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SHEAR-WAVE VELOCITY STRUCTURE AND CORRELATION WITH N-SPT VALUES IN DIFFERENT GEOLOGICAL FORMATIONS IN BEIRUT, LEBANON

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ABSTRACT

In order to retrieve quantitative information on soil deposits characteristics for better understanding site amplification observed in Great Beirut (Brax, 2013), active and passive surface wave measurements were acquired at various sites sampling the main geological units. Besides, more than 40 geotechnical soil reports containing Standard Penetration blow counts (N-SPT) around the city and the surbubs were collected, some being very close to the geophysical measurements location. Geotechnical boreholes outline the presence of a soft clay layer of varying thickness embedded in coarser formation (gravel, sand) in the Quaternary alluvium plain of Beirut, while alternance of clayey sand, sand and silty sand dominates in the Quaternary sandy cover. Surface-wave dispersion estimates were inverted by introducing the a priori knowledge from borehole logs and N-SPT profile in the ground model parameterization. Inverted shear-wave velocity profiles (Vs) indicate shear-wave velocity at the surface between 150 and 300 m/s whatever the site location. Limestone bedrock depth is largely variable, from 25 to 160 m, depending on site location. N-SPT values and corresponding Vs estimates derived for sand and clay formation are consistent with empirical relationships found in litterature. However, additional geotechnical profiles and/or geophysical measurements are required to enable deriving robust specific Vs-N relationship for Beirut soils.

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INTRODUCTION

The city of Beirut, Lebanon, has been severely damaged and even destroyed several times by earthquakes (e.g. the 551 and 1202 A.D. earthquakes). Reliable local seismic hazard assessment and prediction of ground motion for large earthquakes are therefore critical issues in Lebanon. The geology of Beirut consists of marly limestone of Miocene and Cenomanian age that outcrop in two hills. Rest of the city is covered by recent Quaternary alluviums or sandy soils (Dubertret, 1945) (Fig. 1). This spatially variable near surface geology leads to spatially variable ground motion characteristics (amplified frequency range and level of amplification) as recently shown by Brax (2013), after analysing earthquake recordings from seismological stations installed temporarily in the city. In order to retrieve quantitative information on soil deposits characteristics for better understanding and predicting site amplification, active and passive surface wave measurements were acquired close to the sites instrumented by Salloum et al. (2012) and Brax (2013). Furthermore, more than 40 geotechnical soil reports containing Standard Penetration blow counts (N-SPT) around the city and the surbubs were collected, some being very close to the sites instrumented by Salloum et al. (2012) and Brax (2013). The present study focuses on retrieving the shear-wave velocity (Vs) structure from surface waves measurements at these different sites and on correlating N-SPT values and shear-wave velocities, the final aim being to establish a specific Vs-N relationship specific to Beirut soils.

GEOPHYSICAL DATA

Geophysical campaigns were performed in 2008, 2009 and 2011 at different sites in Great Beirut in order to sample the different geological units (Fig. 1). These campaigns included active and/or passive surface wave measurements (Salloum et al., 2012; Brax, 2013). Active experiments were performed at all sites and involved 24 vertical and horizontal 4.5 Hz geophones spaced at an interval ranging between 1 and 3 meters, connected to a 24-channel Geode acquisition unit from Geometrics. The signals were generated by 5 kg vertical hammer drops and horizontal hammer shots on a wooden beam at each side of the profile with source offset of at least 2 meters, each source location involving from 5 to 15 distinct shots. Passive experiments consisted of seismic ambient noise recorded at two to four arrays with different aperture. Table 1 provides the minimum inter-station distance (derived from the smallest aperture array) and the maximum array aperture (derived from the largest aperture array). Each array was composed of 8 three-component Güralp CMG40T sensors connected to Nanometrics Taurus digitizers and had a triangular or circular shape. Ambient noise recordings duration was ranging from 30 minutes to 1 hour. Furthermore, four shear-wave downhole measurements down to 20 meters depth were performed in the Quaternary alluvium plain of Beirut (see site *DH* in Fig. 1). This site has been extensively studied in Salloum et al. (2012, 2014) and involved several geophysical measurements: one of the main findings is the existence throughout the entire area of a shallow conductive layer of varying thickness (from 2 to 12 m) corresponding to a soft clay layer (shear-wave velocity ranging between 150 and 200 m/s) embedded in coarser geological materials. Since these findings can be found in the abovementionned papers, we focuse in this study in analysing the other sites.

Passive seismic array recordings were used to derive dispersion estimates (autocorrelation and dispersion curves) of Rayleigh or Love waves by using *FK* (Lacoss *et al.* 1969), high-resolution *FK* (*HRFK*, Capon 1969), Modified Spatial AutoCorrelation *MSPAC* techniques (Aki 1957; Bettig *et al.* 2001) and the three-component FK algorithm (Poggi and Faeh, 2010), as implemented in the software *Geopsy* (http://www.geopsy.org; Wathelet *et al.* 2008). In addition, ellipticity of Rayleigh waves were extracted by using the RAYDEC technique (Hobiger et al., 2009; Hobiger et al., 2013) while H/V spectral ratios (Nakamura, 1989) were computed in a classical way by using the Geopsy software. Phase velocities for active surface wave data were estimated by using the classical FK technique (Lacoss *et al.* 1969). Dispersion curves extracted from the active and passive data were then combined into a broad-band dispersion curve. Extracted Rayleigh and Love waves dispersion curves are

displayed in Fig. 2 while Table 1 indicates the minimum and maximum measured wavelengths and the H/V peak frequency obtained at each array site.

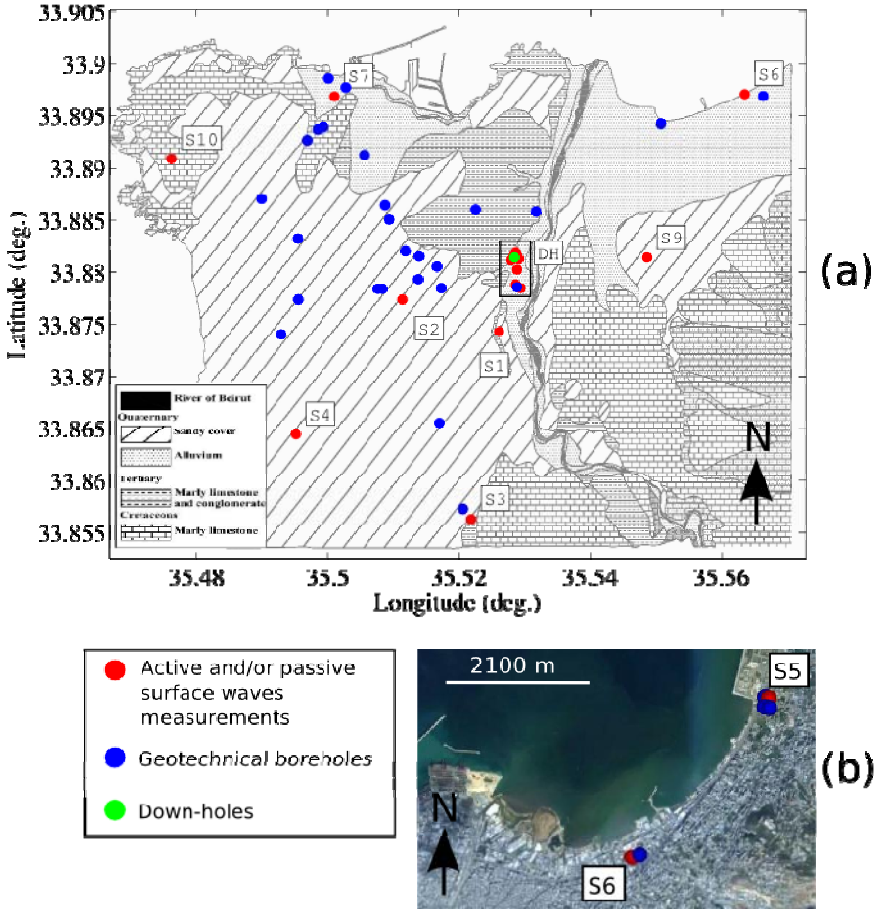

Figure 1. Geological map of Beirut simplified from Dubertret (1945) and location of geophysical and geotechnical tests: active and/or passive surface wave measurements (red dots), geotechnical boreholes (blue dots) and shear-wave downhole measurements (green dots). The black rectangle indicates the area studied in details by Salloum et al. (2012, 2014).

GEOTECHNICAL DATA

Geotechnical reports used in this study were partly collected in Brax (2013) and Salloum et al. (2012). Fig. 1 indicates location of boreholes for which N-SPT (blow counts in Standard Penetration Test) measurements are available. Interestingly, all geotechnical tests – except the one close to S6 site - in the Quaternary alluvium filling of eastern Beirut show the presence of a soft clay layer (with most of N-SPT values ranging from 5 to 25, Fig. 3) with thickness varying between 2 and 15 meters interbedded in coarser formations (sand, pebbles or gravel). As an example, Fig. 4 shows boreholes log and N-SPT profiles at S5 site. In the sandy cover of western Beirut, geotechnical tests indicate alternance of silty sand, sand and clayey sand with a large spatial variability in N-SPT values as illustrated in Fig. 3.

Table 1. Type of surface waves measurements, minimum inter-station distance and array aperture used during passive experiments, minimum and maximum measured wavelengths derived from active and/or passive surface waves data, H/V peak frequency and average Vs30 and corresponding EC8 site class.

Site	Type of measurements: Passive (P), Active (A)	Minimum array interstation spacing	Maximum array aperture (m)	Minimum wavelength (m)	Maximum wavelength (m)	H/V peak frequency (Hz)	Average Vs30 (m/s) / EC8 site class
S1	A,P	12	145	3.5	345	1.60 +/- 0.10	358 / B-C
S2	A,P	10	1400	2.7	940	1.75 +/- 0.25	328 / C
S3	A,P	5	110	2.1	219	3.40 +/- 0.10	464 / B
S4	A,P	5	80	6	172	4.00 +/- 0.20	442 / B
S5	A,P	8	1000	13.7	227	1.65 +/- 0.10	252 / C
S6	A,P	6	100	3	140	4.30 +/- 0.10	446 / B
S7	A	-	-	6.5	15	-	
S9	A,P	5	530	2.1	114	3.30 +/- 0.10	405 / B
S10	A	-	-	4.3	26	-	

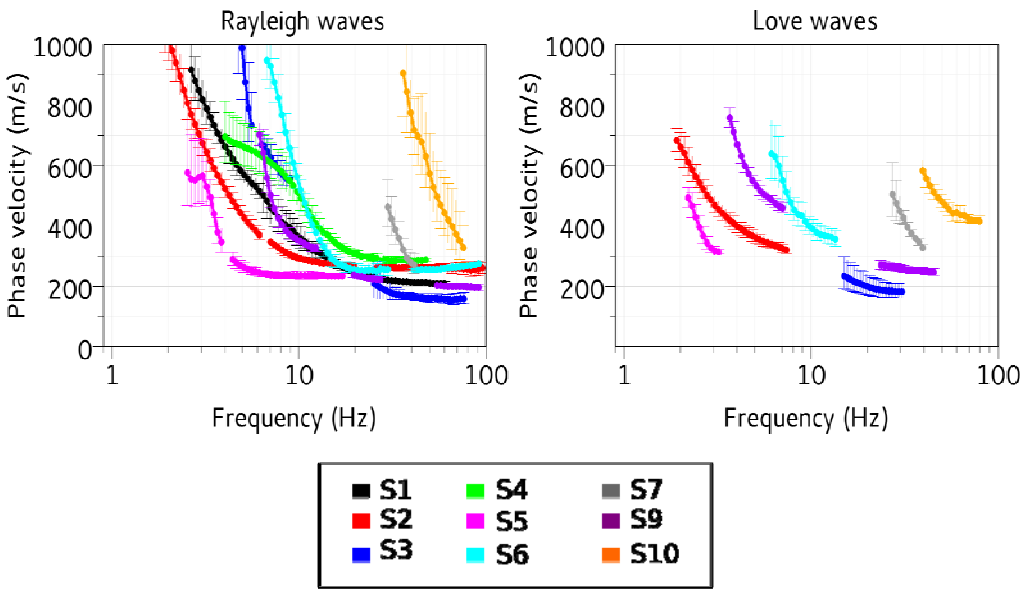

Figure 2. Rayleigh and Love waves dispersion curves

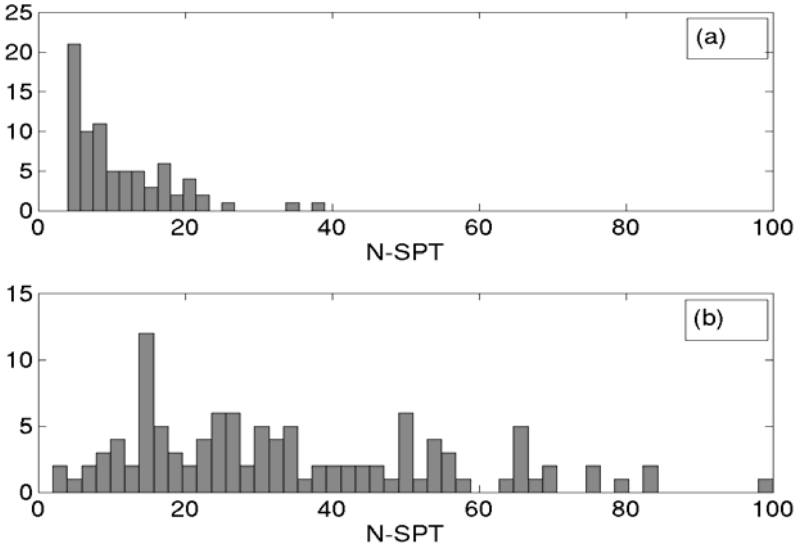

Figure 3. (a) N-SPT values for clay observed at sites located in Quaternary alluvium fill in eastern Beirut and (b) N-SPT values observed at sites located in sandy cover in western Beirut

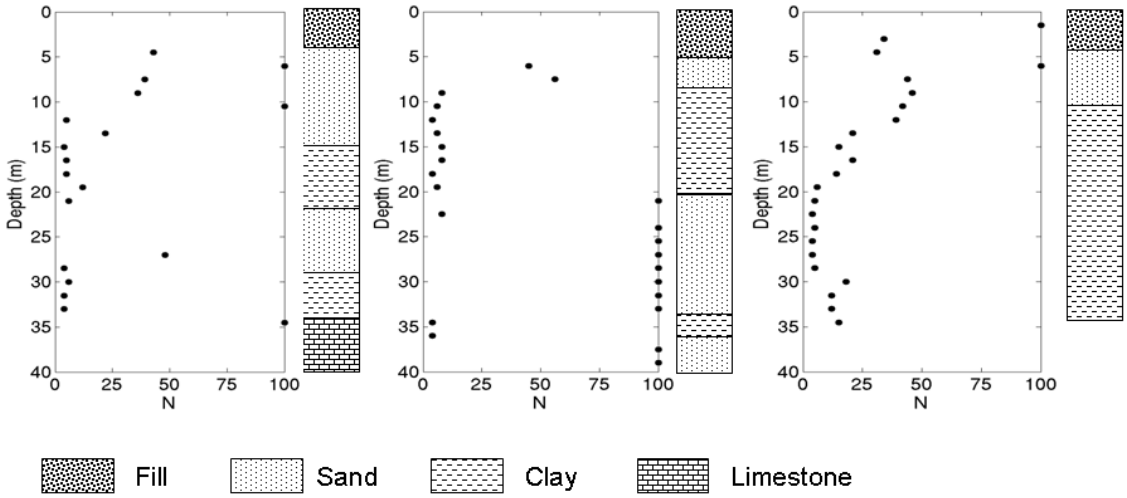

Figure 4. N-SPT profiles and borehole logs at S5 site (Figure 1). N-SPT value of 100 indicates refusal.

SHEAR-WAVE VELOCITIES

The *a priori* knowledge of the underground structure can greatly help in constraining ground model parameterization when inverting dispersion curves to derive shear-wave velocity profiles (Renalier et al., 2010). In this study, the geotechnical information collected close to S2, S3, S5 and S6 site was then introduced in the ground model parameterization in terms of number of layers, layer thickness and possible shear-wave velocity ranges. For example a low velocity layer with bottom depth ranging from 7 to 30 meters and shear-wave value ranging from 50 to 400 m/s was introduced in the ground model parameterization of S5 site. The dispersion and ellipticity curves were then inverted by using the conditional *Neighborhood Algorithm* (Wathelet, 2008) by giving them a similar weight in the global misfit function. The Poisson's ratio was allowed to range from 0.2 to 0.5 for all layers in

order to limit the ratio between the compressional (Vp) and the shear wave (Vs) velocities to an acceptable range. The density of the layers was fixed to 2000 kg/m3.

Inversion results were obtained after more than 50000 theoretical model computations by using the "acceptable solution" concept (Lomax and Snieder, 1994, Souriau et al., 2011): the misfit has the value of 1 when the calculated dispersion curve is completely inside the observed data uncertainty. Such procedure allows extracting an ensemble of shear-wave velocity profiles that explain the data within their uncertainty bounds. The ensemble of statistically acceptable Vs profiles is shown in Fig. 5. Sites located in sandy covers (S2, S3, S4, S9) exhibit variable shear-wave velocities within the first 15 meters: from 150 m/s to 300 m/s at the surface and from 260 m/s to 700 m/s at 15 meters depth. Bedrock is encountered at depths about 120 m, 50 m, 25 m and 40 m in S2, S3, S4 and S9 sites, respectively. The two sites (S5, S6) located in the Quaternary alluvium plain of Beirut indicate similar shear-wave velocities of about 270 m/s over the first 5 meters. The bedrock depth is found at about 25 meters depth at S6 site. At S5 site, a 15 m thickness low velocity layer with shear-wave velocity of about 220 m/s is found at 10 meters depth. The bedrock depth is not well constrained and can vary from 60 to 140 meters. Sites located in marly limestones (S7, S10) exhibit rather low shear-wave velocity (< 500 m/s) within the first five meters, which suggest highly weathered limestone. Finally, derived average Vs30 values (Table1) indicate that the studied sites correspond to EC8 C or B site classes.

CORRELATION BETWEEN VS and N-SPT

As penetration resistance is worldwide used in geotechnical engineering to characterize soil deposits, numerous empirical relationships between shear-wave velocities and N-SPT have been proposed for all soils or discriminating soil type (see Hansancebi et al. (2007) for a recent review). Some of the empirical relationships use uncorrected SPT blow counts while other use energy-corrected counts. In order to build a N-Vs relationship for Beirut soils, we focus in this study on sites S2, S3, S5 and S6 and only consider uncorrected SPT blow counts. From the ensemble of Vs profiles, we computed the average shear-wave velocities at the corresponding available N-SPT depths. We also used Vs derived from downhole measurements and N-SPT values measured at DH site (Figure 1, Salloum et al. (2014)). Figure 6 reports shear-wave velocities as a function of N-SPT values for clay and sand soil types, together with various empirical relationships found in litterature. Our N-Vs estimates are in good agreement with the empirical relationships. However, the lack of N-Vs estimates prohibits deriving robust Vs-N relationships for Beirut soils.

CONCLUSIONS

Passive and active surface wave measurements were performed at various sites sampling different geological units encountered in Beirut in order to retrieve shear-wave velocities. Besides, geotechnical boreholes that include N-SPT values were collected at different location throughout the Great Beirut. These boreholes outline the presence of soft clay layer of varying thickness embedded in coarser formation (sands, gravels) in the Quaternary alluvium plain of Beirut, while alternance of clayey sand, sand and silty sand dominates in the quaternary sandy cover of Beirut. Surface-wave dispersion estimates were inverted by introducing the *a priori* knowledge on underground structure layering from borehole logs and N-SPT profile in the ground model parameterization. Inverted shear-wave profiles indicate shear-wave velocity at the surface ranging between 150 m/s and 300 m/s whatever the site location and bedrock depth varying from about 25 to about 160 m depending on the site. Shear-wave velocity in the clay layer is ranging between 100 and 300 m/s. N-SPT values and corresponding Vs estimates obtained for clay and sand formation are consistent with empirical relationships found in litterature. However, the lack of N-Vs estimates does not allow to derive statistically meaningful N-Vs relationships. There is thus a need to collect additional geotechnical reports as close as possible from the geophysical sites, or to perform geophysical measurements close to well documented greotechnical boreholes.

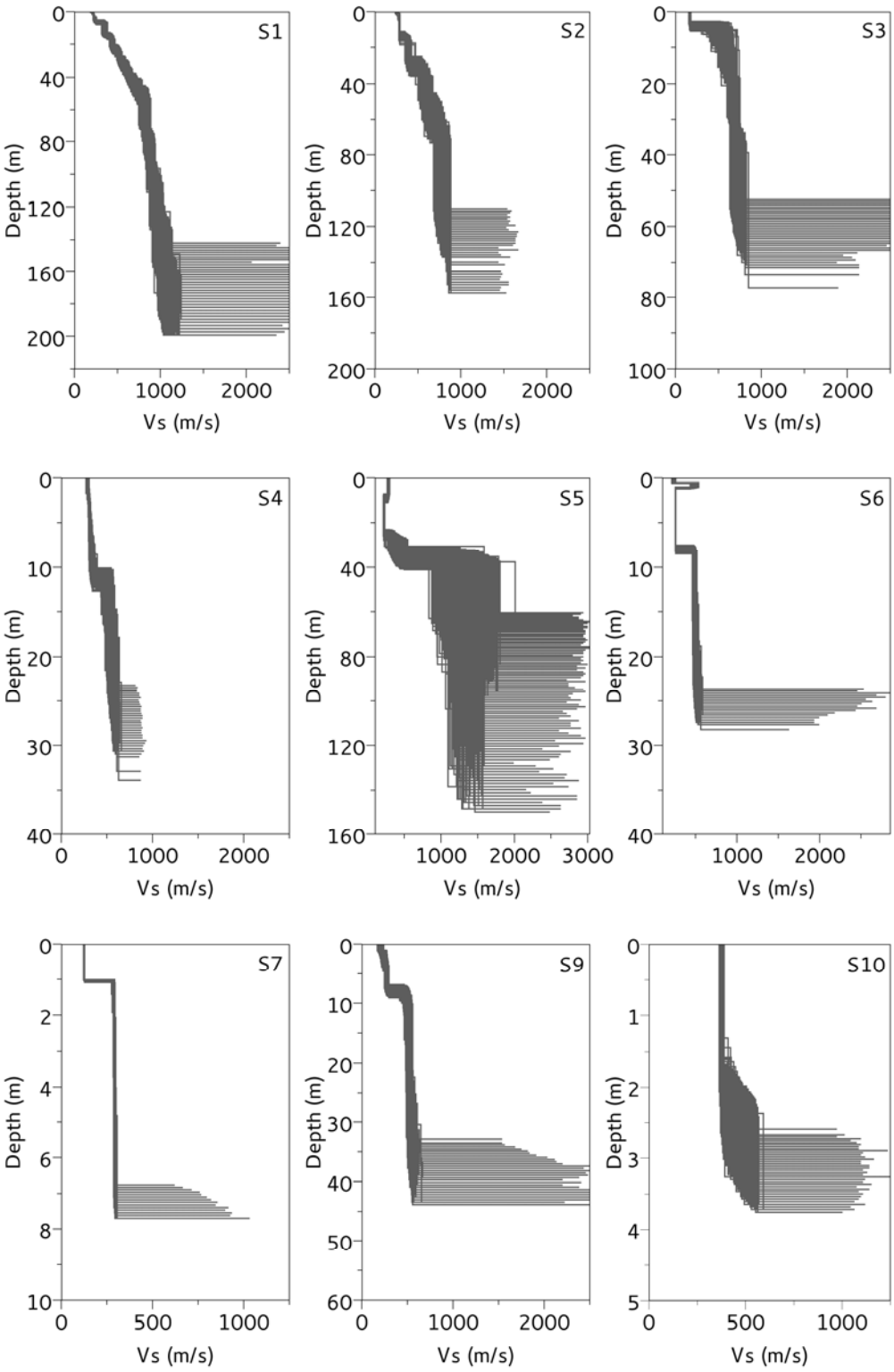

Figure 5. Ensemble of inverted shear-wave profiles that explain the observed dispersion data within uncertainty bound for sites S1, S2, S3, S4, S5, S6, S7, S9 and S10.

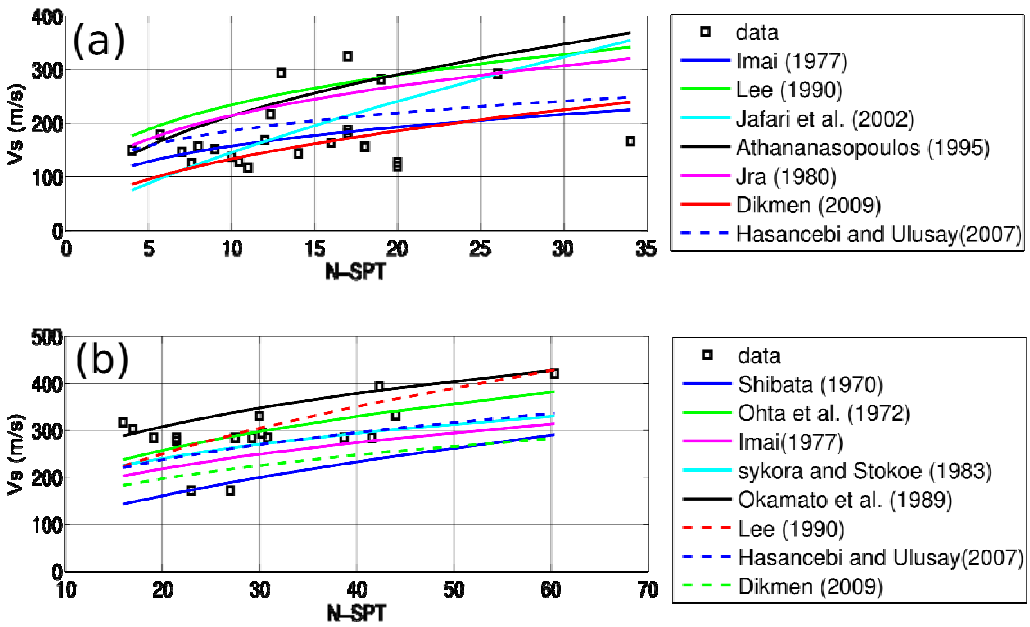

Figure 6. Measured shear-wave velocities as a function of N-SPT (uncorrected blows) (black squares) for (a) clay and (b) sand formation

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