Site Classification of Newly Deployed Strong Motion Stations in the Eastern Mediterranean

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SUMMARY:
Within the scope of the project titled 'Seismic Hazard Assessment for Cyprus and Neighbouring Regions' financed by the Scientific and Technological Research Council of Turkey (TUBITAK) for the period 2010-2013, the first strong motion network for the Northern part of Eastern Mediterranean island Cyprus comprised of 13 instruments was developed. In this study, site conditions at these network stations were investigated within the upper 30m depth by surface seismic and standard penetration tests. Preliminary characterization of the sites was made by making use of both geophysical and geotechnical criteria of NEHRP Provisions and Eurocode 8 site classification systems. The liquefaction susceptibility of these sites which comprise saturated cohesionless deposits was also determined. Mean shear wave velocity, mean penetration resistance, site class, and liquefaction susceptibility of each site were tabulated. The developed network complements the distribution of other regional strong motion networks in the Eastern Mediterranean region.

Keywords: Site classification, Shear wave velocity, Penetration resistance

1. INTRODUCTION

Construction of a complete model to compute the dynamic response of a specific site to the strong motion is generally unfeasible for the purpose of earthquake-resistant design. Hence the seismic design codes, such as NEHRP Provisions (BSSC, 2003) and Eurocode 8 (CEN, 2003) approach this problem by grouping sites into different classes based on the similarities in their dynamic response to strong motion and by varying the shapes of design spectra based on factors that are assigned to each site class. These site factors provided in seismic codes are estimated by empirical and analytical studies on available strong motion databases (e.g. Borcherdt, 1994; Dobry et al., 2000; Rey et al., 2002). Such studies can be improved by introducing new strong motion data from worldwide events.

The Eastern Mediterranean region corresponds to a seismically active part of the world with a number of destructive earthquakes experienced during the last century (Cagnan and Kalafat, 2012). However, available strong motion records originating from this region are rather scarce as strong motion instruments were not deployed until late 1990s. Within the scope of the project titled 'Seismic Hazard Assessment for Cyprus and Neighbouring Regions' financed by the Scientific and Technological Research Council of Turkey (TUBITAK) for the period 2010-2013, the first strong motion network for the Northern part of Eastern Mediterranean island Cyprus comprising of 13 instruments was developed. This network aims to complement the other strong motion networks in the region such as the Turkish National Strong Motion Network managed by the Republic of Turkey, Prime Ministry, Disaster and Emergency Management Presidency, Earthquake Department and the Cyprus Strong Motion Network-managed by the Republic of Cyprus, Ministry of Agriculture, Natural Resources and Environment, Geological Survey Department (Figure 1). Within the scope of Seismic Hazard Assessment for Cyprus and Neighbouring Regions project, site conditions at these network stations were investigated in the upper 30m depth by surface seismic and standard penetration tests. The purpose of this study is to provide explicit descriptions of these strong motion network sites through determination of the site classes according to the well-known site classification systems based on the results of conducted site investigations. This study would allow wide utilization by the engineering community (i.e. for computation of site factors utilized by design codes, for development of regional ground motion attenuation relationships) of past and future accelerographs recorded by the developed network.

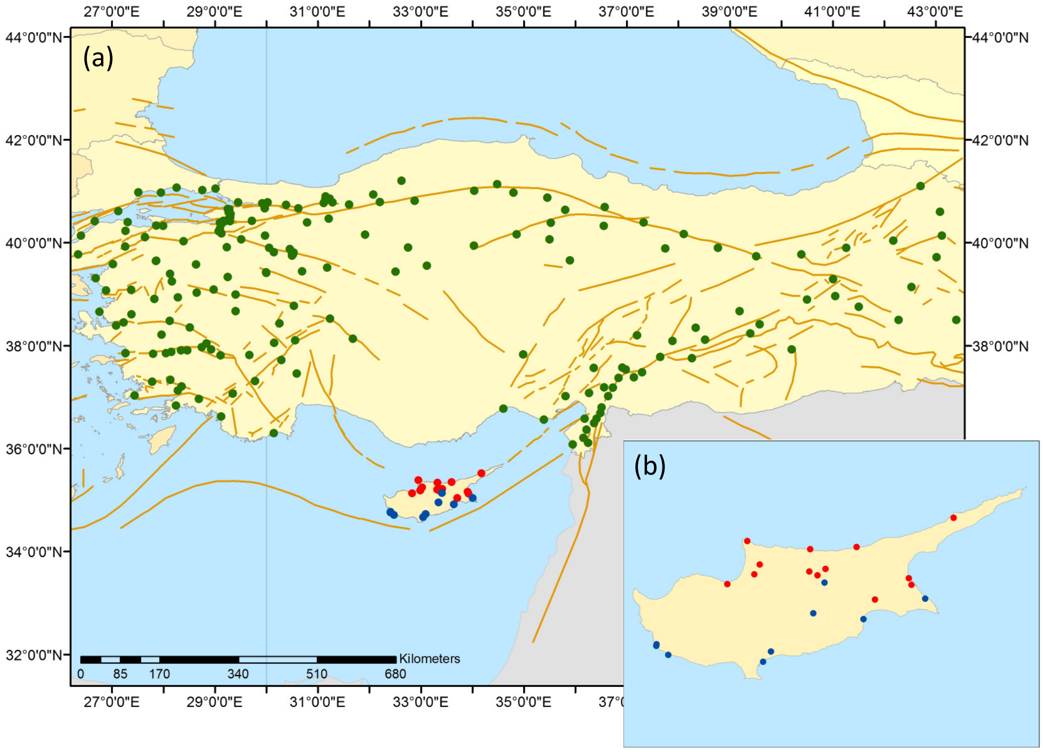

Figure 1. (a) Strong motion stations in the Eastern Mediterranean region together with main regional faults (Barka and Reilinger, 1997). Green symbols indicate station locations of Turkish National Strong Motion Network (Sandikkaya et al., 2010), blue symbols indicate station locations of Cyprus Strong Motion Network (Geological Survey Department of Cyprus, 2012), and red symbols indicate station locations of newly developed networked in North Cyprus. (b) A close up illustration of distribution of strong motion instruments in Cyprus.

2. SHALLOW SEISMIC AND GEOTECHNICAL SITE SURVEYS

2.1. Determination of shear-wave velocity profiles

The propagation characteristics of Rayleigh waves can be used for estimating the shear wave (V_s) profile of a site. The single-channel analysis of surface waves-SASW method (Park et al., 1997) utilizes two receivers to record the surface motions at two points and compares the computed dispersion curve for Rayleigh wave with the modeled curve. However, a more accurate estimation of actual dispersion curve needs a receiver spread with multi geophones positioned at close spacing. The multichannel analysis of surface waves (MASW) method, therefore, aims to overcome the deficiencies of SASW by employing multiple receivers. To advance accuracy by improving the identification of the dispersion curve for the Rayleigh wave fundamental mode and isolation of the noise, the method of MASW is employed in this study for estimation of the V_s profiles of the uppermost 30m.

The field system employed for application of the MASW method in this study involved an impact source, cables, geophones, and seismic recording units. Figure 2 displays the diagram for the field survey: a 47m long 48-channel receiver cable with 48 4.5Hz vertical geophones at 1m intervals was laid out at the site. The midpoint of the seismic spread was positioned as close as possible to the strong motion instrument location. At each site, three shot records were taken at 1m offset from the start and end points of receiver cable (shot points 1 and 3 in Figure 2) and at the center of receiver cable (shot point 2 in Figure 2). An impact source of 9 kg hammer was employed in this study. Data were recorded for 2s with a sampling rate of 1 ms and were transmitted to two 24-channel GEODE recording units via inputs A1 and A2 as illustrated in Figure 2 and converted from analog to digital form. An example of shot records taken during this study is shown in Figure 3.

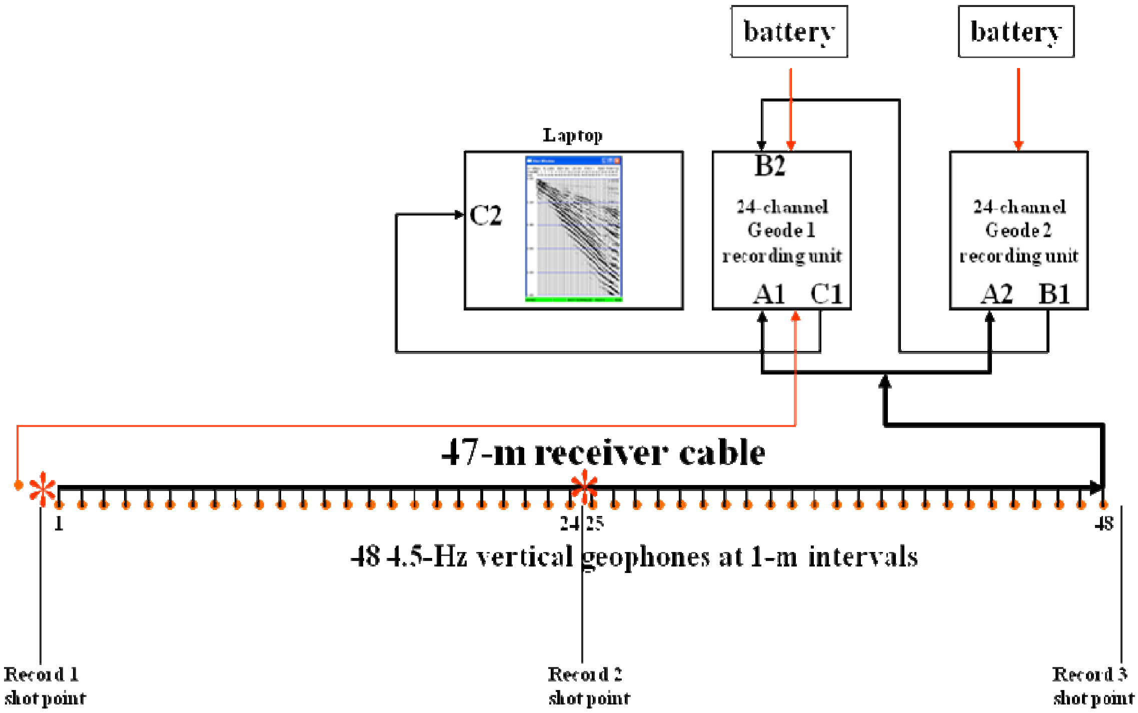

Figure 2. Workflow diagram of field survey in MASW

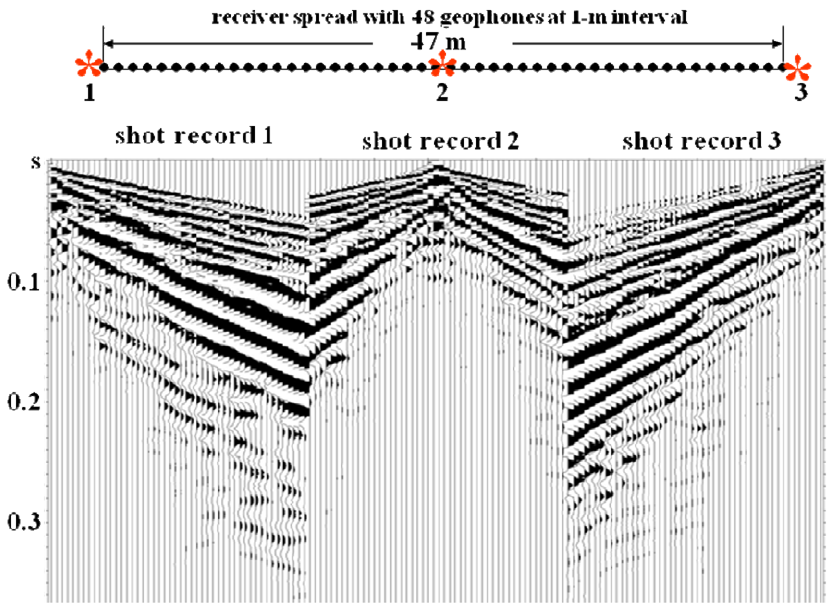

Figure 3. Example shot records at Esentepe station

Within MASW, the workflow for estimating P-wave velocity model is illustrated in Figure 4. First-arrival times were picked from the shot records and the corresponding travel time curves along the spread were obtained. Then, an initial P-wave velocity–depth model was derived from the picked travel times. In order to obtain the final velocity–depth model along the receiver spread, this initial model was perturbed iteratively by nonlinear travel time tomography applied to the first-arrival times

(Zhang and Toksoz, 1998). At each iteration, first-arrival times were modeled and compared with the actual travel times. Iterations were stopped when the difference between the modeled and actual travel times were reduced to an acceptable minimum in the least-squares sense. The P-wave velocity–depth profile for the site was finally computed by laterally averaging the velocity–depth model along the receiver spread.

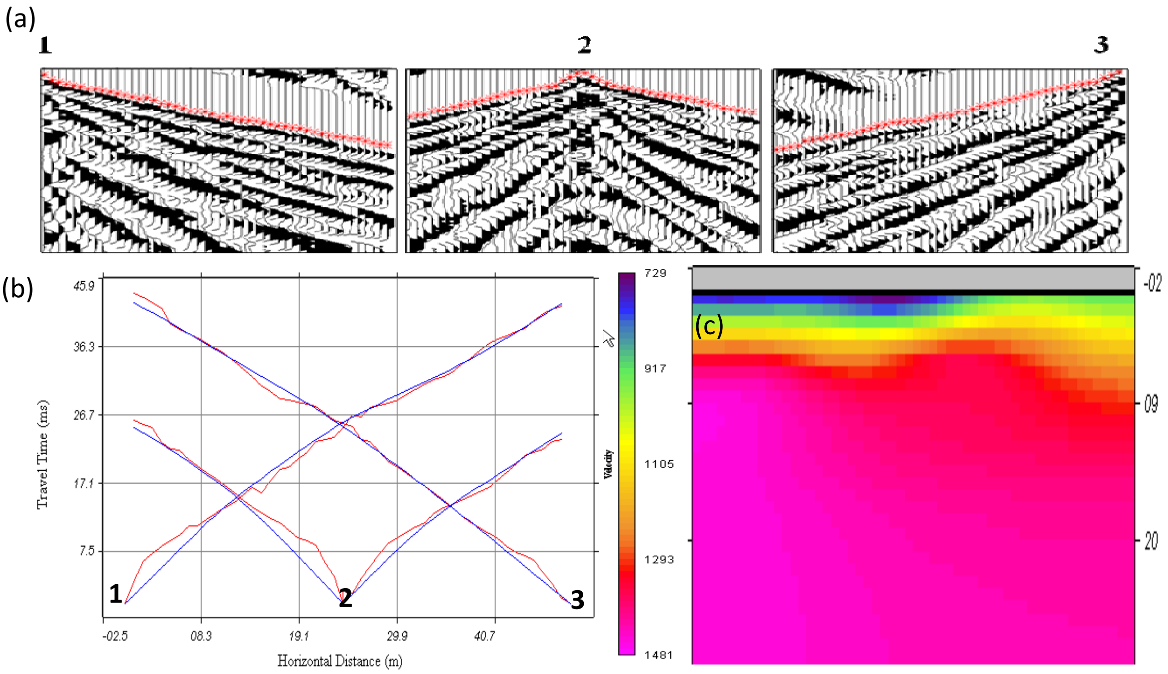

Figure 4. (a) First arrival times, (b) travel time curves with blue curve corresponding to modeled and red curve corresponding to actual travel times, (c) a P-wave velocity-depth model along the receiver spread for the Esentepe station

Main products of the MASW method are illustrated in Figures 5a-5c for one of the station sites investigated in this study. In the analysis of surface waves, we used one of the off-end shot records at each site with the most pronounced dispersive surface-wave pattern, which was first isolated from the refracted and reflected waves by inside and outside mute, then filtered using a 2.4–36.48-Hz band pass to remove low and high frequency noise (Figure 5a). Next, we performed plane wave decomposition to transform the data from offset time to phase velocity versus frequency domain (Park et al., 1999; Xia et al.,1999). A dispersion curve associated with the fundamental mode of Rayleigh-type surface waves was then picked in the transformed domain (Figure 5b) and inverted to estimate V_s as a function of depth (Figure 5c). Each frequency component of the Rayleigh waves travels at a different speed. This gives the dispersive character to the Rayleigh waves within the soil column. The largest portion of the Rayleigh wave energy often, but not always, is associated with the fundamental mode. For this mode, a dispersion curve that represents the change of phase velocity with frequency was picked as shown in Figure 5b. Then, this dispersion curve was used in an inversion algorithm to estimate V_s-depth profile for the soil column at the site (Figure 5c). Although, one may estimate a deeper V_s profile by including the higher modes, common practice is to invert the fundamental mode only. In this inversion phase, we start with an initial S-wave velocity–depth profile with layer thicknesses increasing with depth, a P-wave velocity–depth profile is then computed from the S-wave velocity–depth profile based on Poisson's ratio of 0.4, which is suitable for most soil columns. While keeping the density and thickness of the layers fixed, initial depth profiles for P- and S-wave velocities were iteratively perturbed until a final V_s depth profile was estimated.

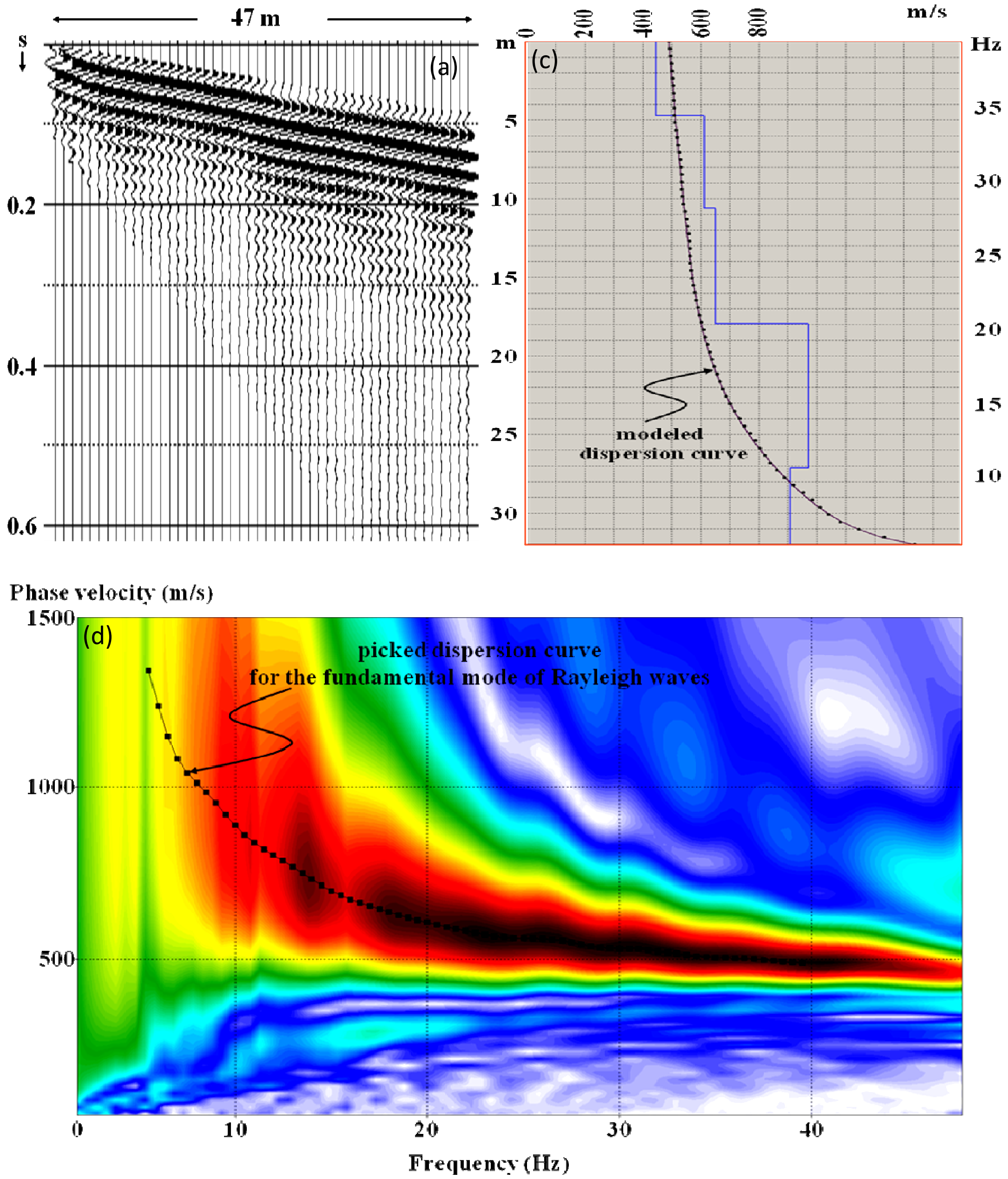

Figure 5. (a) off-end shot record, (b) the dispersion spectrum of the surface waves and (c) V_s-depth profile (blue curve) and the modeled dispersion curve (black curve) for Esentepe station site.

2.2. Geotechnical investigation of sites

One of the most widely used in situ tests in geotechnical practice is the Standard Penetration Test (SPT). During the test, a 63.5-kg hammer is dropped from 76 cm height to drive the sampler tube located at the end of a borehole into the soil, and the number of blows required per 15 cm penetration is recorded. The procedure is repeated three times in sequence at a specific depth. The penetration resistance, N_{30m}, is reported as the number of blows required to drive the sampler in the last 30 cm (2×15) penetration into soil. In SPT, when 50 blows are reached for any 15 cm penetration, the test is halted and the “refusal” is indicated on the borelog by noting the total length of penetration corresponding to 50 blows. During SPT, disturbed samples are retrieved by the split-spoon sampler. Over these samples, which are suitable for soil classification, particle size distribution, natural water content, and Atterberg limit tests were carried out. Geotechnical criteria given by NEHRP Provisions and Eurocode 8 are based on the mean penetration resistance of upper 30 m of the profile. Therefore, we performed SPT at the station sites in order to provide supplementary geological and geotechnical information on the site conditions.

The samples retrieved from boreholes were initially described and classified using a visual and manual procedure. Also, the soil layers were identified in-situ by visually examining the material coming out of the borehole during drilling. By performing laboratory tests on disturbed samples, soil was classified according to the Unified Soil Classification System. When cohesive soils were encountered, undisturbed samples were retrieved with Shelby tubes. Unconfined compression tests were carried out on such samples, from which the undrained compressive strength (q_u) was determined and the undrained shear strength ($S=q_u/2$) of the soil was calculated. It is to be noted that the undrained shear strength is another geotechnical parameter utilized in NEHRP Provisions and Eurocode 8 for site classification. In case a rock layer was encountered, core samples were recovered and total core recovery and rock quality designation of the rock cores were reported. Boring was stopped when more than 3 m of rock was drilled. The ground water level (GWL) at the sites of interest was measured as well the day after the boring.

3. SITE CLASSIFICATION FOR NETWORK SITES

A total of 13 sites were investigated with MASW, and at 14 of these, boreholes were drilled as well in this study. Velocity profiles and soil and rock descriptions are presented for the uppermost 30m where applicable in the outputs. An example output is illustrated below in Figure 6 for the Esentepe station. In Table 1, results are given for all stations in summarized form. However, detailed results involving variations of P and S wave velocity, SPT blow counts, and layer descriptions with depth can be provided to the reader upon request. A total of 13 station sites were investigated in this study; however an entry is added to Table 1 for an additional 14th entry which corresponds to the site at which a separate network of 10 strong motion stations (one free field station) was developed for structural health monitoring of St. Nicholas Cathedral, Famagusta within the scope of project titled 'Earthquake Vulnerability Assessment of Historical Monuments in Cyprus' by the same work group (Cagnan, 2012). With these 10 strong motion instruments, a total of 23 instruments are currently active in Northern part of Cyprus.

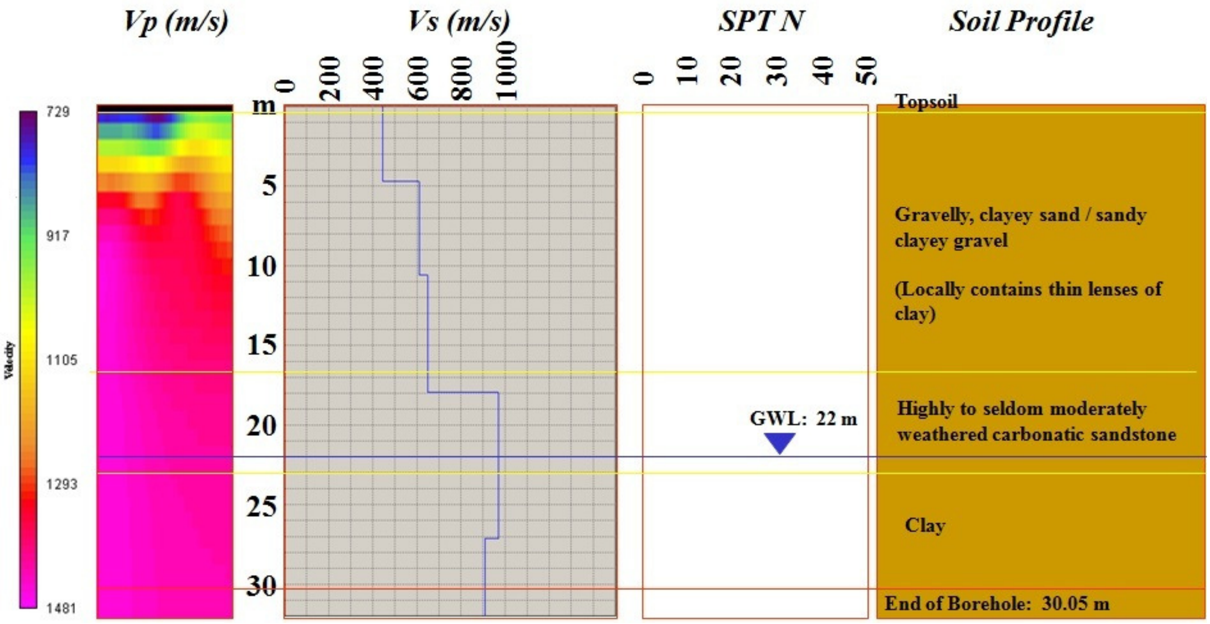

Figure 6. Results of seismic and geotechnical investigations completed at Esentepe station site.

Based on the information acquired from field tests, the sites are classified in accordance with the NEHRP Provisions (BSSC, 2003) and Eurocode 8 (CEN, 2003) (Table 1), both of which suggest criteria based on mean shear wave velocity (V_{S30}) and mean penetration resistance (N_{30m}) of the uppermost 30 m of soil/rock profile. The geotechnical criterion of NEHRP Provisions and Eurocode 8 based on the mean undrained shear strength of the upper 30m (S_{u30m}) was not utilized in the site classification as no continuous cohesive soil deposits were encountered at any of the investigated sites.

Table 1. List of site classes for the newly established strong motion network in Northern part of Cyprus

Station code	Town	Lat (^{o}N)	Long (^{o}E)	V_{s30} (m/s)	N_{30}m	NEHRP (MASW)	NEHRP (SPT)	Eurocode 8 (MASW)	a_{crt}	GWL (m)
1	Lefke	35.13	32.83	592	55	C	C	B	-	24
2	Guzelyurt	35.19	32.99	310	51	D	C	C	-	NA
3	Kalkanli	35.25	33.02	-	50	-	C	-	-	-
4	Sadrazamkoy	35.39	32.95	473	61	C	C	B	-	3.3
5	Girne	35.34	33.32	571	80	C	C	B	-	NA
6	Esentepe	35.35	33.60	732	65	C	C	B	-	22
7	Yenierenkoy	35.53	34.18	637	75	C	C	B	-	19.5
8	Tuzla	35.17	33.91	304	9	D	E	C	0.3g	1.7
9	Magosa	35.13	33.93	449	56	C	C	B	-	4.3
10	Beyarmudu	35.04	33.71	554	37	C	D	B	-	NA
11	Haspolat	35.22	33.42	510	55	C	C	B	-	14
12	Lefkosa	35.18	33.37	344	25	D	D	C	-	15.3
13	Gonyeli	35.21	33.32	570	55	C	C	B	-	14
14	Magosa*	35.12	33.94	560	47	C	D	B		7.6

NEHRP Provisions propose six site classes (A, B, C, D, E, and F) for the identification of site specific design spectra. In this study, 3 out of 13 station sites are classified as class D and 10 as class C according to the V_{S30} criterion of NEHRP. On the other hand, when the station sites are classified according to N_{30m} criterion, the figures were 10, 3, and 1, respectively, for classes C, D, and E (Table 1). Comparison of V_{S30} and N_{30m} based site classes indicate acceptable consistency in this study. According to Table 1, in case of 3 out of 13 station sites, V_{S30} based site class estimates are stiffer than N_{30m} based estimates whereas in case of 10 out of 13 station sites V_{S30} based site class estimates agree with N_{30m} based estimates. Only in 1 case out of 13, N_{30m} based site class estimate is stiffer than V_{S30} based estimate. When evaluating these incosistencies, it should be remembered that MASW yields S-wave profile of the ground beneath the span of seismic spread in the sense of horizontal average, whereas SPT provides penetration resistance of the soil located just along the borehole. Due to these basic limitations inherent in the application of MASW and SPT, inconsistencies are unavoidable. In Figure 7, the N_{30m}-V_{s30} pairs obtained in this study are being compared with results of Sandikkaya et al. (2010) study for the Turkish National Strong Motion Network. Our results show agreement with Sandikkaya et al. (2010) results. It is not possible to talk about a definite N_{30m}-V_{s30} relation as variability suggested by both studies is considerable.

The site classification scheme suggested by Eurocode 8 is quite similar to the NEHRP Provisions. The differences are such that the classes A and B of NEHRP provisions are combined in Eurocode 8 into class A and that the boundary between classes A and B of Eurocode 8 is set to 800 m/s, whereas the corresponding boundary in NEHRP Provisions is 760 m/s.The mean penetration resistance criteria for site classes are consistent between the two references. Hence, Classes D, C, and B in Eurocode 8 correspond to classes E, D, and C in NEHRP Provisions, respectively. The classifications of all station sites according to Eurocode 8 are given in Table 1 as well.

NEHRP Provisions and Eurocode 8 demand special treatment of the sites that have liquefaction potential and group such sites in a separate class due to excessive nonlinear response potential that they possess. Assessment of the liquefaction potential of a site is composed of two essential steps: susceptibility and opportunity analysis (Youd and Perkins, 1978). The liquefaction susceptibility is the capability of the soil layer to resist liquefaction. The liquefaction opportunity can be defined as the seismic demand on soil to initiate the liquefaction. A site will have liquefaction potential if the seismic demand (i.e.,opportunity) exceeds the capacity of resistance (i.e.,susceptibility) of the soil. In this study, the procedure outlined by Youd et al. (2001) was used to determine liquefaction susceptibility at the station sites. As Youd et al. (2001) suggests susceptibility study was undertaken for sites with layers of sand below GWL and shallower than 15m: only for the station site of Tuzla. Although Youd et al. (2001) suggests use of peak horizontal ground acceleration created by an earthquake of moment magnitude 7.5 at the site of interest for assessment of liquefaction potential on a site, we modified this procedure slightly in order to express the liquefaction susceptibility as the critical peak ground acceleration that almost yields to liquefaction potential. Consequently, the site of Tuzla station will have liquefaction potential if the peak ground acceleration on the site exceeds 0.3g during an earthquake with magnitude 7.5. Magnitude-dependent scaling of that measure for liquefaction susceptibility is straightforward after the scaling factors presented by Youd et al. (2001).

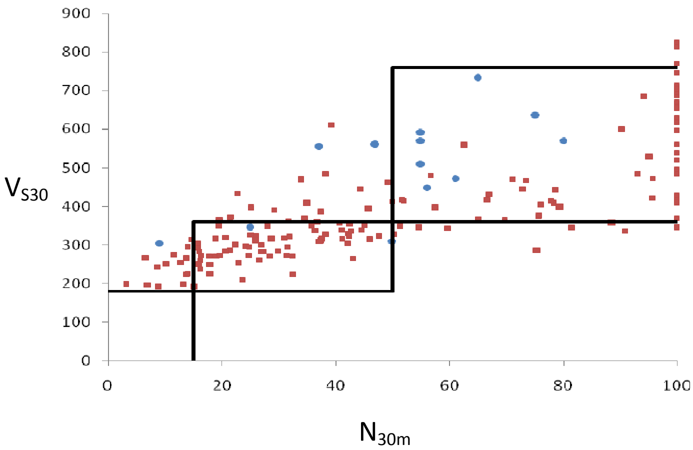

Figure 7. N_{30m}-V_{s30} relationship obtained from this study (blue dots) together with from Sandikkaya et al. (2010) study (red dots). The NEHRP Provision based N_{30m} and V_{s30} bands corresponding to site classes C, D and E are shown as well.

5. CONCLUSIONS

Within the scope of the project titled "Seismic Hazard Assessment for Cyprus and Neighbouring Regions" the subsurface conditions at the strong motion sites of a newly developed network in Northern part of Cyprus were investigated through geophysical and geotechnical tests. The shear-wave velocity profiles of the upper 30 m of 13 sites were determined with MASW technique. In addition, site conditions were also investigated by borings, in which SPT was performed for soils and core samples were recovered from rock formations. Based on the geophysical and geotechnical data, the site conditions for the upper 30 m of the sites, were characterized according to NEHRP Provisions (BSSC 2003) and Eurocode-8 (CEN2003). The majority of station sites were classified as (NEHRP) class C in the network. The site classes of each site are tabulated in this paper. The liquefaction susceptibility of each site was studied as well.

The degree of agreement between the SPT based site classes and MASW based site classes of the station sites was acceptable (70%). Only in the case of 1 out of 13 sites unconservative misclassification occured when the geotechnical criteria of the NEHRP Provisions were undertaken. Only one of the sites was found critical regarding liquefaction susceptibility: Tuzla strong motion site. The liquefaction potential of this site was studies by computing the critical peak horizontal ground acceleration required for triggering liquefaction during a moment magnitude 7.5 event. Since when past seismic activity of the regional sources investigated, the computed peak horizontal ground acceleration in case of a moment magnitude 7.5 event is rather unlikely at the site of interest, liquefaction risk is rather low at this station site. We believe that with the undertaken site conditions study, the newly developed strong motion network in the Eastern Mediterranean region will contribute to the further development of methods for assessing the relationship between the site conditions and strong motion parameters as well as to the understanding of regional ground motion attenuation.

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