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Comparison of Measured and Estimated Shear Wave Velocities in a Seismically Active Area (Erbaa, Turkey)

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COMPARISON OF MEASURED AND ESTIMATED SHEAR WAVE VELOCITIES IN A SEISMICALLY ACTIVE AREA (ERBAA, TURKEY)

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ABSTRACT

Shear wave velocity (V_s) is an important parameter for the design of geotechnical works in seismically active areas. The V_s value commonly reflects geological information and engineering properties such as stiffness and density. It is also an important parameter of soil for design and site response purposes. As a part of a microzonation study, field tests performed in Erbaa, Turkey were evaluated to obtain shear wave velocity profiles. The study area, Erbaa, is located on the eastern segment of seismically active North Anatolian Fault Zone (NAFZ) where a catastrophic earthquake occurred in 1942. In addition, several earthquakes and earthquake-related hazards have occurred along different segments of this fault zone in the recent past. Hence, shear wave velocity profiles of Erbaa were developed for the purpose of performing site response analyses as a part of a microzonation study. The geological units observed in the study area consist mainly of alluvial and Pliocene units. These layers were evaluated on the basis of drilling, in-situ (SPT, SCPTU and SPT-based uphole,) and laboratory testing applications. The relationship between shear wave velocity, Standard Penetration Test (SPT) blow-counts (N) and the soil properties are discussed with the consideration of their variations with depth. A new technique called SPT-based uphole test was performed to measure shear wave velocity during drilling operations. The measured SPT uphole-based V_s values are compared with V_s values from SPT-based empirical formula for the site-specific area. It was concluded that these empirical correlations should be modified to provide the best correlation for this site. Therefore, a site-specific formula was proposed in these empirical calculations in order to obtain V_s profiles for sandy layers in the study area.

INTRODUCTION

Turkey is one of the most earthquake prone countries in the world. The seismicity of the northern part of Turkey is mainly controlled by the active North Anatolian Fault Zone (NAFZ). NAFZ is one of the main active seismic zones, which caused destructive earthquakes and related hazards in the northern region of Turkey.

The study area, Erbaa, is one of the largest towns of Tokat with a population of 47000 in the northern part of Turkey. Erbaa is in NAFZ and partly located on the Kelkit river plain, also referred to as the Erbaa basin (Figure 1). The city center of old Erbaa was on the south side of the Kelkit River. After the disastrous 1942 earthquake (M=7.2), the settlement area was seriously damaged and moved farther southwards of its old place in 1944.

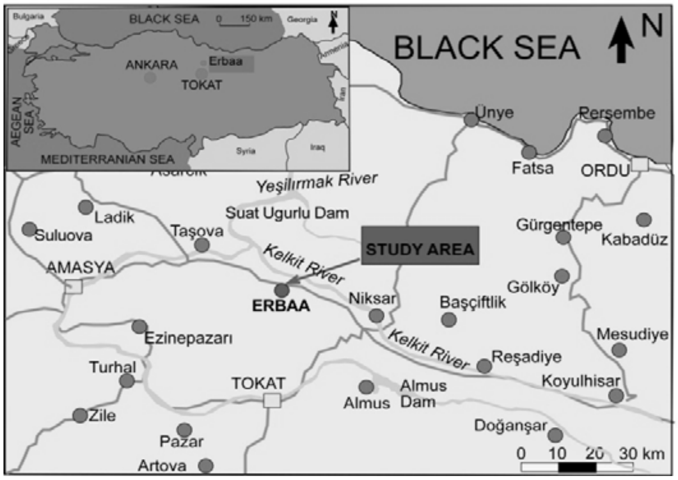


Fig. 1. Location map of the study area

As a part of a microzonation study in Erbaa, shear wave velocity (V_s) values of the geological units exposed in this area were required for site response analyses. The shear wave velocity (V_s) is a unique and essential parameter in all geotechnical works to define dynamic properties of the soils. The value and its measurement commonly give ideas about geologic information such as stiffness and compactness as well as the behavior of the soil materials for design purposes. It is applicable in the evaluation of foundation stiffness, earthquake site response, liquefaction potential, soil density, site classification, soil stratigraphy and foundation settlements (Richart *et al.*, 1970; Seed and Idriss, 1970; Schnabel *et al.*, 1972; Sykora and Stokoe, 1983; Burland, 1989; Sasitharan *et al.*, 1994; Shibuya *et al.*, 1995; Kramer, 1996; Andrus and Stokoe, 1997; Wills and Silva, 1998; Mayne *et al.*, 1999; Dobry *et al.*, 2000; Lehane and Fahey, 2002; Seed *et al.*, 2003; Stewart *et al.*, 2003; McGillivray and Mayne, 2004; Holzer *et al.*, 2005; McGillivray, 2007).

In this study, the geological units were evaluated on the basis of drilling, in-situ testing (e.g. SPT, SPT-based uphole, SCPTU), and laboratory testing applications. The subsurface conditions were evaluated in terms of different soil layers, as well. Two types of units are mainly observed in the study area (Pliocene and alluvial units) and they were distinguished as Pliocene clay and sand layers and/or alluvial clay and sand layers in the calculations. The obtained in-situ and laboratory data was correlated to define proper site-specific V_s profiles in Erbaa. Thus, a typical borehole was selected as an example in this study which belongs to BH-23 data.

A new technique, called as SPT-based uphole method by Bang and Kim (2007), was applied for the measurement of shear wave velocities. The measured V_s value from SPT-based uphole and SPT-N based V_s from empirical approaches were discussed with the consideration of their variations with depth. The comparison of the measured and empirical relations was conducted to point out the efficiency of this new method, as well.

REGIONAL AND SITE GEOLOGY, SEISMICITY

The study area, Erbaa, and its close vicinity are within a pull-apart basin which was formed by the tectonic activity of the North Anatolian Fault Zone (NAFZ). The NAFZ is 1500 km long seismically active right lateral strike slip fault that has a relative motion between the Anatolian Plate and Black Sea Plate (Sengor *et al.*, 1985). Between 1939 and 1967, the NAFZ ruptured by six large, westward-propagating earthquakes with magnitudes greater than 7, and caused approximately 900 km surface break (Allen, 1969; Ketin, 1969; Ambraseys, 1970). The study area, Erbaa, is located on the eastern part of the NAFZ. Surface ruptures of the 1939, 1942 (M=7.2) and 1943 (M=7.6) earthquakes occurred in the Tasova -Erbaa and Niksar basins (Barka *et al.*, 2000). The November, 26, 1943 Tosya earthquake (M_w = 7.6) produced 280 km long surface rupture which could be the second longest surface faulting in that sequence (Emre *et al.*, 2006). The Tasova-Erbaa pull-apart basin is approximately 65 km long and 15-18 km wide (Figure 2). The northern margin of the study area is surrounded by the fault segments that ruptured in the 1942 and 1943 earthquakes (Figure 2). The southern part is bounded by the Esencay fault, which has a different morphological expression; however, no instrumental and/or historical earthquakes have been mentioned in the study of Barka *et al.* (2000) related to this fault.

During the 1900s, several earthquakes occurred in this region. Erbaa is considered in the First Degree Earthquake Zone of Turkey (http://www.deprem.gov.tr/indexen.html). Erbaa is one of the important seismic areas on the NAFZ with past seismic activity. 1942 Niksar-Erbaa earthquake is the most destructive earthquake for the region. Because of this earthquake, the city had to be moved to the southern part of the old settlement. No seismic activity with higher magnitude has been recorded since 1942 Erbaa-Niksar earthquake in this region.

Fig. 2. Geological map of the study area

Metamorphic rocks and the limestone layers as basement rocks can be observed with an age from Permian to Eocene in the study area in a regional macro scale. These rocks are overlaid by Upper Eocene volcanics (basalt, andesite, agglomerate, and tuff) and the alternation of sandstonesiltstone layers. These units are covered by Pliocene deposits consisting of semi-consolidated clay, silt, sand, and gravel with an unconformity and recent Quaternary alluvial unit (Aktimur *et al.*, 1992) (Figure 2). The alluvium including gravel, sand, and silty clay can be observed in the basement of Kelkit river valleys and in the northern part of the Erbaa basin. The alluvial unit consists of heterogeneous materials, derived from various older geological units in the vicinity. Their lateral and vertical extents cannot be easily traced, since they are in the form of wedges and lenses. The Quaternary alluvial unit and Pliocene deposits broadly cover the study area. While the northern part of the settlement area is located on the alluvial unit, the Pliocene deposits dominate the southern part of Erbaa (Yılmaz, 1998) (Figure 2).

SUBSURFACE CONDITIONS

The subsurface conditions were evaluated in terms of different soil layers. Mainly two types of units are observed in the study area: Pliocene and alluvial units. Furthermore, these units were differentiated as Pliocene clay and sand layers and/or alluvial clay and sand layers.

Previous geotechnical investigations of the study area include 56 drillings and the laboratory test results (Canik and Kayabali, 2000; Akademi, 2002; Metropol, 2005). The depths of these boreholes change between 10 and 20m. SPT blow counts which were taken at every 1.5m depth in these boreholes and the laboratory test results were also considered in the evaluations. In addition to that, a total of 48 new boreholes with 30m depth were opened to obtain and correlate SPT based shear wave velocity values. During the 30m depth of drilling, undisturbed sampling and SPT tests were applied at every 0.50m intervals. Thus, a continuous soil profile was achieved. The distribution of the boreholes including boreholes of the previous projects can be seen in Figure 3.

A total of 1390 m of drilling was performed in this study whereas 1341 SPT and 312 UD samples were obtained. The ground water level (GWL) at the study area is varying between 1 and 19 m in general. There are a few dry boreholes in the Pliocene units as well. The GWL in the Pliocene units is deeper (13-19 m) than that of the alluvium. The alluvium unit has a very shallow GWL (1-2 m) with half a meter fluctuation in dry season near the Kelkit River.

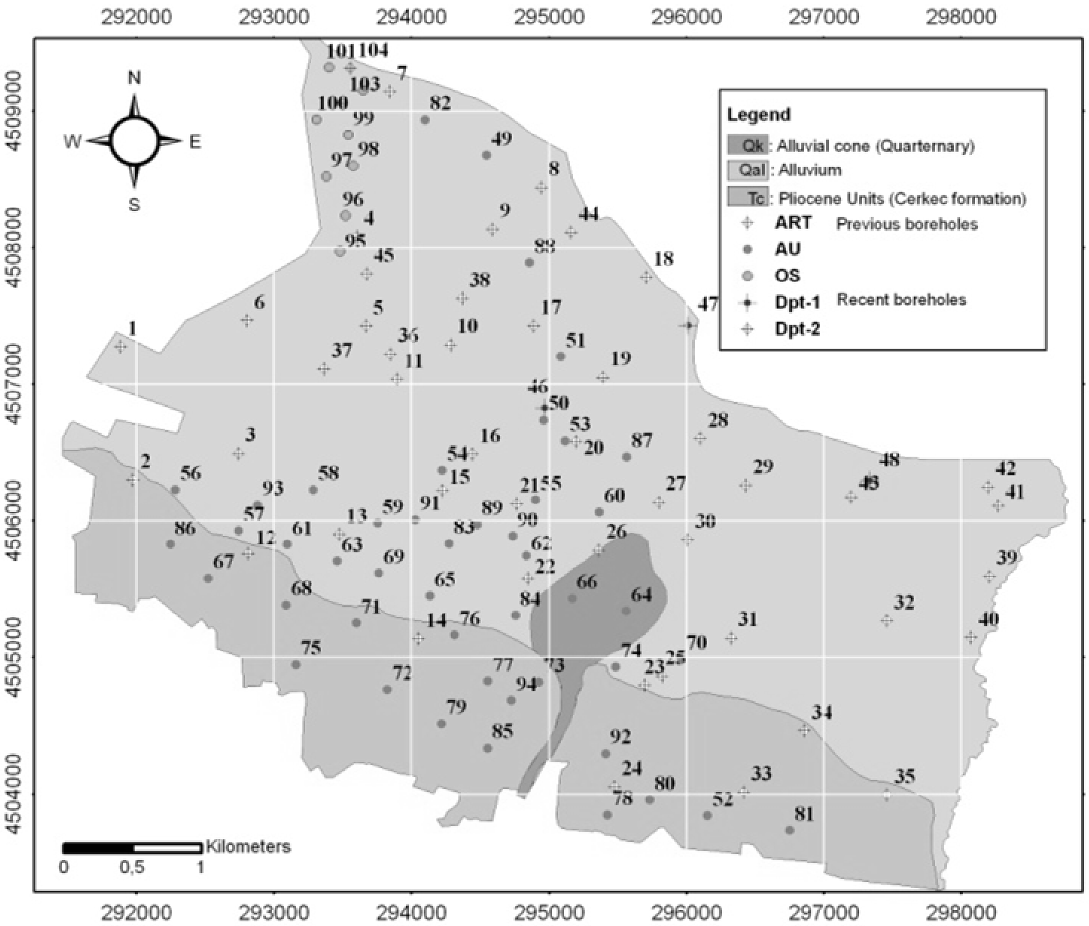


Fig. 3. The distribution of the boreholes in the study area

SPT - N values of the boreholes were evaluated in terms of different geological units. The alluvium units have generally low SPT-N values (N<20) indicating a loose – medium dense sedimentation. Refusal SPT-N blow counts were mostly obtained in gravelly layers of the alluvium. In addition, the Pliocene units mostly reveal refusal during SPT tests after 10-15 m depth (Figure 4).

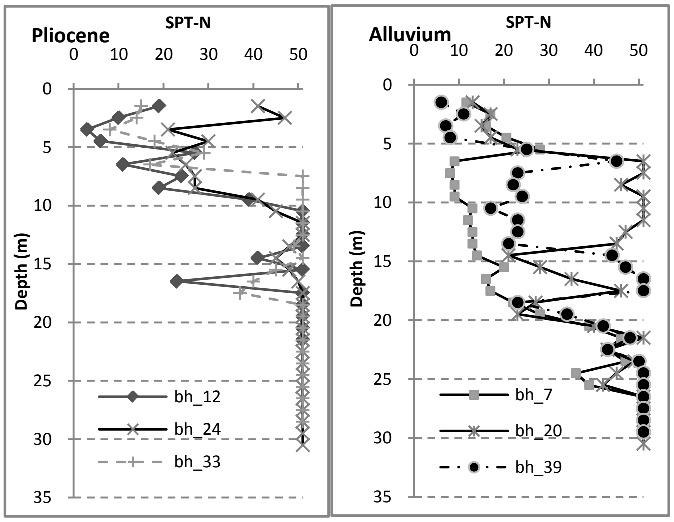


Fig. 4. Variation of SPT-N blow counts in the alluvial and Pliocene layers

The variation of the penetration resistance in three typical borings in both the Pliocene and alluvial units can be seen in Figure 4. As can be seen in Figure 4, the alluvial units have generally lower SPT-N resistance than Pliocene units have.

Laboratory tests were performed on 880 SPT and 110 undisturbed samples to determine the index and mechanical properties of the soils. Based on the test results, soil samples were classified according to Unified Soil Classification System (USCS). On the undisturbed (UD) samples, 125 water content, 102 Atterberg Limits, 123 particle size distribution, 83 natural unit weight, 76 specific gravity, 80 hydrometer, 11 triaxial, and 5 consolidation tests were performed. On the other hand, 564 water content, 455 Atterberg Limits, and 950 particle size distribution tests were performed on disturbed samples. The sieve analysis was used to determine the particle size distribution for particles larger than the No.200 sieve (0.075mm) and the hydrometer analysis was used for soil particles finer than the No.200 sieve. Atterberg limits were also distinguished by means of liquid limit and plastic limit tests. Triaxial tests (UU and CU) and consolidation tests were carried out to reveal the mechanical properties of plastic soils.

In total, 30 seismic cone penetrometer with pore water pressure (SCPTU) measurements were performed with varying depths in accordance with ASTM D5778-95(2000) standards. The performance of the cone penetration test (CPT) apparatus was particularly affected by gravelly layers. Therefore, a limited number of CPT tests could be performed in shallow depths. The distribution of the SCPTUs and an example of SCPTU recording from BH-23 are illustrated in Figures 5-6. The depth of the SCPTU applications has a range in between 1 m to 10 m in the study area.

ESTIMATION OF SHEAR WAVE VELOCITIES

Empirical correlations of penetration resistance

The measured shear wave velocities which are the most reliable to evaluate maximum shear modulus (G_{max}) can also be used in the calculation of G_{max} (Kramer, 1996).

$$G_{max} = \rho\, V_s^2 \qquad (1)$$

When shear wave velocity measurements are not available, G_{max} can be estimated by using different approaches or empirical formulas. SPT-based G_{max} and/or V_s relationships are most commonly used in the literature (Ohta and Goto, 1976; Seed *et al.*, 1986). Depending on different soil types, SPT-N and V_s relationships which use only N-blow count value were proposed by different researchers (Ohba and Toriumi, 1970; Imai and Yoshimura, 1970; Fujiwara, 1972; Ohsaki and Iwasaki, 1973; Imai, 1977; Ohta and Goto, 1978; Seed and Idriss, 1981; Imai and Tonouchi, 1982; Sykora and Stokoe, 1983; Jinan, 1987; Lee, 1990; Sisman, 1995; Iyisan, 1996; Kayabali, 1996; Jafari *et al.*, 1997; Pitilakis *et al.*, 1999; Kiku *et al.*, 2001; Jafari *et al.*, 2002; Andrus *et al.*, 2006; Hasancebi and Ulusay, 2006; Hanumantharao and Ramana, 2008; Dikmen, 2009).

One of the empirical SPT-based relationships considered in this study belongs to Ohta and Goto (1976) and Seed *et al.* (1986) for sandy layers. This approach is based on corrected N-blow count $(N_1)_{60}$ and effective stress with a constant coefficient.

$$G_{max} = 20000\, (N_1)_{60}^{\;0.333} (\sigma'_m)^{\,0.5} \qquad (2)$$

where σ'_m : the mean principal effective stress in lb/ft^2
$(N_1)_{60}$: the corrected SPT-N blow–count

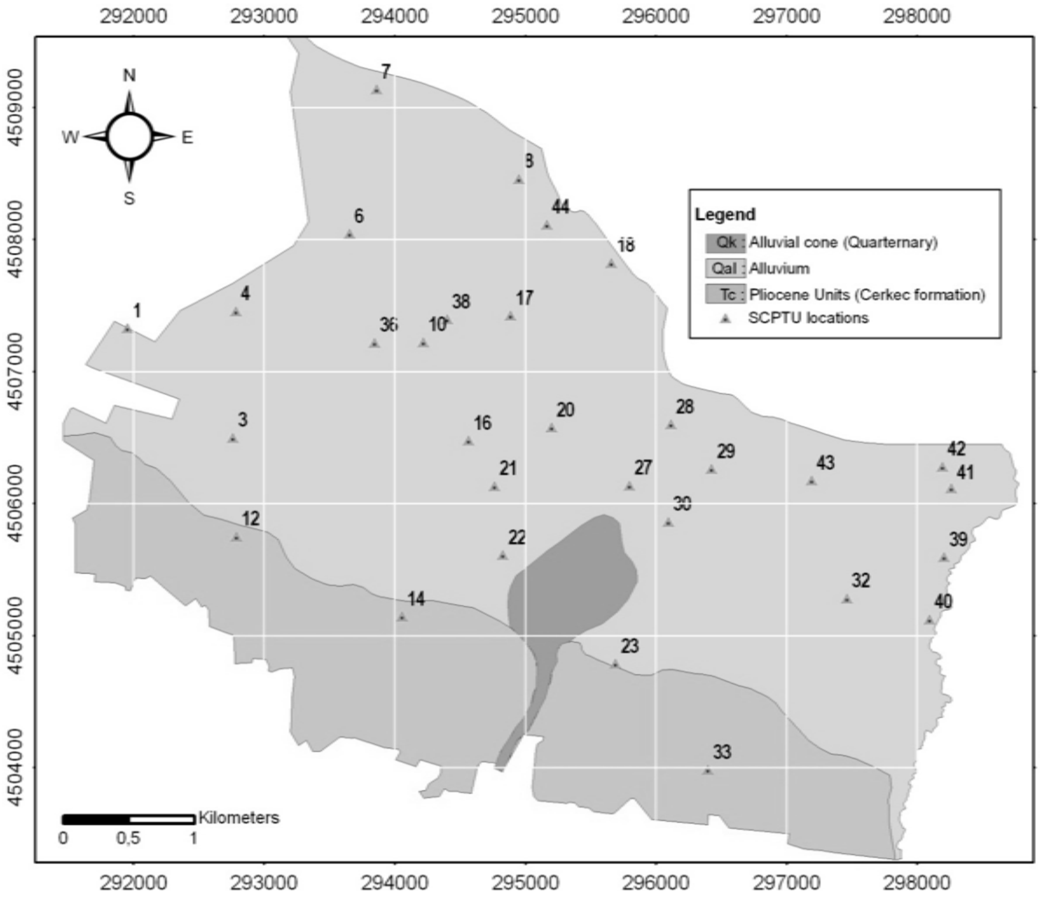
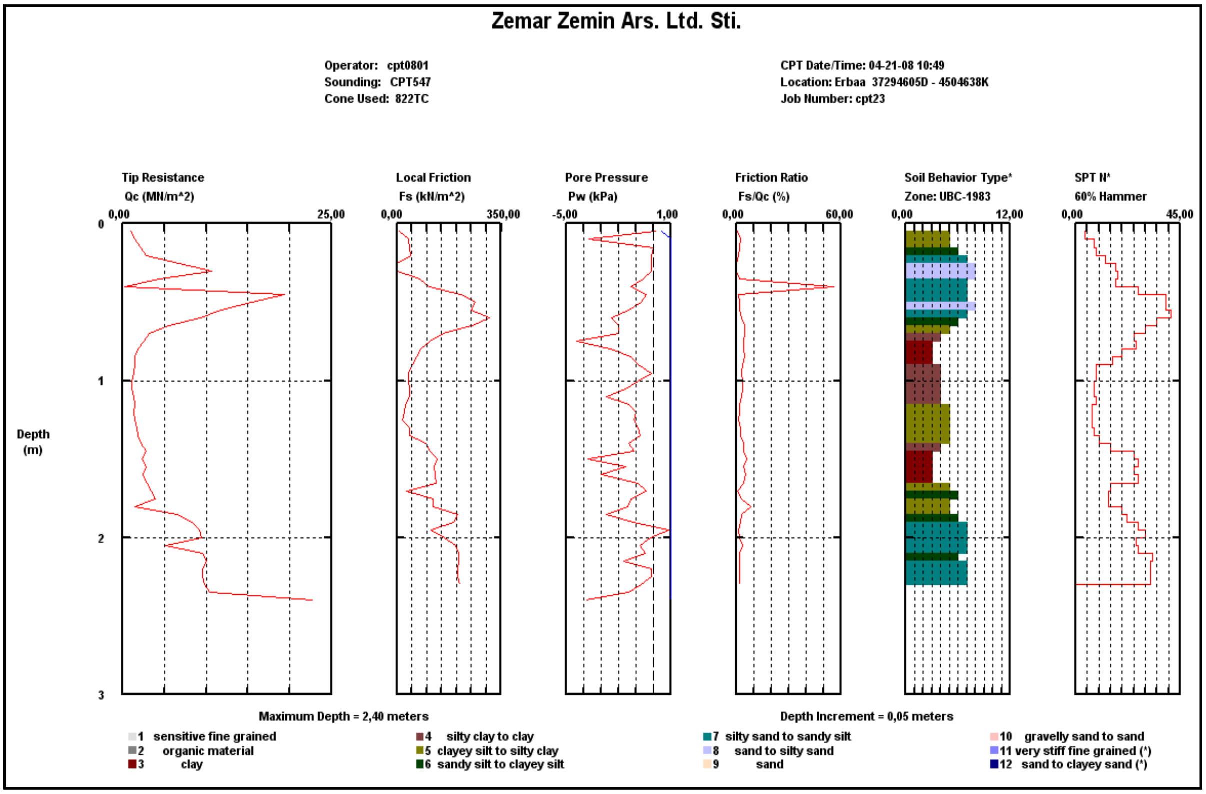


Fig. 5. The distribution of the SCPTU locations



Zemar Zemin Ars. Ltd. Sti.

Operator: cpt0801
Sounding: CPT547
Cone Used: 822TC

CPT Date/Time: 04-21-08 10:49
Location: Erbaa 37294605D - 4504638K
Job Number: cpt23

Maximum Depth = 2,40 meters

Depth Increment = 0,05 meters

Fig. 6. An example of the SCPTU recording

SPT-N blow-counts were corrected to achieve $(N_1)_{60}$ values. One of the essential corrections is the correction factor (C_N) for the equivalent overburden stress of 100 kPa. Idriss and Boulanger (2006) method was considered for the iteration of the overburden pressure in the corrections.

$$C_N = (P_a / \sigma'_v)^\beta \leq 1.7 \qquad (3a)$$

$$\beta = 0.784 - 0.0768 \sqrt{(N_1)_{60}} \qquad (3b)$$

The other necessary corrections were concerned for energy correction, hole-diameter, rod-length and the type of sampler to calculate corrected SPT N-value $(N_1)_{60}$. The corrections for C_R, C_S, C_B and C_E employed as recommended by the NCEER Working Group (NCEER, 1997). The depth of the ground water table and the unit weights of the soils were also considered for the calculations.

$$(N_1)_{60} = N\, C_N\, C_R C_S C_B C_E \qquad (4)$$

where C_R = correction for rod length,
C_S = correction for sampler configuration,
C_B = correction for borehole diameter, and
C_E = correction for hammer energy efficiency (60%).

On the contrary, depending on the available data, different approaches were applied for clayey layers. Firstly, Pliocene and alluvial clays were separately explored as mentioned previously. Secondly, alluvial clay units were evaluated on the basis of the following formula (Kramer, 1996).

$$G_{max} = 625\, F(e)\, (OCR)^k\, P_a^{\,1-n}\, (\sigma'_m)^n \qquad (5)$$

where $F(e)$ is a function of the void ratio, OCR is over consolidation ratio, k is an over-consolidation ratio component which depends on Plasticity index, σ'_m is the mean principal effective stress, and P_a is the atmospheric pressure.

Moreover, Pliocene clay layers were evaluated depending on this approach which is given in Table 1. G_{max} value is calculated by using this approach for Pliocene clay layers, since there is limited number of CU type triaxial compression test results. After completing G_{max} value calculations for different layers, V_s values were determined.

Table 1. Values of G_{max}/s_u (After Weiler, 1988)

	Overconsolidation ratio, OCR		
Plasticity Index	1	2	3
15-20	1100	900	600
20-25	700	600	500
35-45	450	380	300

s_u : Undrained strength measured in CU triaxial compression

Measured V_s values

The measurement of the shear wave velocities by field tests is commonly used in practice. In general, low strain field tests including seismic reflection, seismic refraction, suspension logging, and spectral analysis of surface waves, seismic crosshole and downhole-uphole tests and seismic cone tests are used to obtain dynamic soil properties. Standard penetration, cone penetration, dilatometer and pressuremeter tests correspond to high strain test levels. A combination of low- and high-strain tests was newly introduced by Bang and Kim (2007). This test is a modified form of the seismic uphole method. This method uses the impact energy of the split spoon sampler of SPT test as a source and it is called the SPT-based uphole method (Kim *et al.*, 2004; Bang and Kim, 2007). The impact energy generated by the SPT test can be used as a source for the uphole method. In this method, it is aimed to record the shear waves during the SPT test without any additional explosives or mechanical sources.

A schematic diagram of the SPT based uphole method is shown in Figure 7. The significant amount of compression and shear waves caused by tip and side stresses (σ_t and σ_s in the circle of Figure 7) are generated in the ground when the split spoon sampler is penetrated into the soil through hammering at the ground surface (Bang and Kim, 2007).

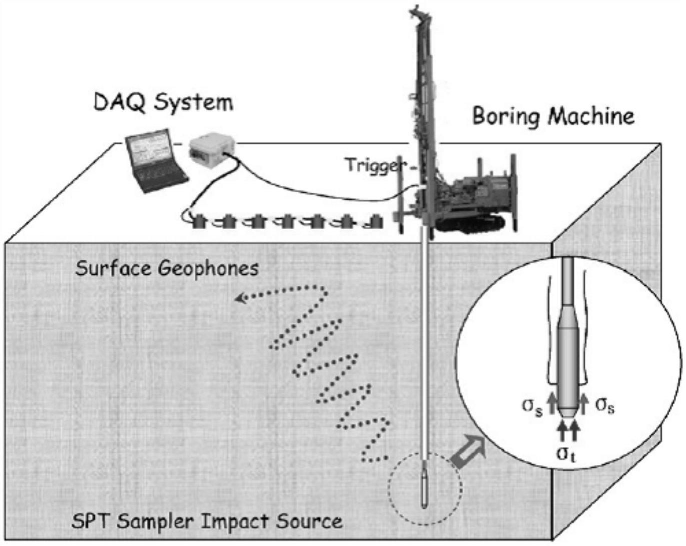


Fig.7. A schematic diagram of the SPT-based uphole method (After Bang and Kim, 2007)

The testing procedure can be briefly described as follows: the surface geophones are placed on the ground at the selected intervals from the boring point. A minimum of two receivers are required and the use of more than five receivers is recommended, as using more receivers provide better results. In the interpretation part, the site is assumed to be horizontally layered and the closer receivers should be preferred for accurate results. On the contrary, closer receivers can easily be affected by engine noise of the boring machine. Generally, the SPT is performed at intervals of 1 or 1.5m. After drilling to a given depth, an uphole method can be performed with the SPT simultaneously. It is advised to drop the hammer manually after turning off the engine in order to reduce the noise from the machine. In order to check the repeatability, signal traces should be obtained by hammering more than twice at each testing depth. Measuring the exact source depth is important, and the length from the tip of the split spoon sampler to the ground surface should be measured at each hammering and recording of the signals. After drilling to the next testing depth, these steps should be repeated until the final depth for the site investigation (Bang and Kim, 2007).

This method was applied during the boring operations to obtain shear wave velocity at the same time in 10 boreholes. 7 geophones were used during the application of this method with 2 m intervals. As it is recommended, two-component (radial, horizontal and vertical) geophones were preferred in order to obtain better travel time information. Two recordings were conducted during the application.

Comparison between measured and empirical V_s values

In this study, it is aimed to correlate measured shear wave velocities with SPT-N-based V_s from empirical formulas. G_{max} value was calculated with respect to these different approaches by using Equation 1 for sands. Then, calculated results were compared to G_{max} values retrieved from uphole-based shear wave velocities.

At the beginning, time delay measurements from all 7 geophones were considered. However, the measurements of closer geophones (geophones 1-2) which were placed on the ground surface with 2 and 4m distance to the boring machine revealed inappropriate results which mean these recordings were affected by the boring machine noise. The more distant geophones (4, 5, 6 and 7th) were most strongly affected by refraction-influenced path irregularities and gave higher values comparing the calculated empirical results. The third geophone gave closer results compared to the others. As a result, the most proper V_s value was achieved from the third geophone. Therefore, the interpretations of third geophone time measurements were taken into account for the comparisons. An example of the comparison that belongs to BH-23 was shown in Figure 8.

The results of measured V_s from SPT-based uphole test (3rd geophone) and the calculated ones for alluviual sands were illustrated with a linear relationship in Figure 9.

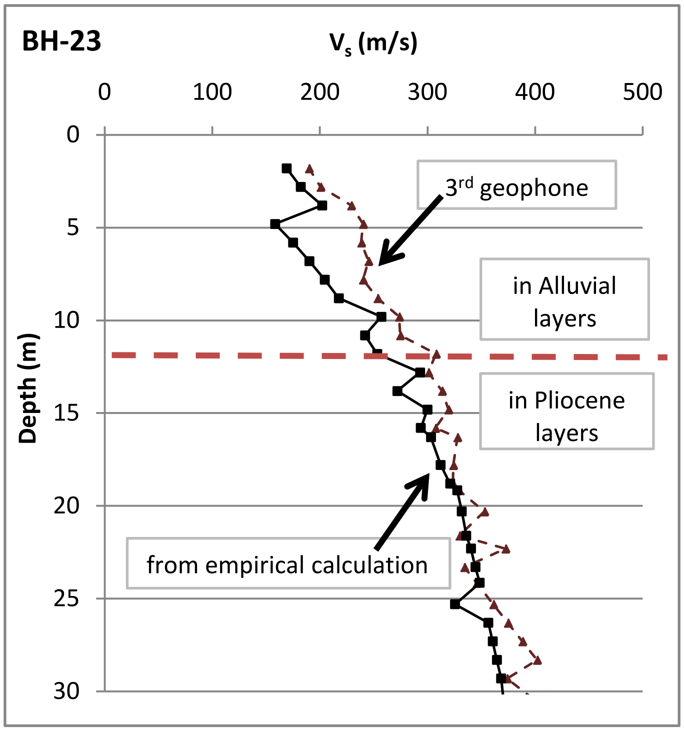


Fig.8. A comparison of measured and *empirical V_s values with depth*

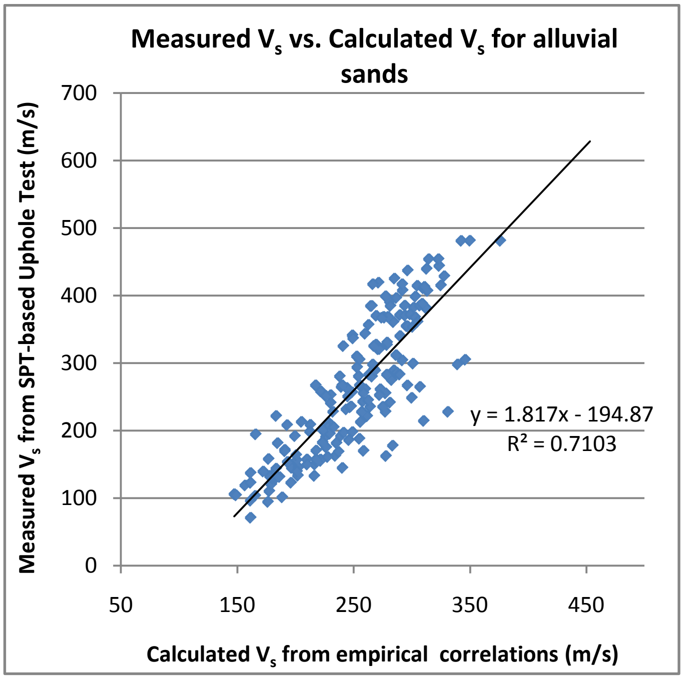


Fig.9. A comparison of the measured and *empirical V_s values for alluvial sands*

The comparison of the measured V_s from SPT-based uphole test (3rd geophone) and the calculated values for Pliocene sand layers were also given in Figure 10.

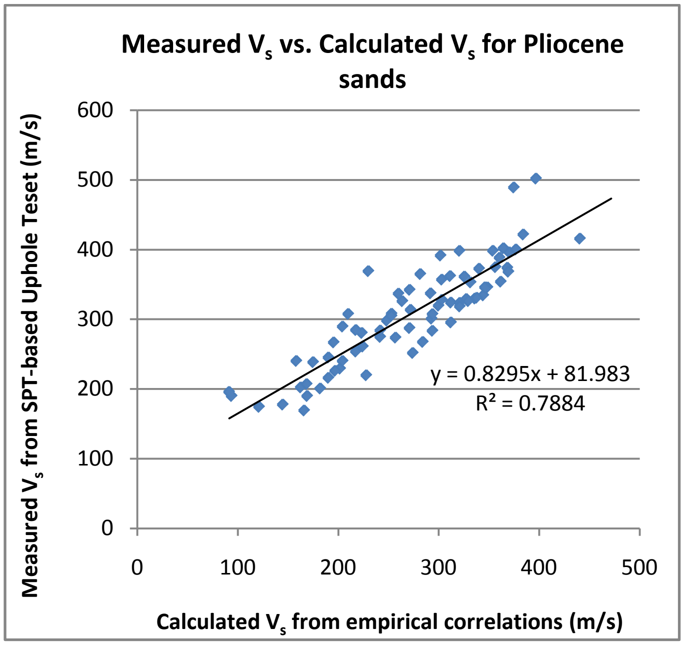


Fig.10. A comparison of the measured and empirical V_s values for Pliocene sands

Using this approach, all available SPT-based uphole boreholes (10 boreholes) were evaluated. As shown in Figure 8, some of the levels at different depths do not fit the measured V_s values in BH-23. Afterwards, the empirical calculations were re-performed depending on the correlation of G_{max}-V_s relationship, and site-specific version of Equation 2 (Ohta and Goto, 1976; *Seed et al.*, 1986) is proposed for the study area.

To develop a site-specific formula, a new α coefficient was defined for each layer instead of the value 20000 (Ohta and Goto, 1976; *Seed et al.*, 1986) for sandy layers.

$$G_{max} = \alpha \, (N_1)_{60}^{\ 0.333} (\sigma'_m)^{\ 0.5} \qquad (6)$$

Plots of the α coefficient with depth are shown in Figures 11 and 12 for different units. Although there is another depth-dependent coefficient in this equation (σ'_m), the exponent of σ'_m was left at 0.5 to be consistent with laboratory data for uncemented sandy soils. The variation of the new α coefficient with depth may reflect in-situ effects such as different cementation, grain-size distribution, overconsolidation, and/or site-specific conditions for different type of sandy soils. Therefore, this new depth-dependent coefficient may not be universally applicable.

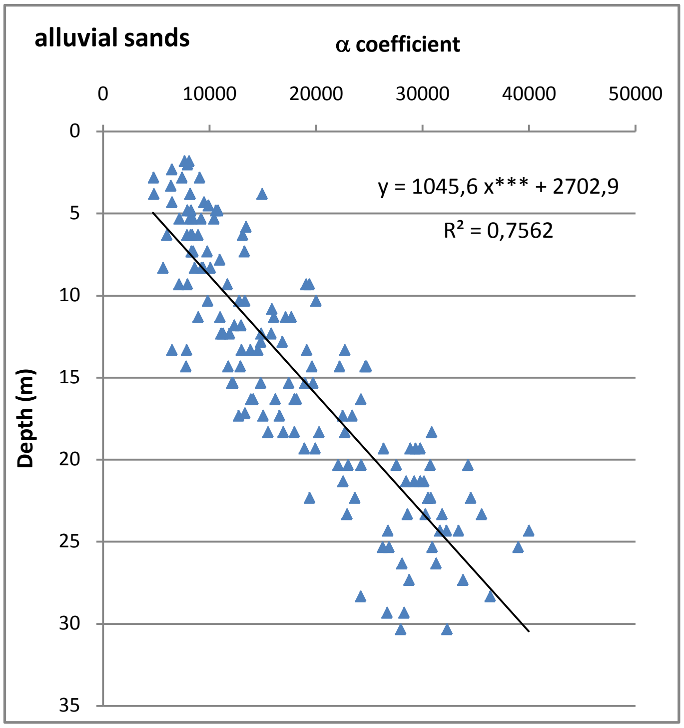


*Fig.11. The distribution of the new α coefficient for alluvial sands (*** x represents the depth value, y represents the α coefficient in the formula)*

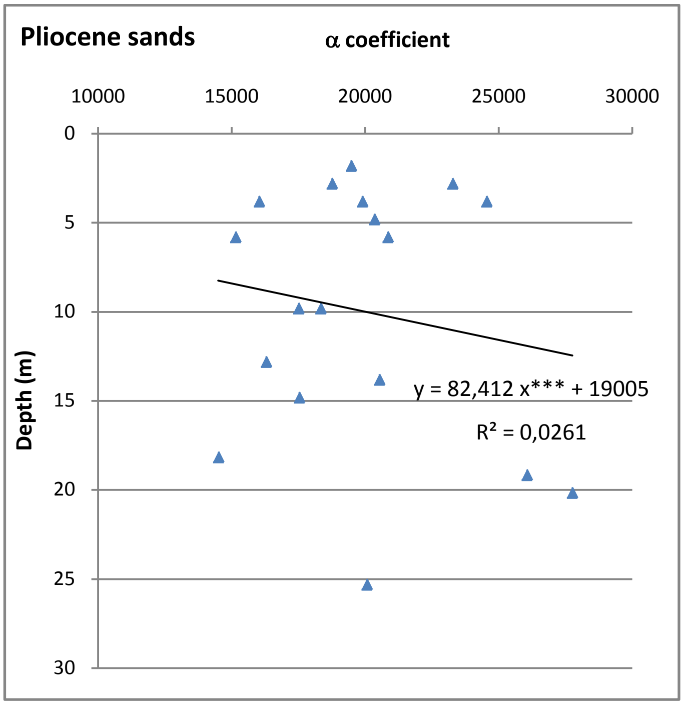


*Fig.12. The distribution of the new α coefficient for Pliocene sands (*** x represents the depth value, y represents the α coefficient in the formula)*

The new α coefficient is more applicable in the Erbaa alluvial sands, since it gave a reasonable relationship with depth. However, the results of the Pliocene layers only give limited support for a new α coefficient since it ranges from 14000 to 27000 with no apparent pattern with depth. This observation may be attributed to the fact that the Pliocene unit is semi-consolidated clay and silt dominant lithology with only a few sandy layers. Therefore, limited data are available for this unit. Furthermore, it should be noted that refusal SPT-N blow counts were mostly obtained in the Pliocene layers. Additionally, groundwater level is deeper in the Pliocene unit than the alluvial unit. These factors can be the cause of scattering of new α coefficient shown in Figure 12.

Moreover, these calculations were modified depending on the site-specific equation (Eq. 4) with a new α coefficient. BH-23 is given with updated calculations in Figure 13. The updated results reveal that the calculations are quite well-correlated with the measurements. As can be seen in Figure 13, the updated empirical calculations give similar results when it is compared with the measured shear wave velocities. The comparison was also made for different units including empirical calculations vs. measured V_s values after the new α coefficient (Figures 14 and 15). G_{max} values were re-calculated with respect to the new approach by using Equation 6. Then, calculated results were compared to G_{max} values retrieved from uphole-based shear wave velocities as done before (Figures 14 and 15).

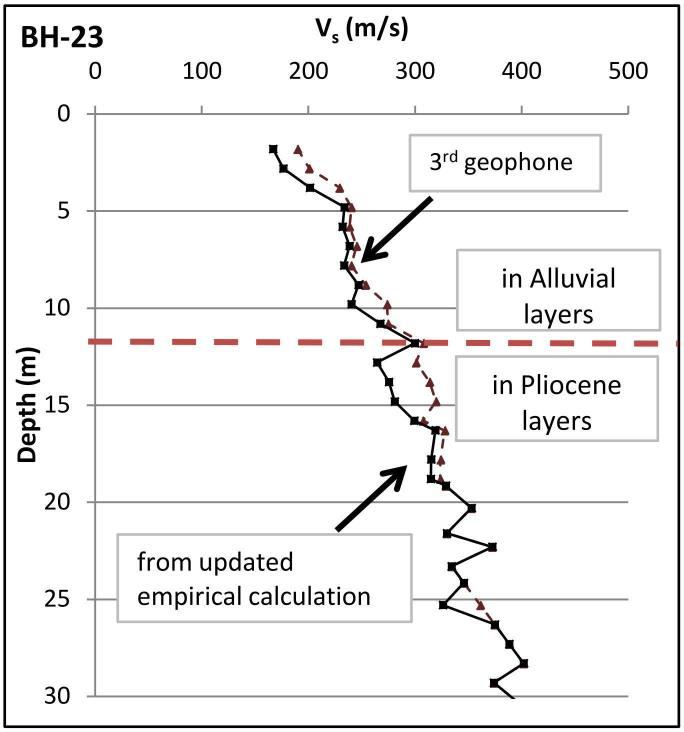


Fig.13. A comparison of measured and updated empirical V_s values with depth.

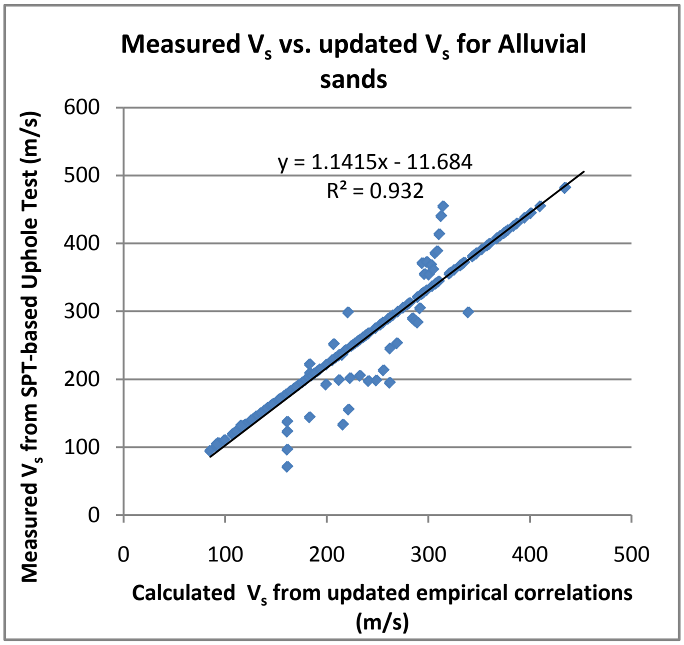


Fig.14. A comparison of the measured and updated empirical V_s for alluvial sands

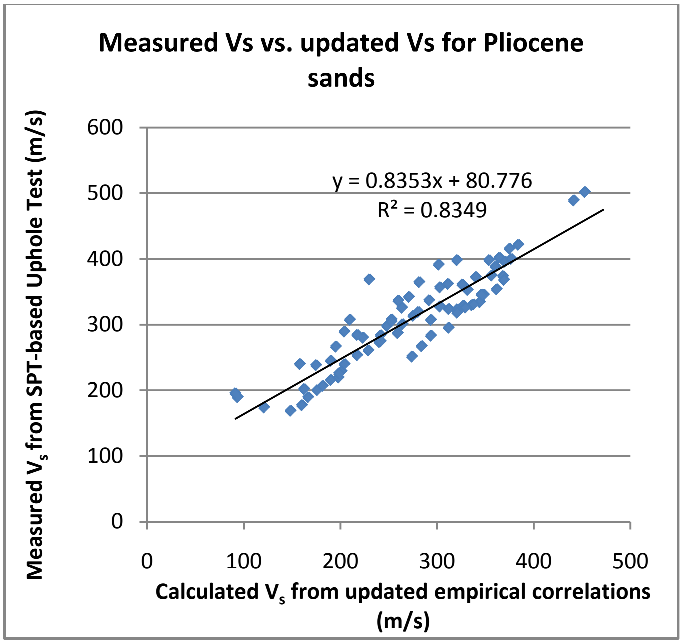


Fig.15. A comparison of the measured and updated empirical V_s for Pliocene sands

The modified, site-specific equation produced significantly better agreement with measured shear wave velocities at the Erbaa site. The agreement was particularly improved for the alluvial sands. As a final point, the measured shear wave velocity profiles can be considered for further site response analyses.

SUMMARY AND CONCLUSIONS

Shear wave velocity profiles of Erbaa were developed to perform site response analyses as a part of a microzonation study. The geological units observed in the study area consist of alluvial and Pliocene mostly clayey-sandy units. The layers were separately evaluated on the basis of the in-situ and laboratory tests, and field explorations.

A modified and a new form of the seismic uphole method which uses the impact energy of the split spoon sampler of SPT test as a source was applied in this study (SPT-based uphole method) to obtain shear wave velocity measurements. The measured SPT values were computed with different empirical formulas and compared with V_s measurements for the site-specific area.

These calculations were modified to fit the site-specific conditions by using a new, depth-dependent α coefficient. The new α coefficient was found to be more applicable in alluvial sands, since it confirms quite well correlation with depth. However, the results of the Pliocene layers only give a limited range for the new α coefficient due to high SPT-N resistance and the changes in the groundwater level in this unit.

The updated empirical calculations reveal that the measured shear wave velocity profiles can be considered for further site response analyses.

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