Seismic Characterisation of Soils with SPT: Comparison of Calculated vs Values and Measured vs Values

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SEISMIC CHARACTERISATION OF SOILS WITH SPT: COMPARISON OF CALCULATED Vs VALUES AND MEASURED Vs VALUES

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ABSTRACT

Italian seismic regulatory guidance (O.P.C.M. n. 3274 of 20 March 2003, O.P.C.M. n. 3519 of 28 April 2006, implemented within the "Norme Tecniche per le Costruzioni" – D.M. of 14 January 2008) which conforms to European guidance (Eurocode 8), advises a seismic classification of foundation soils through the Vs_{30} value or alternatively the Nspt value. Several correlations between the Nspt parameter and the Vs parameter are known in literature (Otha & Goto, 1978; Imai & Tonouchi, 1982; Ohsaki & Iwasaki, 1977; Seed, 1983). Each of these correlations can only be applied in certain geological-technical contexts. The validity of these correlations should be discussed considering that geophysical investigations are undertaken under elastic deformation conditions where induced stress causes reversible deformations. Instead, SPT investigations cause rupture of the investigated material and they cannot be conducted within all types of deposits.

This note presents the results obtained by comparison of Vs values from SPT investigations and the Vs values from down-hole investigations measured on the same vertical and at the same depth. The study is based on a great quantity of data (153 pairs of Nspt-Vs values) which were acquired from different geological-technical contexts. The data were acquired within the VEL project of the Tuscany Region (Central Italy) aimed at assessing local effects in areas where different seismic hazards exist. Limits and applicability of these empirical correlations are discussed.

INTRODUCTION

Seismic characterisation of soils for assessing local seismic hazards is a well discussed issue within the scientific community. Italian regulatory guidance (O.P.C.M. n. 3274 of 20 March 2003, O.P.C.M. n. 3519 of 28 April 2006, implemented within the "Norme Tecniche per le Costruzioni" – D.M. of 14 January 2008) which conforms to European regulations (Eurocode 8) classifies foundation soils through soil categories. Each soil category defines a seismic behaviour within the field of very low deformations. The category is identified on the basis of the Vs_{30} values or alternatively the Nspt values for granular soils and the cu for cohesive soils. These parameters are equivalent for the definition of the engineering spectrum of a building according to regulatory guidance. The widespread use of Standard Penetration Tests (SPT) for the on-site characterisation of granular foundation soils has induced researchers to search for correlations between the resistance to penetration and the propagation of shear waves (Barrow and Stokoe, 1983; Carrubba and Maugeri, 1988; Crespellani et al. 1989; Jamiolkowski et al. 1988; Mayne and Rix, 1995; Imai, 1977; Lee, 1990; Lo Presti et al., 2006; Sykora and Stokoe 1983, Fear and Robertson 1995, Nagase et al., 2006; Quartero 2003, Vessia et al. 2007).

These correlations, that were obtained for different types of soils belonging to different geological contexts (Japan, United States, Canada, etc), were used to characterise italian soils in the field of very low deformations. Comparison of measured Vs values against calculated values from Nspt investigations, shows an extremely local correlation and a constant underestimation of the Vs values. The equivalence of the two parameters requires a further investigation in this sense. The validity of these correlations should be discussed considering that geophysical investigations are undertaken under elastic deformation conditions where the induced stress causes reversible deformations. Instead, SPT investigations cause rupture of the investigated material and they cannot be conducted within all types of deposits. This note presents the results obtained from comparison of Vs values obtained from SPT investigations and those measured on the same site from down-hole investigations. The study made use of a great quantity of data acquired within different geological-technical contexts and made available from the VEL project of the Tuscany Region (Central Italy, fig. 1). The applicability limits of these empirical correlations are discussed.

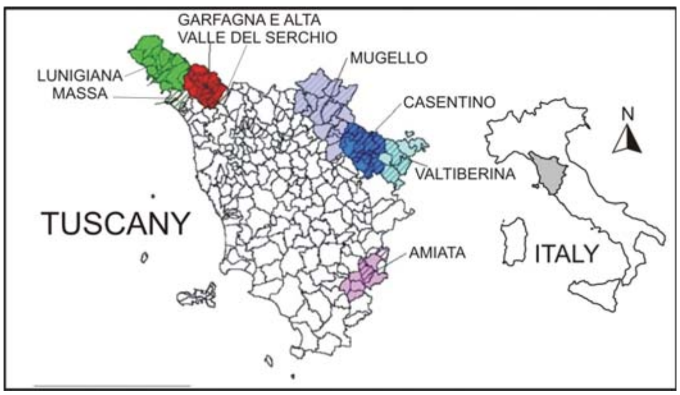


Fig. 1. Location of areas in which the pairs of Nspt-Vs values where acquired in Central Italy.

NSPT – VS EMPIRICAL CORRELATIONS

There are several authors that have attempted to correlate the resistance to penetration, Nspt, with the in-situ measurement of the shear waves velocity Vs. Among these we can recall:

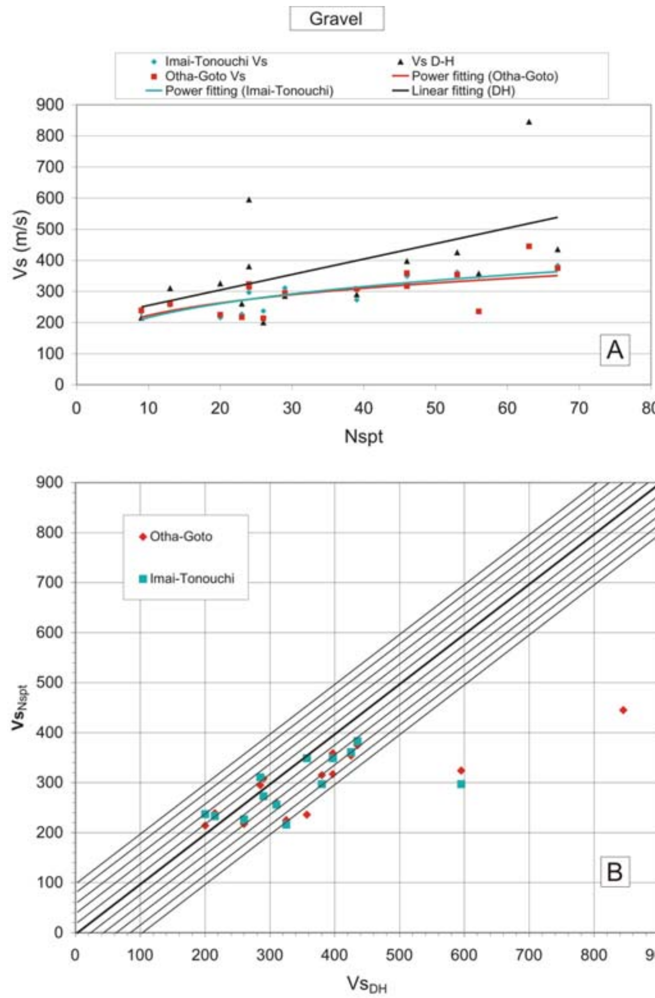
- Ohsaki e lwasaki (1973):

After having analysed a great amount of data, the authors concluded that the Nspt-Vs correlation is not dependant on the nature of the deposit and its geological age. They suggested the following relationship:

$Vs = 81.4\ Nspt^{0.34}$ (m/s)

that with incoherent deposits becomes:

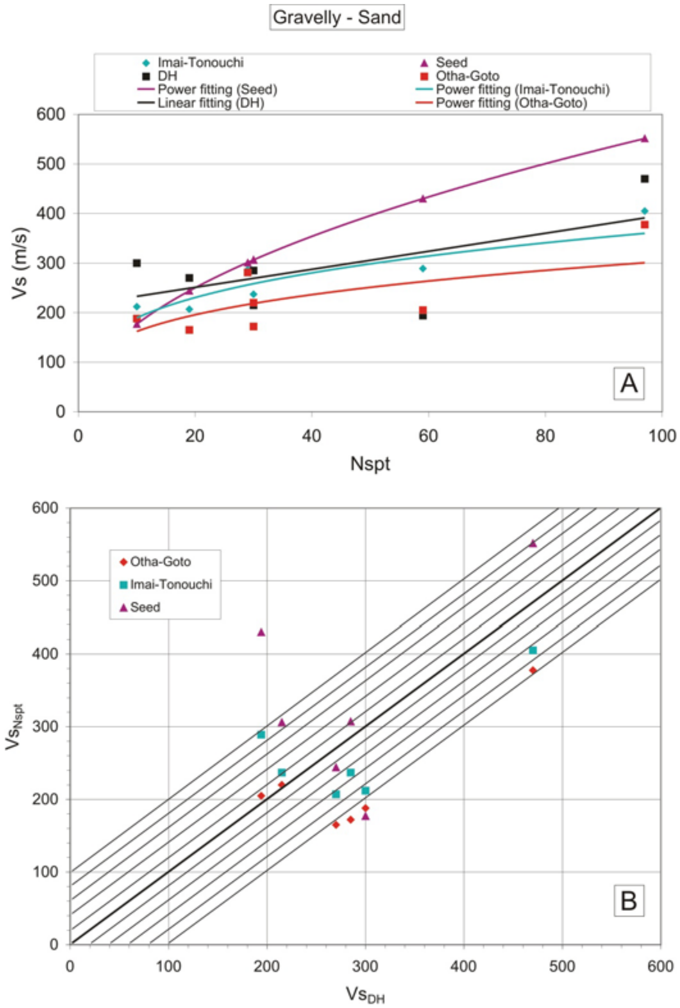
$Vs = 59.4\ N_{spt}^{0.4}$ (m/s)



	DH	Otha-Goto	Imai-Tonouchi
Standard Deviation	162.05	67.34	56.32
Correlation		0.81	0.61

C

Fig. 2. Comparison of measured Vs values against calculated values for gravel: A regression analysis; B error analysis; C statistical analysis.



	DH	Otha-Goto	Imai-Tonouchi	Seed
Standard Deviation	97.73	75.82	68.77	123.70
Correlation	—	0.80	0.71	0.49

C

Fig. 3. Comparison of measured Vs values against calculated values for gravelly-sand: A regression analysis; B error analysis; C statistical analysis.

- Otha-Goto (1978)

These authors suggest that the Vs value is connected to the depth of the Nspt, the nature of the soil and the age of the geological deposit. This equation was proposed to the scientific community after several correlations:

$$Vs = 68.79\ Nspt^{0.171}\ Z^{0.199}\ Fa\ Fg \quad (m/s)$$

where:
N_{spt} = value of resistance to penetration of the SPT device; **Z** = depth (m); **Fa** = coefficient that is connected to the geological age of the deposit; **Fg** = coefficient that depends on the granulometric distribution. Fa e Fg are equal to the following values:

	Clay	Fine sand	Medium sand	Coarse sand	Sand and gravel	Gravel
Fg	1,000	1,086	1,066	1,135	1,153	1,448
Fa	**Olocene**			**Pleistocene**		
	1			1,303		

- Imai e Tonouchi (1982)

These authors proposed the following relationship after having analysed different types of deposits of different ages:

$$Vs = a\ N^{b}_{spt}$$

where *a* and *b* are indices that are connected to the lithology and the age of the deposit (H=Olocene; P=Pleistocene; T=Tertiary; r =correlation coefficient; a = clay, s = sand, g = gravel, R = made ground).

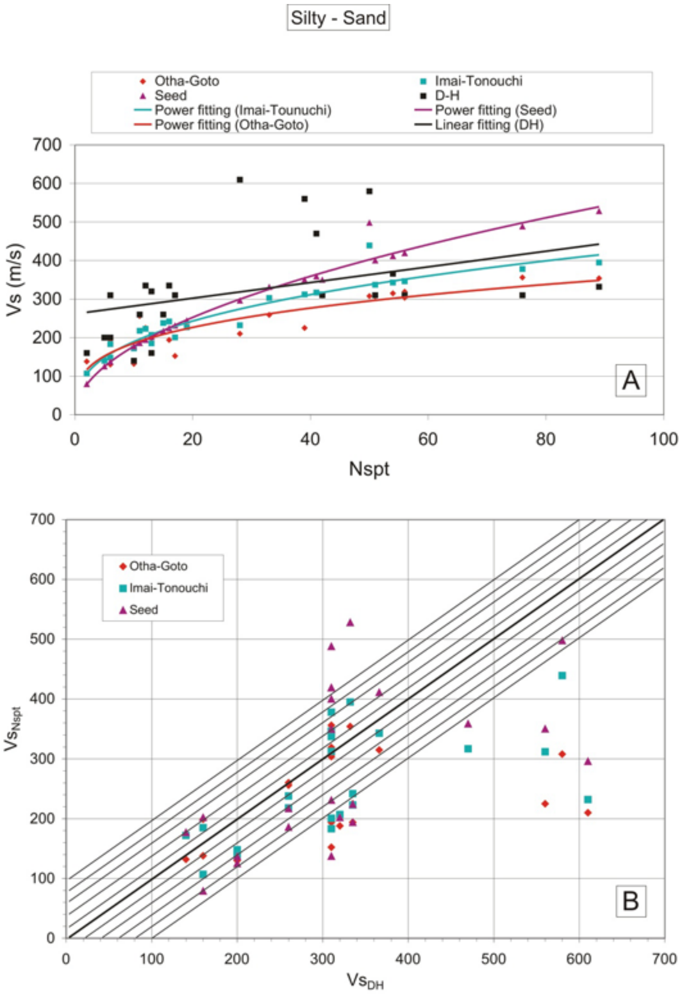
	H-a	**H-s**	**H-g**
a	107	87,8	75,4
b	0,274	0,292	0,351
r	0,721	0,690	0,791
	P-a	**P-s**	**P-g**
a	128	110	136
b	0,257	0,285	0,246
r	0,712	0,714	0,550
	T-a/T-s	**R-a**	**R-s/R-a**
a	109	98	91,7
b	0,319	0,248	0,257
r	0,717	0,574	0,647

- Seed (1983)

Seed proposed a direct correlation in 1983 between the Nspt index and the shear wave velocity (Vs).

$$Vs = 56\ N_{spt}^{0.5} \quad (m/s)$$

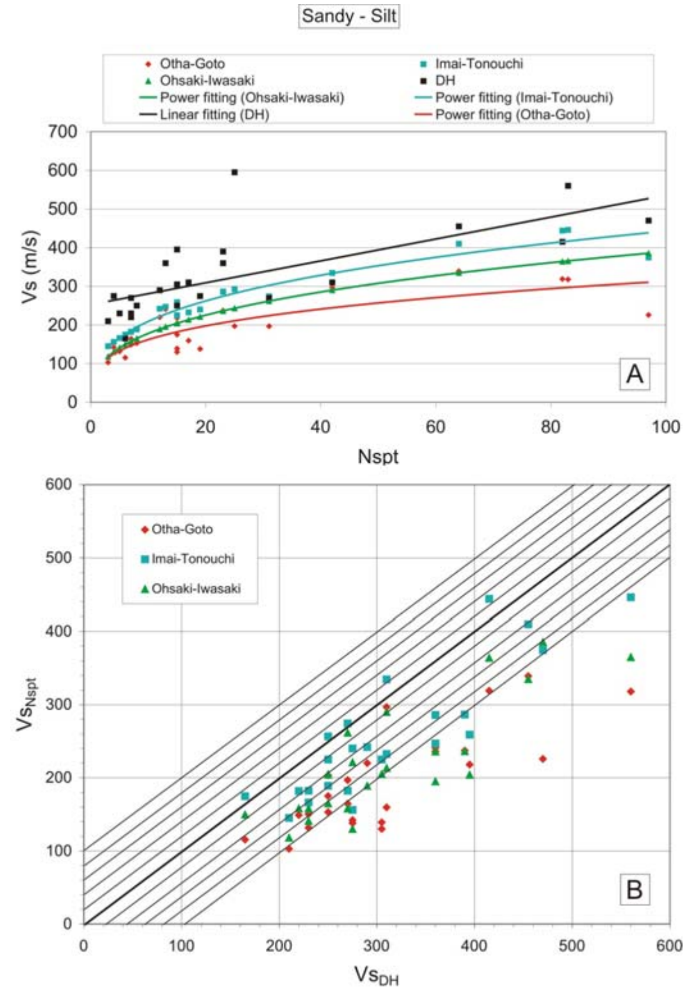
This relationship is solely valid for sands.



	DH	Otha-Goto	Imai-Tonouchi	Seed
Standard Deviation	126.92	72.15	87.63	128.25
Correlation		0.40	0.57	0.54

C

Fig. 4. Comparison of measured Vs values against calculated values for silty-sand: A regression analysis; B error analysis; C statistical analysis.



	DH	Otha-Goto	Imai-Tonouchi	Ohsaki-Iwasaki
Standard Deviation	106.58	66.34	85.01	74.10
Correlation	-	0.69	0.79	0.75

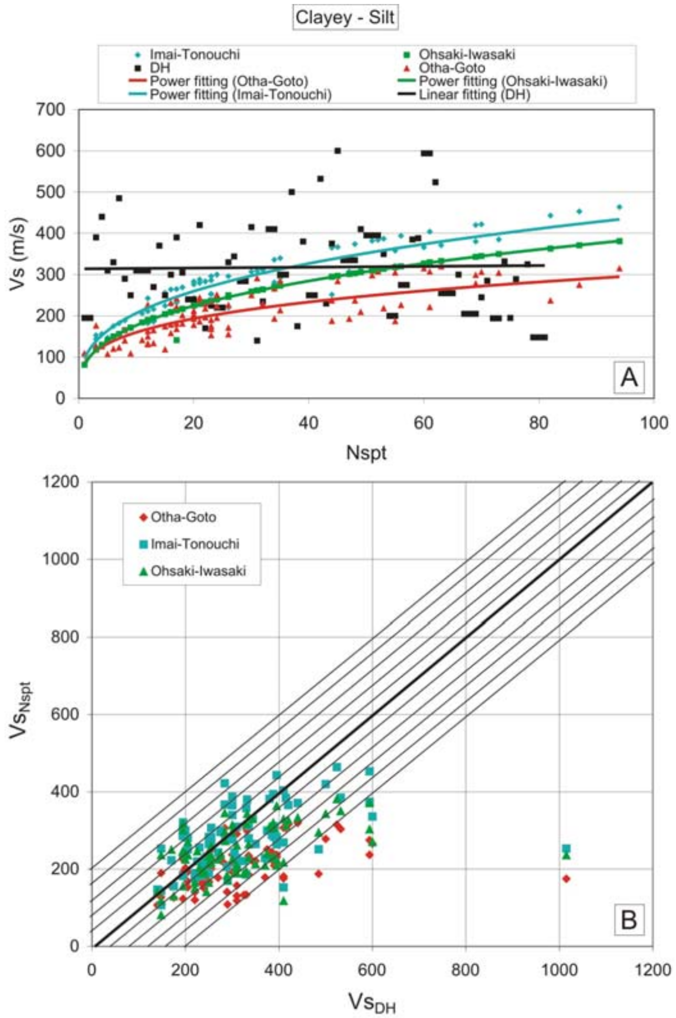
C

Fig. 5. Comparison of measured Vs values against calculated values for sandy-silt: A regression analysis; B error analysis; C statistical analysis.

ANALYSIS

The data used within this work were extracted from the database relative to the geophysical and geognostic investigations undertaken in several areas of the Tuscany Region (Central Italy) within the V.E.L. project.

In particular, 153 pairs of Nspt-Vs values were analysed and compared. These values were acquired from SPT and down-hole investigations that were undertaken at the same site, for the same lithotype and at the same depth.



	DH	Otha-Goto	Imai-Tonouchi	Ohsaki-Iwasaki
Standard Deviation	131.51	57.91	78.28	65.06
Correlation	-	0.42	0.45	0.44

C

Fig. 6. Comparison of measured Vs values against calculated values for clayey-silt: A regression analysis; B error analysis; C statistical analysis.

The correlations that were used, require the understanding of the granulometric distribution of the deposits that were being analysed. Therefore, the same amount of granulometric distribution tests were undertaken, according to AGI (1977) guidance. This permitted the derivation of the characteristic lithological coefficients.

Five granulometric distribution classes were derived from laboratory tests:

1. Samples with a weight percentage of silt and clay greater than 50% (81 samples);
2. Samples with a weight percentage of silt and sand greater than 50% , with percentage of silt greater than the percentage of sand (25 samples);
3. Samples with a weight percentage of sand and silt greater than 50%, with percentage of sand greater than that of silt (25 samples);
4. Samples with a weight percentage of sand and gravels greater than 50% (7 samples);
5. Samples with a weight percentage of gravels greater than 50% (15 samples);

The empirical corrections proposed by Otha-Goto e Imai-Tonouchi were used for all analysed samples. Corrections proposed by Ohsaki-Iwasaki and Seed were used on clayey and sandy deposits respectively.

DISCUSSION OF RESULTS

Figures 2-6 shows the results of the correlations and the following can be observed:

<u>Gravels</u> (fig. 2): there is a strong underestimation of the Vs values measured on-site from the down-hole investigations, for both the Imai-Tounochi and Otha-Goto correlations. The trend curves associated with the two correlations show small differences between them (fig. 2A). The error between the measured Vs values and the calculated values increases when the N_{spt} value increases (when $N_{spt}>20$, fig. 2B). The highest correlation value is by Otha-Goto (fig. 2C).

<u>Gravelly sand</u> (fig. 3): The Imai-Tounochi and the Otha-Goto correlations underestimate the Vs values on average (fig. 2B), while the Seed correlation produces an underestimation only with very small values of $N_{spt.}$ ($N_{spt} < 20$). The Imai-Tounochi correlation produces a better approximation for the regression analysis (fig. 3A), but the Otha-Goto equation produces the highest correlation value (fig. 3C).

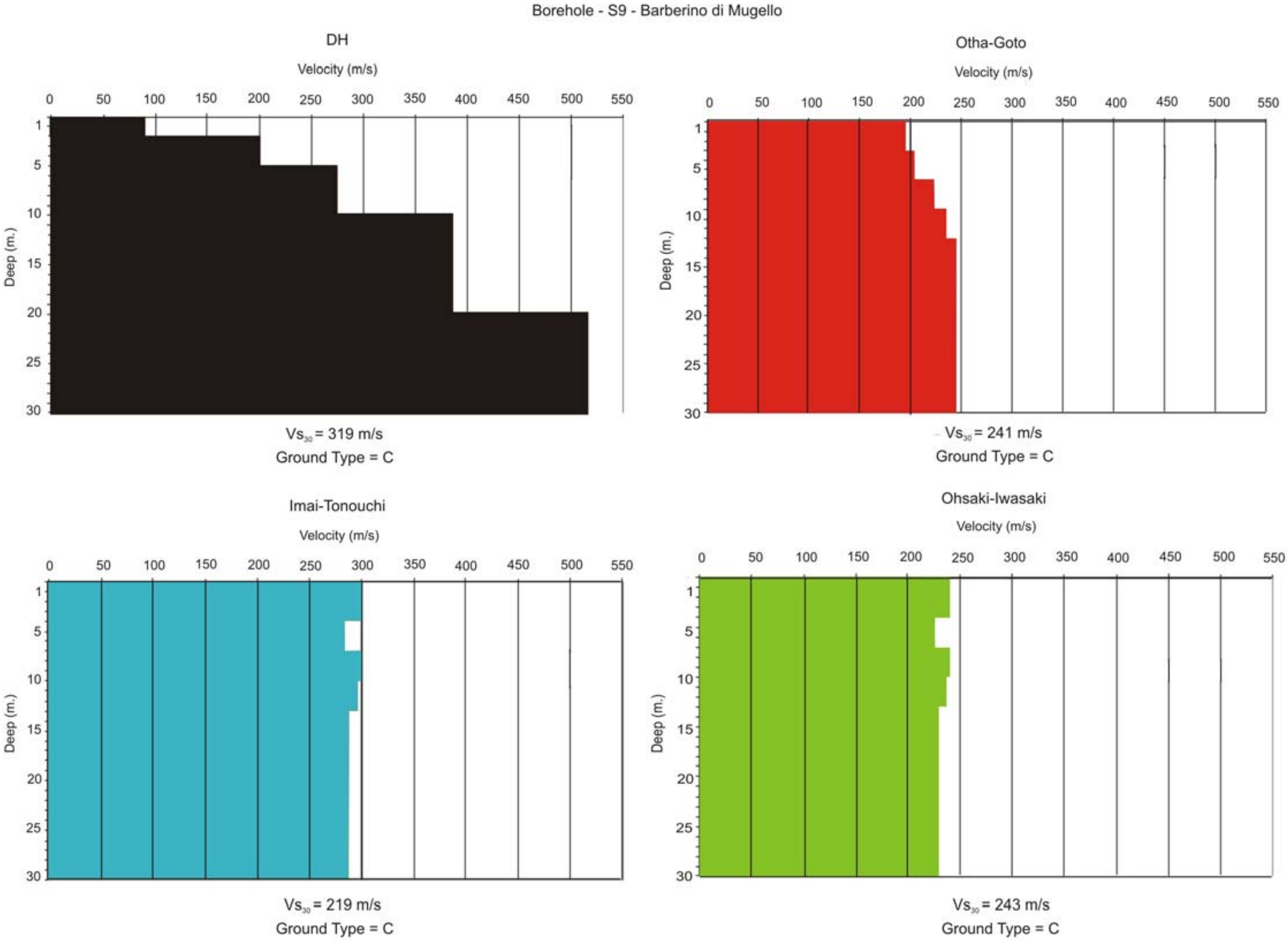


Fig. 7. Comparison of Vs values measured on-site with down-hole techniques and values estimated through empirical correlations (borehole S9, Barberino di Mugello – Florence).

Silty sand (fig. 4): the Otha-Goto and Imai-Tonouchi correlations (the latter appears to better approximate the measured Vs values) produce an underestimation of the Vs values on average; the Seed correlation has a different behaviour. On average it underestimates the Vs values for low values of N_{spt} (N_{spt} <35) and overestimates the Vs values for high values of N_{spt} (figg. 4A, 4B). The highest correlation value is by the Imai-Tonouchi equation (fig. 4C).

Sandy silt (fig. 5): there is a strong underestimation of the Vs values with the correlations used for these deposits (fig. 5A, 5B). The Imai-Tonouchi correlation appears to better estimate the measured Vs values. The error between the measured and the calculated Vs values tends to increase with both low and high values of N_{spt}.

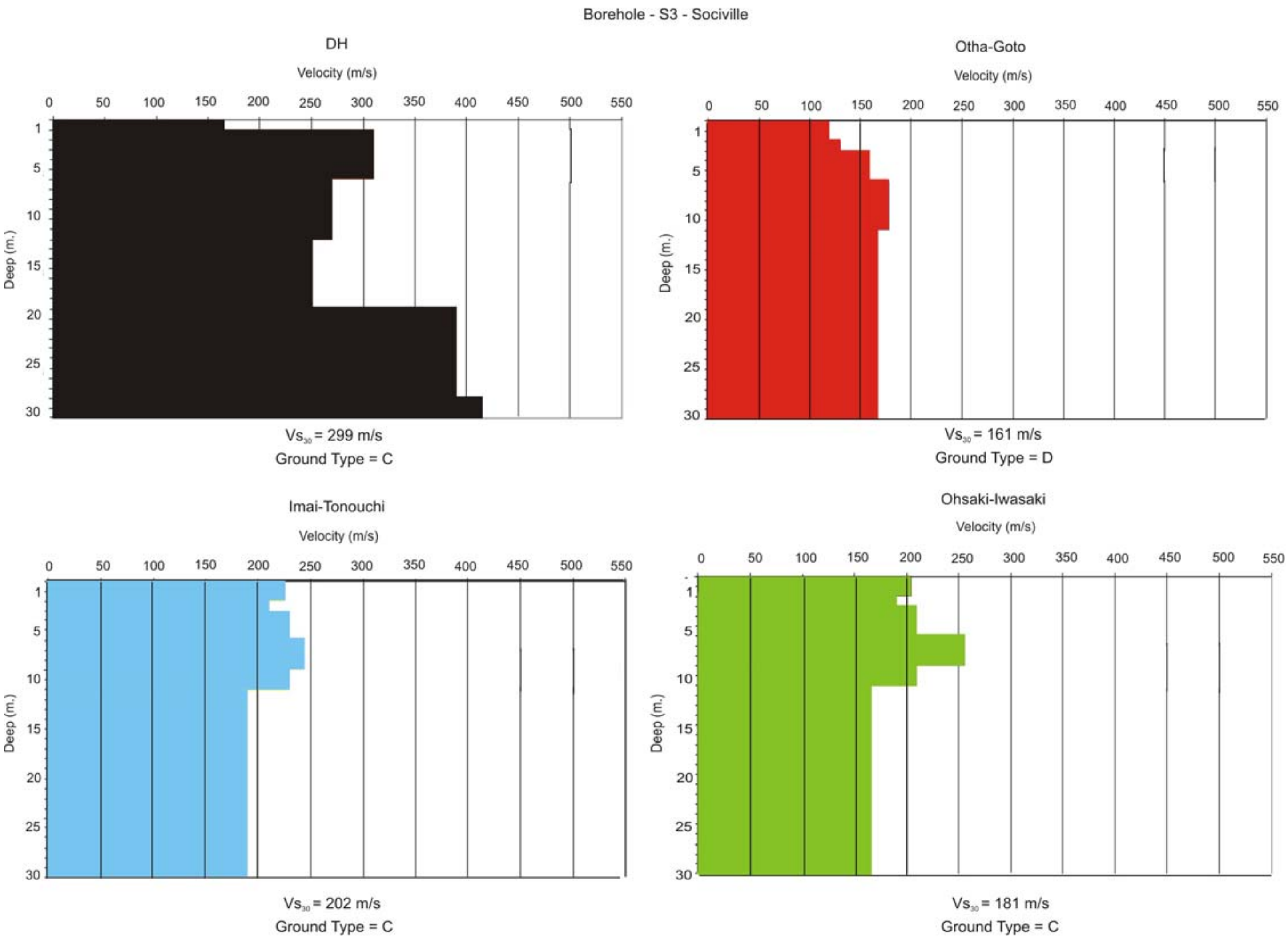


Fig. 8. Comparison of Vs values measured on-site with down-hole techniques and values estimated through empirical correlations (borehole S3 at Sociville – Siena).

Clayey silt (fig. 6): the Otha-Goto correlation underestimates the Vs value on average, while the Imai-Tonuochi and Ohsaki-Iwasaki correlations tend to overestimate the Vs value for high values of N_{spt} (Nspt> 35 and Nspt> 60 respectively, fig. 6A). The best approximation is obtained for low N_{spt} values with the Imai-Tonouchi correlation. High N_{spt} values give good Vs values with the Ohsaki-Iwasaki correlation (fig. 6A). The highest correlation value is by the Imai-Tonuochi equation (fig 6C).

In summary, an underestimation of the Vs values is obtained on average with gravels and sandy silt. The Otha-Goto correlation seems to deliver the best approximation of measured Vs values for gravel and gravelly-sand, while the Imai-Tonouchi equation gives the best approximation for silty-sand, sandy-silt and clayey-silt.

On average, the Seed correlation overestimates the measured Vs values when $N_{spt}>35$ with silty sand. It also overestimates the measured Vs values with gravelly sand when $N_{spt}>20$. The Imai-Tonouchi correlation (silty sand and gravelly sand) and the Otha-Goto correlation (silty sand) always underestimate the Vs values obtained from in-situ geophysical investigations. In the presence of low, medium or high values of N_{spt} with clayey-silt, the best approximations of the measured Vs value is obtained from the Imai-Tonouchi, Ohsaki-Iwasaki and Otha-Goto correlations respectively.

The approximation obtained from the use of the correlations that have been considered for the estimation the Vs value, have a repercussion on the calculation of the foundation soil category proposed within the Italian regulatory guidance ("Norme Tecniche per le Costruzioni" – D.M. of 14 January 2008) and by the european Eurocode 8.

Two examples of seismic category calculations for soils are shown in figures 7, 8. The examples consider both Vs values measured on-site with down-hole techniques and values estimated through empirical correlations. The foundation soil category does not change at one location (fig. 7, borehole S9, Barberino di Mugello – Florence); a change in category occurs from category C to category D at the other location (fig. 8, borehole S3 at Sociville – Siena) when Vs values obtained from the Otha-Goto correlation are used. These figures clearly show that there is no correlation between measured values and values obtained from SPT investigations.

CONCLUSIONS

This note presents the results obtained by comparing Vs values derived from empirical correlations that use Nspt data and Vs values that were measured from down-hole investigations undertaken on the same vertical and at the same depth. The study relied on a substantial dataset collected in areas of major seismic hazard in the Tuscany Region (Central Italy) and relative to different geological contexts.

There is a bad correlation between the measured Vs values and the calculated Vs values. The error associated in the estimation of the Vs value is generally too big and can cause a change in foundation soil category on the basis of the Italian and European regulatory guidance. The correlation values obtained are very low (ranging between 0.4 and 0.81) and the lowest values are for silty-sand and clayey-silt. The analysed empirical correlations tend to underestimate the Vs value on average; however, it has been noted that the Seed correlation for silty-sand and gravelly sand and the Imai-Tonuochi and Ohsaki-Iwasaki correlations for clayey silt tend to overestimate the Vs parameter with high values of Nspt.

The significant difficulty that originates from the attempt to correlate parameters that are intrinsically different from each other (elastic deformation for the Vs values and rupture of the material with Nspt values) is emphasised by the different behaviour due to granulometric differences and to the granulometric heterogeneity of the deposits.

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