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ORIGINAL PAPER

ASSESSING GROUND COMPACTION VIA TIME LAPSE SURFACE WAVE ANALYSIS

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ABSTRACT

Through a case study, the paper presents an example of application of surface-wave analysis for the assessment of the ground compaction process accomplished in order to stabilize a harbour bank. After briefly recalling the fundamental points characterizing the adopted technique, seismic data acquired before and after the soil compaction are analyzed by means of the Full Velocity Spectrum approach and compared also with the penetrometer data commonly adopted to assess the performances of the compaction process.
The results demonstrate that the analysis of surface-wave propagation represents an efficient and non-invasive tool for efficiently and reliably determining the near-surface characteristics also in a time-lapse perspective.

1. INTRODUCTION

The analysis of Surface-Wave (SW) propagation is used to investigate the subsurface since the 20's (Gutenberg, 1924). While first and classical works relate to crustal studies (Evison et al., 1959; Novotný et al., 1997), a number of NDT (Non-Destructive Testing) and near-surface applications have been proposed in the last decades (e.g. Shtivelman, 1999; Ryden et al., 2001; O'Neill et al., 2006; Forbriger, 2003a; 2003b; Luo et al., 2011; Dal Moro, 2014).

Depending on the specific goals and site characteristics, surface wave dispersion can be analyzed for both active (e.g., MASW - Multichannel Analysis of Surface Waves) as well as passive acquisitions (e.g., ReMi [Refraction Microtremors], SPAC [SPatial AutoCorrelation], ESAC [Extended Spatial AutoCorrelation], frequency-wave number analysis, interferometry - Ohori et al., 2002; Poggi and Fäh, 2010; O'Connell and Turner, 2011).

In any case, the final outcome is represented by the subsurface shear-wave velocity (V_S) profile whereas other material properties such as the compressional-wave velocity (V_P) and density cannot be soundly determined (Xia et al., 1999).

The MASW technique is often meant as the analysis of the Rayleigh-wave modal dispersion curves which can be identified by considering the data recorded by a certain number of vertical geophones. The analysis of the data acquired through such a classical single-component approach, can reveal problematic since a number of issues can actually occur and lead to ambiguous data interpretations and, consequently, erroneous subsurface models - for a wider scenario see for instance O'Neill and Matsuoka (2005) and Dal Moro (2014). For these reasons, various authors have for instance considered Love waves as well (Winsborrow et al., 2003; O'Neill et al., 2006; Safani et al., 2005; Dal Moro, 2014).

In general terms, the solution to this sort of problems is in fact represented by the acquisition of multi-component data and by analyses performed while considering the entire velocity spectrum (or the so-called effective dispersion curve) and not the interpreted modal curves (Dal Moro et al., 2014; 2015a).

All the above-mentioned methodologies rely on the acquisition of multi-channel data, which necessarily require long and relatively-complex

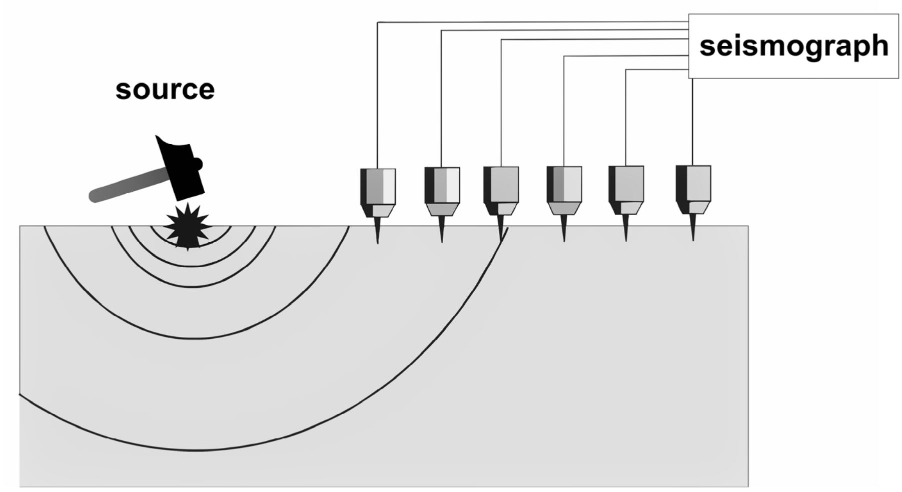

Fig. 1 Classical MASW acquisition setting. The seismic perturbation artificially produced by a seismic source (typically a simple sledgehammer) is acquired by a certain number of geophones. The analysis of the surface-wave dispersion eventually allows the reconstruction of the subsurface shear-wave velocity profile down to a depth which is proportional to the length of the geophone array.

acquisition procedures. On the other side, a different approach based on the active data acquired by a single 3-component geophone and which can be considered as an evolution of the classical *Multiple Filter Analysis* (Dziewonsky et al., 1969) is also possible (Dal Moro, 2014; Dal Moro et al. 2015b; 2015c; 2015d).

For this first exploratory work aimed at evaluating the potential of surface-wave analysis for assessing the effect of the ground compaction procedures commonly adopted in the construction industry, a very classical setting based on just the vertical component of Rayleigh waves (traditional single-component MASW approach - see Fig. 1) was adopted.

Because of the high background noise related to the harbour industrial activities and the saturation of the sediments (a sequence of soft sediments largely dominated by sands in a coastal/marine environment), for the present case it was impossible to consider the compressional-wave refraction travel times.

Furthermore, the very nature of surface-wave propagation and analysis makes the analysis of surface-wave propagation more suitable for the purpose. In fact, while body-wave refraction is related to the presence of horizons where V_P (or V_{SH}) significantly changes, surface-wave propagation depends on the properties of the material itself and does not necessarily require the presence of clear velocity contrasts between different layers.

In other words (and to consider an extreme case), Rayleigh waves generate even in a perfectly-homogenous medium and their propagation depends on its geomechanical properties (V_S, density, quality factors etc.), while in classical body-wave refraction studies, the presence of clear contrasts (horizons) is instead a fundamental assumption.

For the present study, data acquired before and after the ground compaction process performed via vibroflotation, were inverted according to the *Full Velocity Spectrum* (FVS) approach (Dal Moro, 2014) and obtained V_S values also compared with the information obtained via penetrometer tests.

2. SITE AND DATA

The test site is located in the Livorno harbour, NW-Italy (Fig. 2), an area largely dominated by sandy deposits occasionally mixed with silty layers and, as expected for this kind of low-energy coastal environments and as confirmed by all the geotechnical data collected in the area, quite homogenous without relevant lateral variations.

Data acquisitions were performed using 24 4.5 Hz vertical geophones (classic end-off shooting configuration shown in Fig. 1), an 8-kg sledgehammer and the acquisition parameters reported in Table 1.

Ground compaction was performed by means of a *vibroflotation* process down to a depth of 15 m. During such an operation, horizontal vibrations are applied with the aim of reducing the inter-particle friction and increase the overall strength of the material (for a general overview see for instance Mcreery and Zepeda, 2014).

Table 1 Acquisition parameters.

Sampling rate	1000 Hz (1 ms)
Acquisition length	1 s (then limited to 0.7 s)
Geophones spacing	2 m
Minimum offset	5 m
Sensors	24 vertical 4.5Hz geophones
Stack	4

A quick preliminary comparison of the pre- and post-compaction data can be done by plotting (overlaying) the seismic traces of the two datasets (Fig. 3).

Considering that the acquisitions were performed in a harbour where heavy industrial activities are constantly going on, the overall background noise appears definitely acceptable and does not compromise the analysis of the Rayleigh-wave dispersion.

As expected, although some differences are apparent, the data in the space-time domain does not allow straightforward and quantitative considerations about the effect of the applied soil compaction procedure. However, by transforming the data into the frequency-velocity domain via phase shift (Dal Moro et al., 2003), the differences (i.e. the effect of the ground compaction) become evident. In fact, the velocity spectra indicate that, at least for frequencies higher than about 5 Hz, after the compaction process the Rayleigh-wave phase velocities are larger (compare Figs. 4a and 4b).

In order to quantitatively assess the increase in the subsurface shear-wave velocities induced by the ground compaction, in the following section, we will show the results of the phase-velocity spectra inversion performed according to the *Full Velocity Spectrum* (FVS) approach.

3. FVS INVERSION OF PRE- AND POST-COMPACTION DATA

The *Full Velocity Spectrum* (FVS) analysis is based on the computation of the synthetic seismic traces (performed for instance via *modal summation*) of a tentative model and on their transformation into the *frequency–velocity* domain to obtain the related velocity spectrum. Such a velocity spectrum (obtained from a synthetic dataset) is then compared with the one of the field data in the framework of an optimization scheme aimed at identifying the model that better matches with the field data (for details see Dal Moro, 2014 and Dal Moro et al., 2015a).

This means that the velocity spectrum of the field data is not interpreted in terms of dispersion curves (which necessarily represent a subjective interpretation of the data) and the velocity spectrum is considered as a whole (i.e. in its entirety). The heavier computation load required by the FVS approach mirrors in a more complete analysis that is performed without a preliminary (and subjective) data interpretation thus partially leading to a more robust solution (details and examples are provided in the above-mentioned publications as well as in Dal Moro et al., 2015b; 2015d).

The most important variables considered during the inversion are clearly the V_S and the thickness of the layers (Xia et al., 1999). In addition to this, the Poisson's ratios are also considered as variables and set free to change between 0.25 (typical value for dry shallow soft sediments) and 0.495 (saturated sands). For each layer, the V_P is computed by combining the V_S and the Poisson's ratio while the density is fixed from the V_P value on the basis of some well-known empirical relationships between V_P and density (Gardner et al., 1974). Further details about the optimization process are reported in Dal Moro et al. (2007).

Considering the length of the array (50 m) and the classical single-component approach here adopted (analysis of the vertical component of Rayleigh waves), the obtained V_S profiles can be considered highly reliable down to a depth of about 8-10 m (down to this depth the solution can be considered as unique) and approximate (at least15 % uncertainty) for the next (deeper) 10 m (see also Dal Moro, 2011; 2014).

Figueres 5, 6 and 7 summarize the results of the FVS inversion accomplished for the pre- and post-compaction data.

By comparing the shear-wave velocity profiles presented in Figure 7, it is clear that between about 3 and 11 m of depth, the shear-wave velocity increased by up to 50 %.

4. DISCUSSION AND CONCLUSIONS

In the previous sections we illustrated the results of the time-lapse analyses of Rayleigh waves before and after soil compaction. In order to mutually validate data and analyses, in this final paragraph we briefly discuss the results also presenting some correlations with the geotechnical data obtained by means of classical penetrometer tests traditionally adopted to assess the efficiency of the ground compaction process.

Figure 8 reports the N30 (number of blows per 30 cm penetration) values before and after the vibroflotation process.

In order to evaluate the consistency of the penetrometer and seismic-data analyses, we considered four common empirical relationships between NSPT and VS values (NSPT are obtained from the N30 values - Lacroix and Horn, 1973; Spagnoli, 2008).

We should recall that such relationships are to some degree a function of the specific type of sediments and different equations are available for different materials (for a review on the most common relationships see for instance Boominathan and Suganthi (2007); Akin et al., (2011); Thaker and Rao, 2011; Wair et al., 2012).

Considering the nature of the local sediments, we adopted the equations pertaining to sandy materials.

Figure 9 reports the V_S estimated from four common relationships proposed by Imai (1977), JRA (1980), Hasancebi and Ulusay (2007) and Uma Maheswari et al. (2010) for sandy materials [for an overview about the relationships between N_{SPT} and V_S see also].

By comparing these estimated values with the ones obtained from the inversion of the Rayleigh-wave dispersion (see previous section and in particular the V_S profiles summarized in Fig. 7), the overall mutual consistency is apparent.

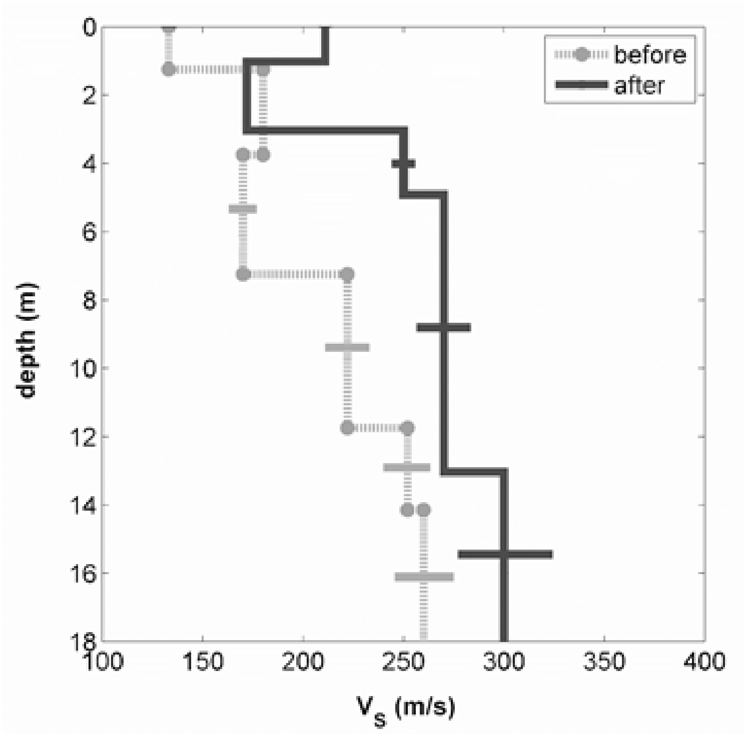

Fig. 7 V_S vertical profiles before (light dotted line) and after (darker continuous line) the *vibroflot* process (also indicated the standard deviations).

It can be then concluded that the relatively simple acquisition and analysis procedures necessary to assess the effects of the compaction via surface-wave analysis, make such a technique a suitable and reliable tool for verifying the actual effect of the applied compaction process without the need for invasive and punctual penetrometer tests.

The accuracy of the results would anyway highly benefit from the analysis of multi-component data (Dal Moro et al., 2015a), not adopted for the present study which was intended as a mere pilot test.

Actually, compared to the very classical multi-channel seismic-data acquisitions considered for the present pilot study, new and optimized techniques for the joint analysis of several surface-wave components have been recently developed (compare Dal Moro, 2014; Dal Moro et al., 2015b; 2015c; 2015d). Such techniques would allow both quicker acquisition procedures (based on just one single 3-component geophone), both a very-constrained (multi-objective) inversion, thus eventually a more detailed V_S subsurface model.

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Fig. 2 Site location (the Livorno Harbour - NW Italy).

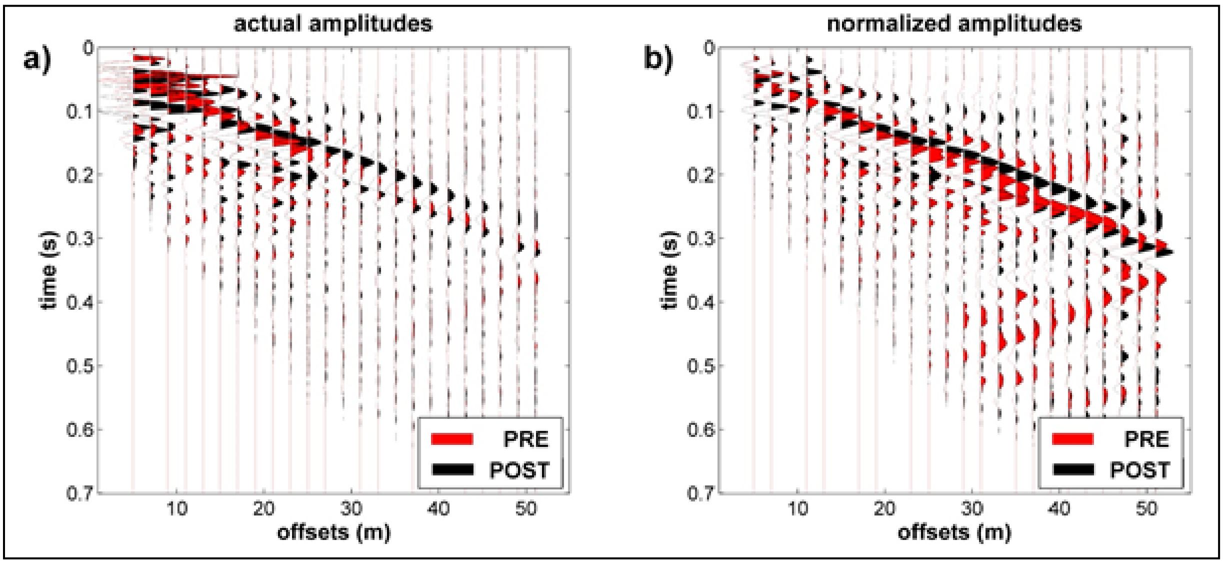

Fig. 3 Seismic traces before and after the soil compaction (on the left the actual amplitudes, on the right the normalized data).

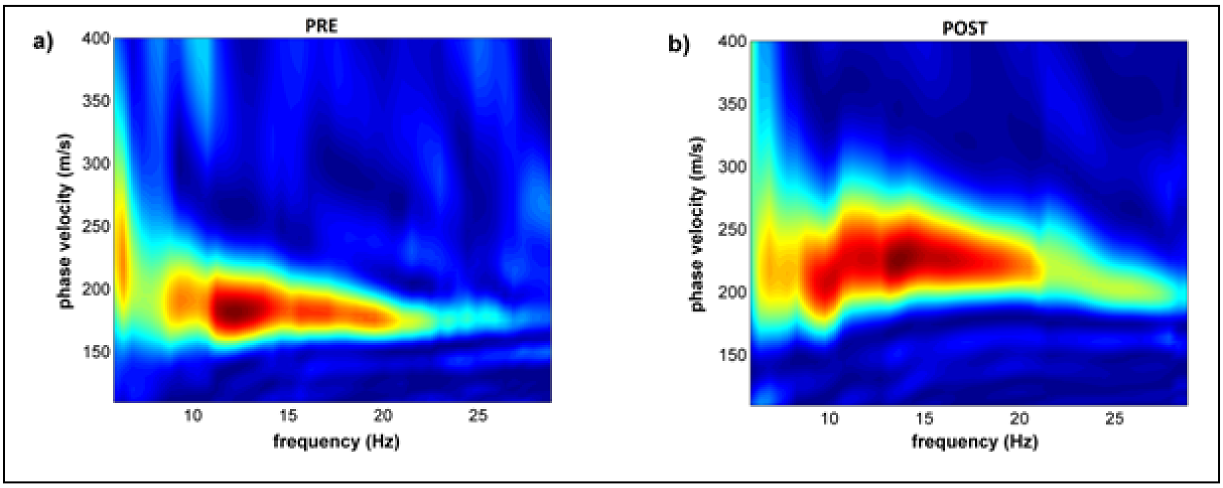

Fig. 4 Phase velocity spectra before (on the left) and after (on the right) the vibroflotation process applied in order to improve the geotechnical properties of the sandy materials characterizing the study area.

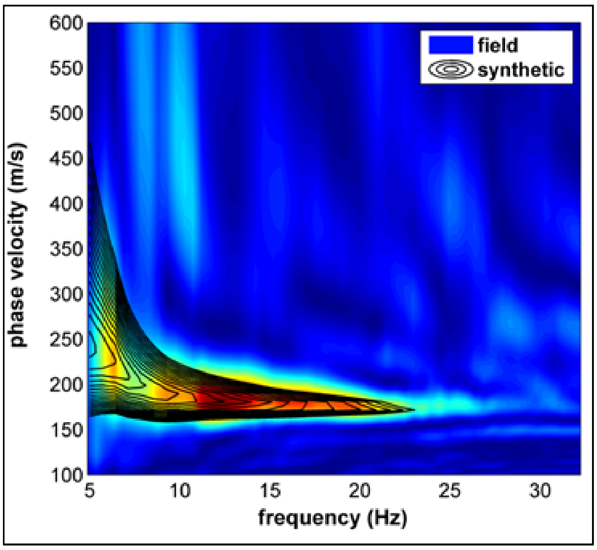

Fig. 5 FVS inversion of the pre-compaction data: field (background colours) and synthetic (overlaying black contour lines) phase-velocity spectra. The obtained V_S vertical profile is reported in Figure 7.

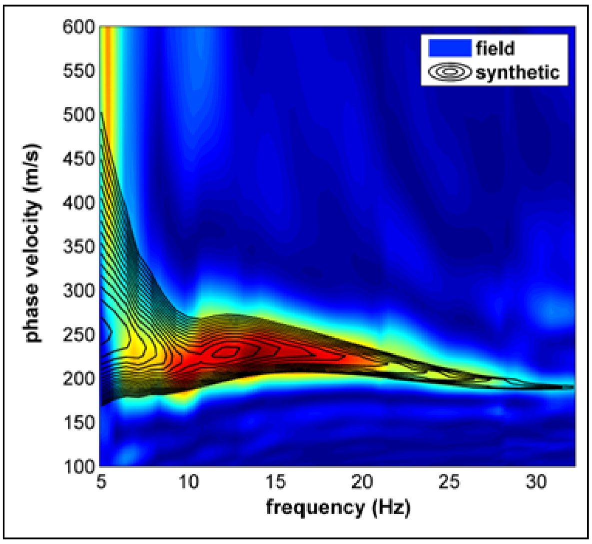

Fig. 6 FVS inversion of the post-compaction data: field (background colours) and synthetic (overlaying black contour lines) phase-velocity spectra. The obtained V_S vertical profile is reported in Figure 7.

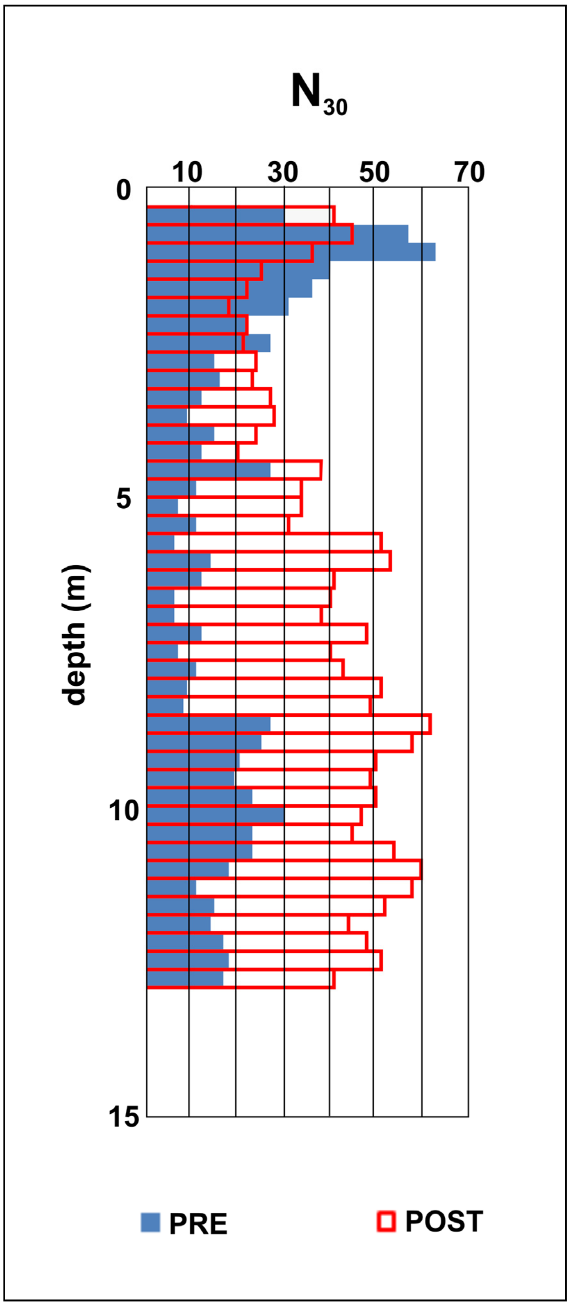

Fig. 8 N_{30} (number of blows per 30 cm penetration) values before (blue) and after (red) the ground compaction via vibroflotation.

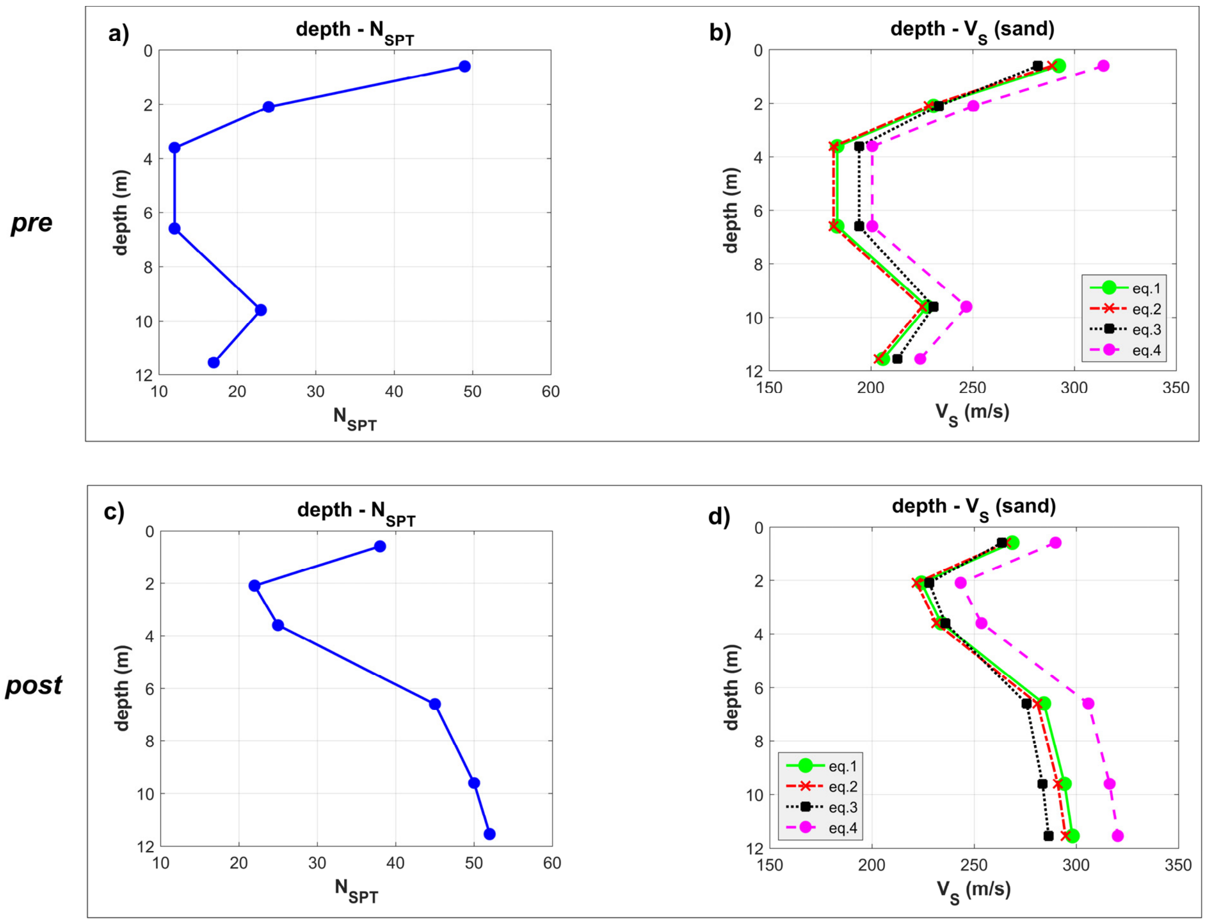

Fig. 9 V_S values estimated from the penetrometer data (N_{SPT}) collected before (upper panel) and after (lower panel) the *vibroflotation* while considering the 4 empirical relationships proposed for sandy materials by Imai (1977) [eq.1], JRA (1980) [eq.2], Hasancebi and Ulusay (2007) [eq.3] and Uma Maheswari et al. (2010) [eq.4]. Compare with the V_S profiles presented in Figure 7.