 9) is characterized by the presence of eluvial sands on NYT pozzolana. The V_S DH measurements at the nearby S52 drilling, about 200 m distant, are in good agreement with the velocity range defined by the hedgehog nonlinear inversion, except in the peat intercalation zone which is present only at drilling site S52.

Site 6 (Fig. 1 and Fig. 9) has a typical stratigraphy of the historical centre of Napoli, that is, recent pyroclastic products, NYT pozzolana and tuff. The pozzolana thickness changes within few hundred meters, as testified by S43 drilling, 350 m from the surface measurements site. A quite good agreement can be observed between DH and the velocity range defined by the hedgehog nonlinear inversion, except at depths exceeding 10 m.

Sites 7 and 8 (Fig. 1 and Fig. 9) are located in the western sector of Napoli and are both characterized by a cover of recent pyroclastic products. A good agreement exists between DH and the hedgehog velocity range, 400 m apart. The discrepancy between CH and DH measurements in site 8 is indicative of the reliability of such measurements.

5. *Conclusions*

Neapolitan pyroclastic soils can be classified as silty sands or sandy silts, originally deposited with different hardening degrees and textural conditions and often altered by the influence of the meteoric and marine agents, and the anthropic action. As a consequence of such a complex volcanological environment, we may expect soil and lithoid facies, with the lithoid facies depending on the degree of lithification, porosity, and percentage of the pumiceous and/or lithic elements. As a result lateral and vertical inhomogeneities, and consequently, wide scattering of V_S are found (Fig. 10), even for the same formation. Such scattering is particularly evident for DH and CH measurements, and it may be related to the pumiceous and scoriaceous nature of the Neapolitan soil and also to the peculiarity of borehole measurements, that are point measurements, strongly dependent on the casing quality. However, hedgehog solutions obtained from the inversion of FTAN group velocity dispersion curves, are representative of the average V_S over distances of about one hundred meters.

Compact tuff, both Vesuvius and NYT, and fractured NYT tuff, at a depth of 20 m, can be assumed as a soft rock basement characterized by V_S greater than 650 m/s. The same probably applies to eluvial and marine sands at depths greater than 60 m. Consequently, the isobath map of the compact tuffs (Fig. 3) can be considered as the isobath map of the bedrock seismic horizon of Napoli (V_S > 650 m/s) for any evaluation of site effects.

Surface measurements of V_S are requested for any evaluation of seismic response analysis at Napoli, and, for this purpose, FTAN measurements are preferable. In fact they give average values, comparable with borehole tests, are not destructive and request the use of just one receiver. All these properties are particularly important in

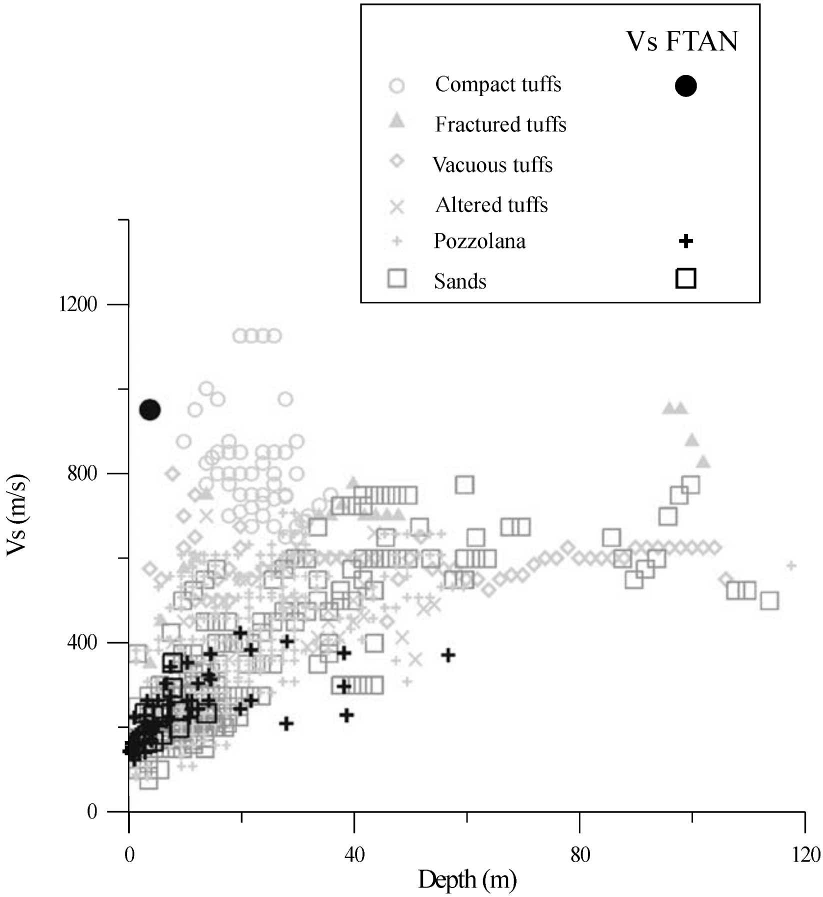

Figure 10
V_S velocities relative to all Neapolitan products obtained by down- and cross-hole measurements (grey symbols) and by the hedgehog nonlinear inversion of FTAN measurements (black symbols).

urban areas. Alternatively, a sound approach might be to make a parametric study of the ground motion by means of modeling (PANZA *et al.*, 2000) that allows us to take into account the wide range of variability of the Neapolitan pyroclastic products already determined (Fig. 10).

Acknowledgements

We thank Dr. B. Garofalo for collecting data and assisting in drawing figures 1 and 3.

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(Received May 20, 2002, accepted November 8, 2002)