EMPIRICAL CORRELATION BETWEEN THE SHEAR-WAVE VELOCITY AND THE DYNAMIC PROBING HEAVY TEST: CASE STUDY, VARAŽDIN, CROATIA

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Keywords

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Abstract

Varaždin is located in the north-western part of Croatia in shallow quaternary alluvial sediments of the Drava River basin. Local site effects due to the alluvial soft sediments can play a crucial role in the amplification of seismic-wave ground motions. The shear-wave velocity (V_S) is one of the most important parameters for determining dynamic soil properties and ground-response analyses.

The seismic surface wave method (MASW) is the simplest and a very efficient way of measuring the shear-wave velocity in the field. The Dynamic Probing Heavy (DPH) test is suited to determining the soil strength and the soil deformation properties. However, there are a lack of correlations between the shear-wave velocity and the DPH tests (V_S - N_{DPH}) in the literature. In this paper we present empirical correlations between the shear-wave velocity V_S and the soil penetration resistance N_{DPH} with: a) raw (original) N_{DPH} data: $V_S = 97.839 \cdot N_{DPH}^{\ 0.395}$, ($R^2 = 0.723$); b) a groundwater correction N_{DPH} data: $V_S = 92.998 \cdot N_{DPH}^{\ 0.363}$ ($R^2 = 0.815$). From the measured DPH data, the shear-wave velocity (V_S), the shear modulus (Go) and the Young's modulus (Eo and Er) were estimated. Two different approaches (low vs. high strain) were compared, and the results were found to be in good agreement when the relative difference between the velocities is small and smooth.

Dynamic probing tests are good for studying a discrete point of interest in a large field area based on preliminary seismic tests. The suggested correlation V_S - N_{DPH} can be used for a rough estimation of V_S from N_{DPH} (they are site-specific, and so not applicable worldwide). In this way valuable information about dynamic soil properties can be extracted for ground-response analyses and the study of local site effects.

1 INTRODUCTION

The influence of local geological and soil conditions on the intensity of ground shaking and earthquake damage has been known for many years. Local site effects play an important role in earthquake-resistant design and must be accounted for case by case. Ground-response analyses are used to predict ground-surface motions for the development of design spectra, and to evaluate dynamic stresses and strains for the determination of earthquake-induced forces. For many important problems, particularly those dominated by wave-propagation effects, low-level strains are induced into the soil, but when concerned with the stability of masses of soil, large strains are induced in the soil [1, 2, 3].

There are many V_S - N_{SPT} correlations in the literature, as shown by Hanumantharao and Ramana [4], Marto, Soon and Kasim [5], Jafari et al. [6], Uma Maheswari et al. [7], Kuo et al. [8], Akin et al. [9] and Anbahzgan et al. [10]. However, there is a lack of information regarding the existence of correlations when taking a combined approach to the shear-wave velocity and Dynamic Probing Heavy tests (V_S - N_{DPH}). Iyisan [11] presented correlations between the shear-wave velocity and different in-situ probing tests (Standard Penetration Test - SPT, Dynamic Probe Heavy - DPH, Cone Penetration Test - CPT). In his research, he mentioned V_S - N_{DPH} correlations for all soils according to the empirical equation: V_S=86.4·$N_{DPH}^{0.367}$, with R^2=0.7. It was stated that such correlations, although developed for particular types of soil, could be applicable worldwide, but were actually found to be site-specific due to a number of factors pertaining to local soils (particle distribution, plasticity, soil texture, etc.) and thus should be used with caution. Given V_S - N_{DPH} correlations should not be thought of as a substitute for seismic (geophysical) measurements, they can be useful for verifying the measured values of the shear-wave velocity V_S or in supplementing seismic (geophysical) testing due to some impossibilities (space constraints, structure of terrain, environmental noise, etc.).

In this paper we present statistical empirical correlations between the shear-wave velocity V_S (geophysical seismic surface MASW method at low strains γ_S~10^{-6}, Fig. 1) and the soil penetration resistance N_{DPH} (Dynamic Probing Heavy test DPH at high strains γ_S~10^{-1}, Fig. 1), in shallow quaternary alluvial sediments for a local geological site-specific case study at four locations in Varaždin using the power-law relation:

$$V_S = A \cdot N_{DPH}^{B} \qquad (1)$$

From measured DPH data, the shear-wave velocity (V_S), the shear modulus (G_{MAX} or Go) and the Young's modulus (Eo and Er) were estimated.

The main aim of this paper is not to give an empirical correlation between V_S - N_{DPH} as a substitute for seismic measurements, but to show a reliable way of comparing two different experimental approaches at low strain vs. high strain for the determination of site-specific dynamic soil properties. The suggested correlation between V_S and N_{DPH} can be used to make rough estimates of V_S from N_{DPH} (they are site-specific, and so not applicable worldwide), particularly for preliminary studies and/or non-critical projects that are under consideration.

2 DYNAMIC SOIL PROPERTIES

A medium is said to be elastic if it possesses a natural state (strains and stresses are at zero) to which it will revert to when applied forces are removed. Under the influence of applied loads, the stress and strain will change together, and the relation between them, known as the constitutive relation, is an important characteristic of the medium [13].

A determination of the dynamic soil properties is a critical task in any solution of geotechnical earthquake-engineering problems. The selection of testing techniques for the measurement of dynamic soil properties requires a careful consideration and understanding of the specific

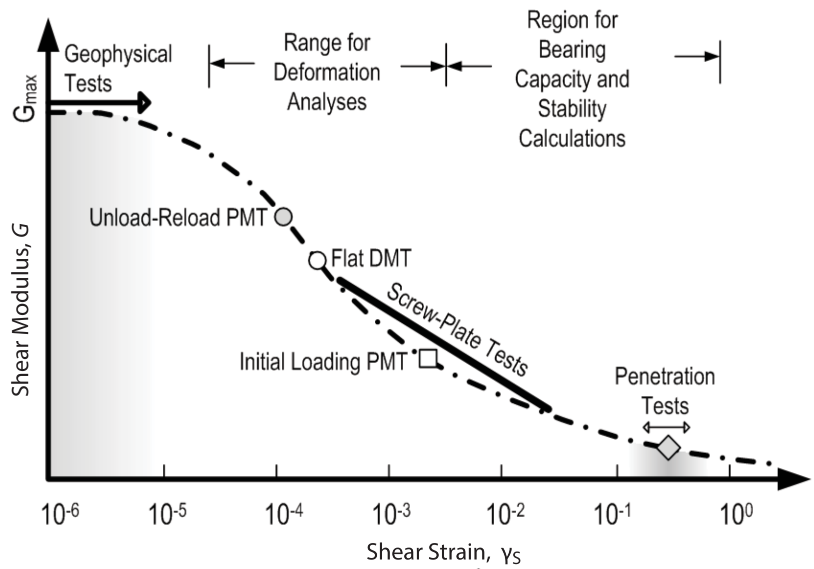

Figure 1. The starting point of the stress-strain curve (at low strain γ_S~10^{-6}) can be accurately established from seismic tests and its end point (at high strain γ_S~10^{-1}) by dynamic tests [12].

problem at hand. Low strain tests generally operate at strain levels that are not large enough to induce significant nonlinear stress-strain behaviour in the soil (below $\gamma_S<10^{-3}$) and are based on the theory of wave propagation in the material. High-strain tests are used to measure the high-strain characteristics of soils (elastoplastic behavior), such as soil strength and soil deformation during irrecoverable deformations in the soil [1].

The dynamic modulus is the ratio of stress to strain under vibratory conditions (calculated from data obtained from either free- or forced-vibration tests, in shear, compression or elongation), the so-called low-strain modulus. The shear modulus describes the material's response to shear stress. Most seismic geophysical tests induce low shear strains and the measured shear-wave velocity V_S can be used to compute the maximum dynamic shear modulus or stiffness of the soil G_{MAX} or Go with a knowledge of the soil density ρ [1, 13, 14, 15]:

$$Go = \rho \cdot V_S^2 \qquad (2)$$

The soil density ρ can be evaluated from the measured shear-wave velocity V_S and the depth h [12]:

$$\rho = 0.85 \cdot \log(V_S) - 0.16 \cdot \log(h) \qquad (3)$$

A small strain shear modulus is the key benchmark and establishes the highest, achievable soil stiffness that other moduli can be compared to on a relative basis.

The Young's modulus Eo describes the material's response to linear stress. Its relation to the shear modulus Go is defined as:

$$Eo = 2 \cdot Go(1+\upsilon) \qquad (4)$$

where υ is the Poisson's coefficient.

With Go and Eo being operable at non-destructive small strains and a shear strength τ_{MAX} at failure strains, it is possible to relate small - high strain modulus (two opposite ends of the strain spectrum). For monotonic static loading a modified degradation hyperbola (Fig. 1) relates the normalized shear modulus G/Go and the normalized Young's modulus E/Eo to the mobilized shear stress τ/τ_{MAX} in the form [12]:

$$G/Go = 1 - f\left(\tau/\tau_{MAX}\right)^q \qquad (5)$$

or for the Young's modulus:

$$E/Eo = 1 - f\left(\tau/\tau_{MAX}\right)^q \qquad (6)$$

where f and q are empirical parameters controlling the rate of modulus decay (Fig. 1). For practical problems, the mobilized shear stress can be considered as the reciprocal of FS (factor of safety). Burns and Mayne [16] found that $f = 1$ and $q = 0.3$ provide reasonable first-guess values for the degradation parameters in non-structured and non-cemented soils. The Young's modulus E in Eq.6 is used in deformation analyses as a reference modulus of elasticity ($E = Er$) because it is directly dependent on the implemented stress and failure stress.

The shear-wave velocity V_S is one of the most important parameters for the determination of the dynamic soil properties and ground-response analyses. Seismic geophysical methods are effective in preliminary field tests since they can cover large volumes of soil at low strains. To induce soil deformation similar to that induced by an earthquake, dynamic probing tests are suited to studying a discrete point of interest in a large field area based on preliminary seismic tests. In this way very useful information about dynamic soil properties can be extracted for further ground-response analyses and the study of local site effects.

The measured dynamic soil properties (V_S, Go, Eo, Er) can be used for the seismic design of structures based on Eurocode 8 - EC8 [17, 18, 19], site response studies [2] and settlement analyses. In a liquefaction assessment, V_S is also widely used [1].

3 FIELD MEASUREMENTS

Field measurements were carried out at four test locations in and nearby Varaždin (Fig. 2, marked with a black circle). The geophysical seismic surface method MASW (Multichannel Analysis of Surface Waves) was used to obtain the shear-wave velocity (V_S) and in-situ dynamic probing tests DPH (Dynamic Probe Heavy) were used to obtain the penetration resistance of the soil (N_{DPH}).

3.1 Geological setting

Varaždin is a baroque city located in the NW part of Croatia in shallow quaternary alluvial sediments of the Drava River basin. In this seismic zone there have been a couple of strong earthquakes in the past. The archives mention a strong earthquake in 1459, with its epicentre near Varaždin ($I_0 = IX^o$ *MCS*). The largest earthquake in modern times occurred in 1982 beneath the Ivančica Mt. ($M_L = 4.7$, $I_0 = VII^o$ *MCS*), and there were also a number of smaller-intensity events in the past according to [20].

The geological characteristics of the Varaždin area are quaternary alluvial soft sediments of the Drava river basin (Fig. 2). It was formed during the Pleistocene and

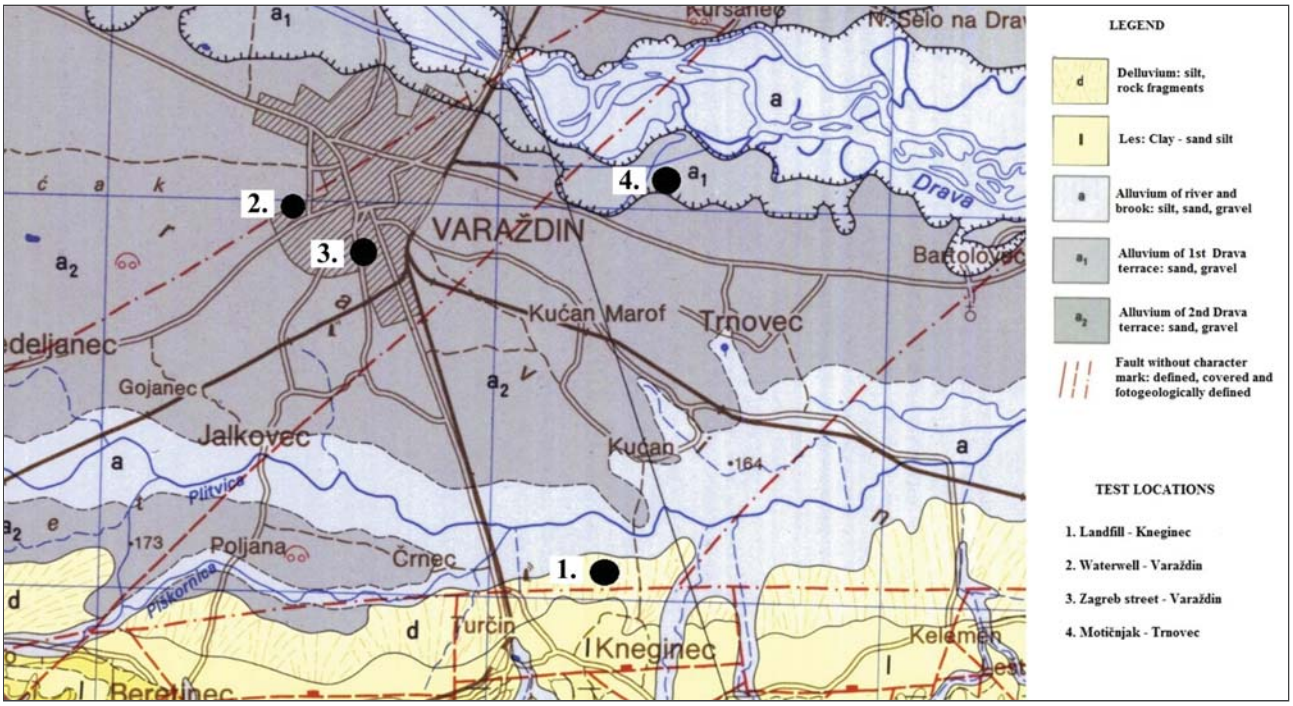

Figure 2. Geology (Quaternary: Pleistocene and Holocene) of Varaždin region at four test locations (1. Landfill - Kneginec, 2. Water well - Varaždin, 3. Zagreb street - Varaždin, 4. Biogas facility Motičnjak - Trnovec)[21].

Holocene as a result of the accumulation processes of the Drava river, as mentioned by Prelogović [21]. It is composed of gravel and sand with variable portions of silt and clay [22, 23, 24]. The thickness of the sand-gravel deposits in the NW area are less than 5 metres, gradually increasing in the downstream direction (WE) to reach more than 60 metres thick in the eastern part. The water table is relatively high at 2–6 m. The general ground-water flow direction is NW–SE and is parallel to the Drava river. The basin is cut by several faults in an SW direction towards the Ivančica Mt. and a WE direction parallel to the Drava River.

3.2 Multichannel analysis of surface waves

Spectral Analysis of Surface Waves (SASW) was introduced in the early 1980s by Nazarian and Stokoe [25, 26, 27] to make use of the spectral analysis of surface waves generated from an impact source like a hammer on a surface. It is used for shallow, shear-wave velocity characterization in which only two receivers (geophone) are used and the spacing between the receiver and the source is changed many times to cover the desired range of the investigation depth. Since this repetition takes several hours, the Multichannel Analysis of Surface Waves by Park et al. [28] and Xia et al. [29] was introduced.

The Multichannel Analysis of Surface Waves (MASW) is a non-destructive seismic method used to evaluate the material layer thickness, the shear-wave velocity V_S (1D or 2D profile with depth), the Poisson's ratio and the soil density [28, 29, 30, 31, 32, 33, 34]. This method is fast and simple because of the strong nature of the surface wave (Rayleigh waves) energy that can be generated by a simple impact source (e.g., a sledgehammer) and the entire range of the investigation depth can be covered with multiple receivers (geophones) without the need to change the receiver's configuration [28, 29, 30, 31, 32, 33, 34]. A schematic diagram of an active MASW field survey is shown in Fig. 3. The MASW profile consist of 24 geophones with a natural frequency of 4.5 Hz in a linear array (69 m spread length, 3 m spacing and 6 m offset), a sledgehammer of 10 kg, a hammer metal plate, and a 24-channel Geode seismograph with supporting software for the data acquisition. The maximum investigation depth (z_{max}) depends on the length of the geophone spread (D) and the source impact energy, while the resolution depends on the minimum geophone spacing (dx).

The data analysis of the captured surface waves (Rayleigh waves) created by the sledgehammer impact on the metal plate was analysed using SeisImager (OYO Corp.) and SurfSeis (Kansas Geological Survey) software packages to obtain a 1D and 2D shear-wave velocity profile with depth. The data analysis consisted of three

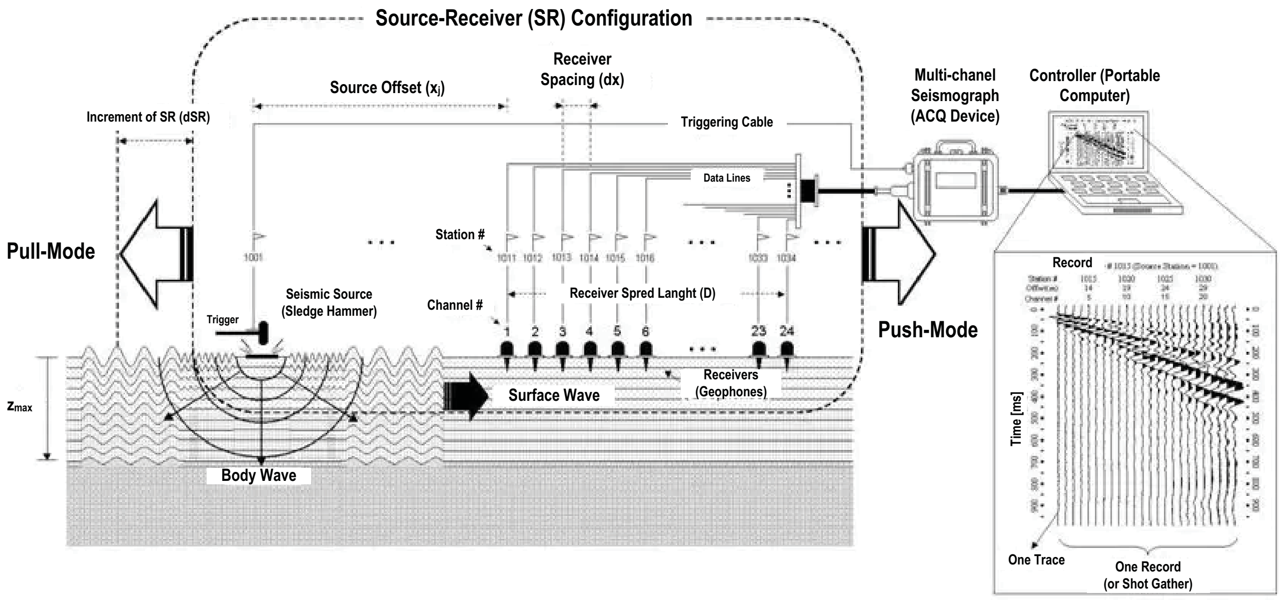

Figure 3. Schematic diagram of active MASW field survey data acquisition [34].

steps: 1) preparation of a MASW record (field file or shot gather), 2) dispersion analysis of Rayleigh waves - fundamental mode and 3) inversion for V_S profiles [28, 29, 30, 31, 32, 33, 34].

The 1D soil profiles for all the test locations obtained from the MASW are shown in Fig. 4., and the 2D profiles are shown in Fig. 5 for the test locations 2.Water well - Varaždin and 4. Motičnjak - Trnovec. The top first layer in all four locations consists of clay having a V_S range of 110–170 m/s from 0 up to 4 m in depth. The second layer consists of sand having a V_S range of 190–260 m/s from 0 up to 9 m depth. The third layer consists of gravel having a V_S range of 270–400 m/s from 5 up to 20 m and above depth. The maximum investigation depth was cut to 20 m for the V_S - N_{DPH} correlation analysis.

Based on the EC8 classification of subsoil classes according to Table 3.1 [17, 18, 19] all the investigated area can be classified as ground type C ($V_{S,30}$ = 180-360 m/s) (Fig. 4).

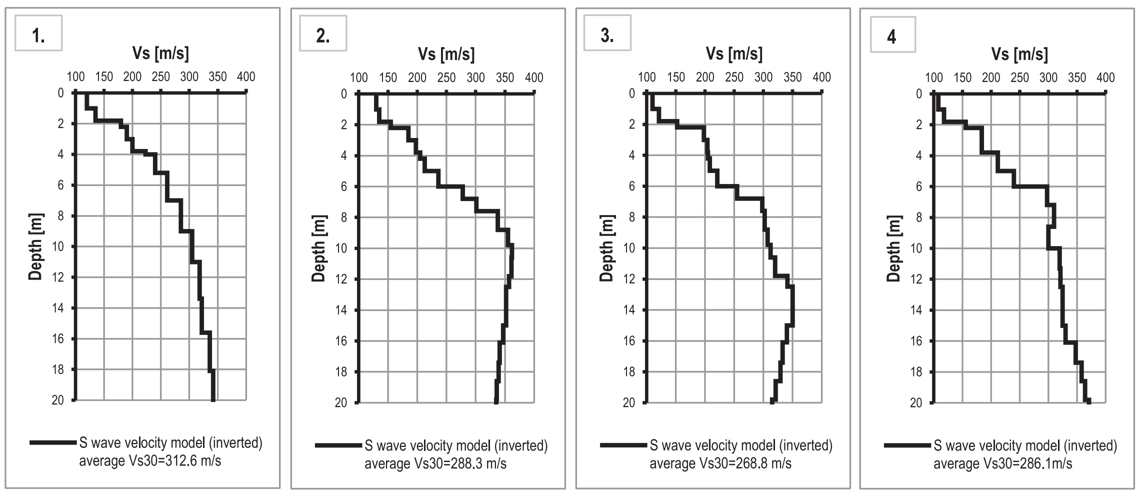

Figure 4. 1D V_S profile vs. depth. Location: 1) Landfill - Kneginec, 2) Water well - Varaždin, 3) Zagreb street - Varaždin, 4) Motičnjak - Trnovec.

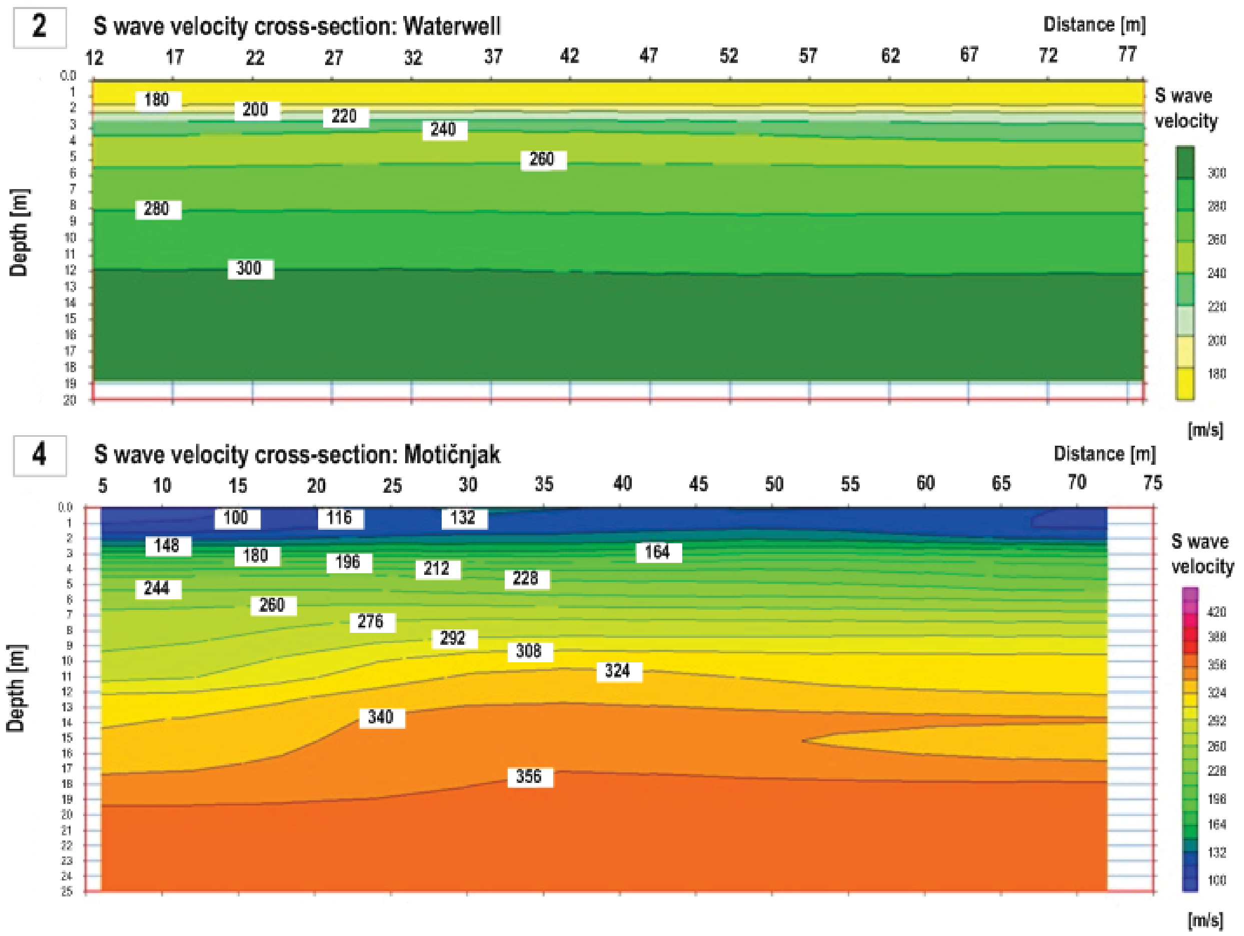

Figure 5. 2D V_S profile vs. depth. Location: 2) Water well - Varaždin, 4) Motičnjak - Trnovec.

3.3 Dynamic probing heavy (DPH) test

The purpose of an in-situ dynamic probing test is to determine the resistance of soils and semi-rocks in-situ via the dynamic penetration of a cone in order to characterize the soil layers by their depth, position, nature, density or thickness [35, 36]. It can be used to determine the strength and deformation properties of soils or to distinguish non-cohesive soils from cohesive soils [37]. In our study we used one type of dynamic penetrometer, Dynamic Probe Heavy (DPH - Fig. 6), which is more economically efficient and faster than SPT (borehole is needed), in line with EN ISO 22476 - 2 [38] and the European German DIN 4094 - 2 standards [39].

DPH is performed so that the cone (base area of cone point 20 cm^2) is driven into the soil (no borehole needed) by free-fall hammer strokes with a specified mass (50 kg) and height of the drop (50 cm). The numbers of strokes required for a 100-mm penetration of the cone N_{DPH} are recorded.

The penetration resistance is defined as the number of strokes N_{DPH} per 100 mm of penetration. A continuous record is collected in accordance with the length of sinking (depth). The test does not allow for soil sampling. The results from the DPH test are presented as the number of strokes N_{DPH} against the depth from the direct field record and are in the range of standardized values (usually 3 up to 50) (see Fig. 7). The "harsh" spikes that appear occur when encountering obstructions such as a boulder or very hard, dense soil. When the test is carried out in granular soils below the water table, the soil may become loosened, and the number of strokes N_{DPH} can decrease. Groundwater influence (loosening) on the number of strokes N_{DPH} is significant, and corrections have to be made according to EN ISO22476 - 2 and DIN 4094 - 3 [38, 39].

A groundwater-level correction was made for sand: $N_{DPH}{}^{CORR} = 1.3 \cdot N_{DPH}{}^{ORIG} + 2$ and for gravel: $N_{DPH}{}^{CORR} = 1.2 \cdot N_{DPH}{}^{ORIG} + 4.5$ [40, 41, 42], but was not necessary for clay, which was above the groundwater level. Remov-

Figure 6. Geotool dynamic probing rig (Dynamic Sampling Ltd, UK). The rig is capable of dynamic probing (DPL-light, DPM-medium, DPH-heavy and DPSH-super heavy) in accordance with DIN 4094. Specification: Width 78 cm, Length 78.5 cm, Height 23.4 cm, Drop Height 50 cm, Rod/Tool Length 120 cm (max) and Basic Weight 125 kg. Reference penetration every 100 mm. Base area of cone 20 cm^2. Cone diameter 43.7 mm. Rods diameter 32 mm. Hammer mass 50 kg. Drop height 50 cm. Angle of the cone point 90º. Torque wrench for impact of rod skin friction.

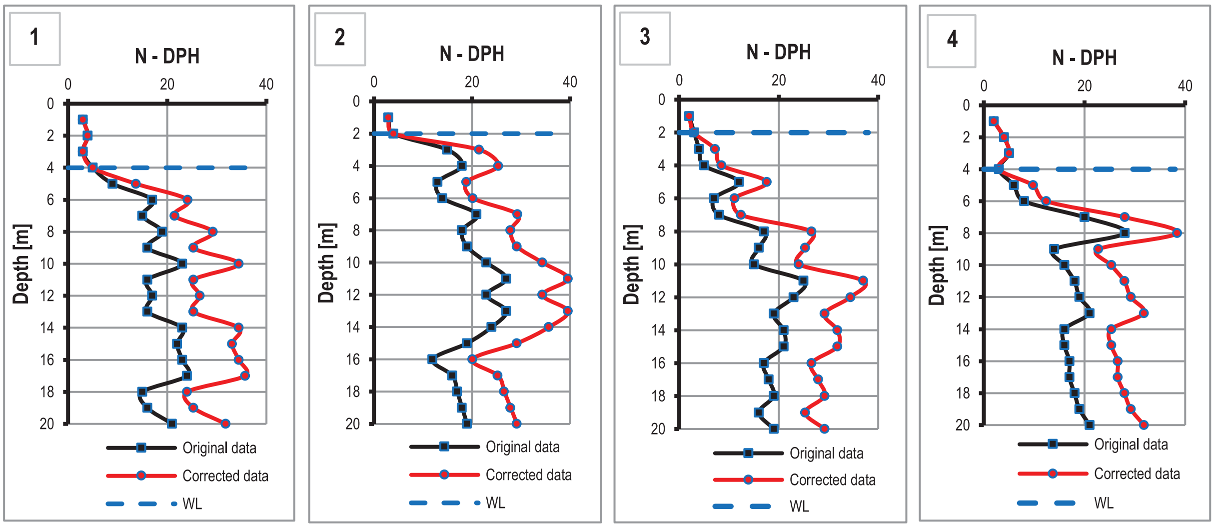

Figure 7. N_{DPH} profile vs. depth.Location: 1) Landfill - Kneginec, 2) Water well - Varaždin, 3) Zagreb street - Varaždin, 4) Motičnjak - Trnovec (depth to 15 m). WL - water level mark.

ing the effect of water increases the number of recorded strokes (Fig. 7). Fig. 7 shows how the numbers of strokes N_{DPH} are changing with depth. The top first layer is clay with a N_{DPH} range from 1 to 5 (without groundwater correction), the second layer sand with N_{DPH} range from 4 to 25 (corrected 7–38), while the third layer is classified as gravel with N_{DPH} from 12 to 27 (corrected 20–40).

4. EMPIRICAL CORRELATION BETWEEN THE SHEAR-WAVE VELOCITY AND THE DYNAMIC PROBING HEAVY TEST

In this section we present an empirical correlation between the shear-wave velocity V_S and the dynamic probing test DPH in shallow quaternary alluvial sediments for a local geological site-specific case study at four locations in Varaždin using the power law given by Eq. 1.

From the V_S and N_{DPH} profiles we extracted good data for the statistical correlations with depth. The following example (location 3 - Zagreb street) of the measured data shown in Fig. 4 and 7 depicts the development of the V_S - N_{DPH} empirical correlations. Example: for a depth of 10 m, the measured shear-wave velocity is V_S = 320 m/s and the number of blows N_{DPH} = 17 are taken as a mean value between depths of 9–10 m. Since at this depth the soil is classified as gravel below the water table, we performed a groundwater-level correction:

${N_{DPH}}^{CORR} = 1.2 \cdot {N_{DPH}}^{ORIG} + 4.5 = 25$. In this way we extracted more than 200 points from all the measurements at all four locations with two different field methods (MASW and DPH).

In Fig. 8 empirical V_S - N_{DPH} correlations shown for a particular test location are presented. V_S - N_{DPH} correlations for the original (black) and corrected (red) N_{DPH} data are shown on all four graphs. It is evident that the data correction due to the groundwater effect on N_{DPH} causes the curve to shift down on the V_S axis (red vs. black) and that in all four cases R^2 (determination coefficient) is higher than in the original N_{DPH} data.

The V_S - N_{DPH} correlation is statistically better for a groundwater-level correction on N_{DPH}. It can also be seen that R^2 is above 0.85 at two locations, i.e., 1. Landfill and 3. Zagreb street, irrespective of the groundwater correction (WL = 4 m and 2 m of depth). For the other two locations, i.e., 2. Water well and 4. Motičnjak, R^2 is comparatively low and shows a significant change from the groundwater correction. Since all the field measurements were performed in shallow quaternary alluvial sediments, the main aim of this study is to propose a site-specific V_S - N_{DPH} correlation, rather than more general correlations. Fig. 9 presents empirical V_S - N_{DPH} correlations for the site-specific region of Varaždin compared to a few previously published empirical V_S – N_{SPT} correlations for all soils [5]:

Original N_{DPH}: $V_S = 97.839 \cdot {N_{DPH}}^{0.395}$; $R^2 = 0.723$

Corrected N_{DPH}: $V_S = 92.998 \cdot {N_{DPH}}^{0.363}$; $R^2 = 0.815$.

5 DISCUSSION

From the empirical V_S - N_{DPH} correlation (Fig. 9) it can be seen how corrections for the groundwater effect on DPH measurements can "enhance" the correlation (R^2 is higher).

But, to see real meaning in this correction, we compared the MASW measured $V_{S,meas}$ with the estimated $V_{S,orig}$ and $V_{S,corr}$ from the original ${N_{DPH}}^{ORIG}$ and the corrected ${N_{DPH}}^{CORR}$ data (Fig. 10). There is a small difference between the MASW measured $V_{S,meas}$ and the estimated $V_{S,orig}$ and $V_{S,corr}$ from the V_S - N_{DPH} correlation. The residuals are from 0 to 50 m/s, and this difference falls

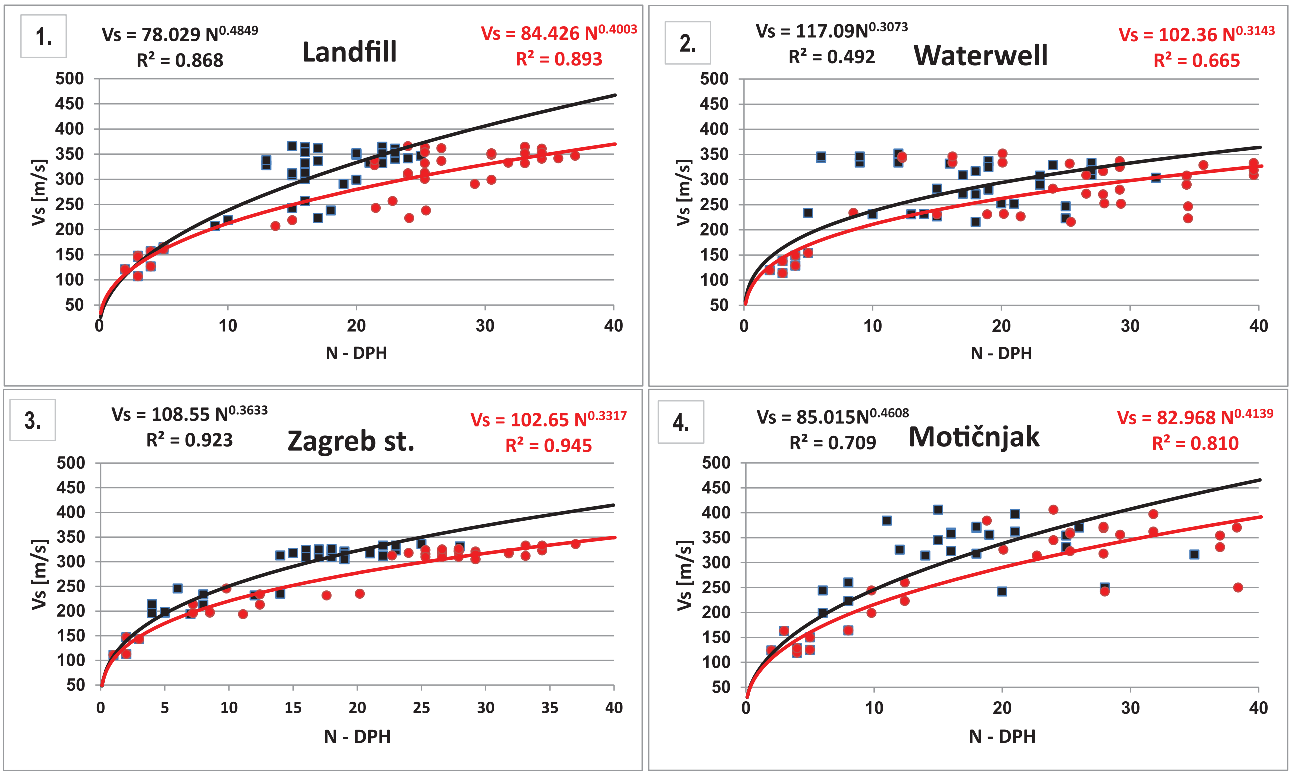

Figure 8. V_S - N_{DPH} correlations by test location: 1) Landfill - Kneginec, 2) Water well - Varaždin, 3) Zagreb Street - Varaždin, 4) Motičnjak - Trnovec. Black - original N_{DPH} data. Red - corrected N_{DPH} data.

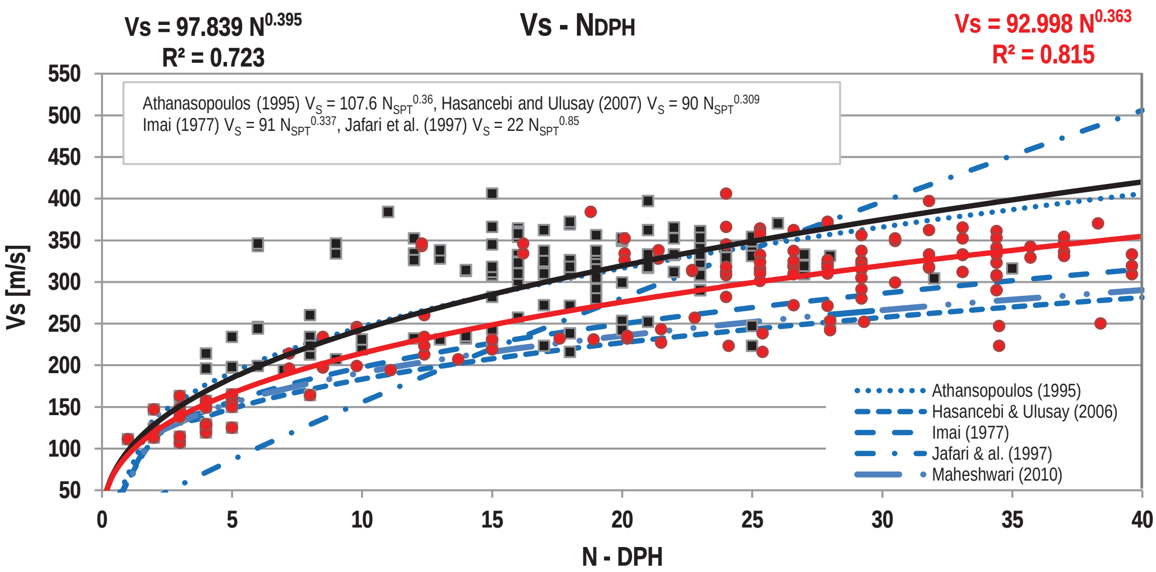

Figure 9. V_S - N_{DPH} correlations for site-specific region of Varaždin (all locations, all soils; black line: original N_{DPH}, red line: corrected N_{DPH}). Also presented are a few previously published V_S - N_{SPT} correlations for all soils [5]: blue dotted and dashed lines).

within statistical error bounds and so the given results can be used as a rough estimation of V_S from N_{DPH}. A groundwater-level correction is a good way to "statistically enhance" an empirical correlation, but as seen in Fig. 10 there is a very small difference between the $V_{S,orig}$ estimated from N_{DPH}^{ORIG} and the $V_{S,corr}$ estimated from N_{DPH}^{CORR}. Both empirical correlations are sufficient for a rough estimation of V_S from N_{DPH} and the groundwater-level correction can be applied to lower the statistical error, but the correlation with raw (original) data can also be effective in estimating V_S from N_{DPH}.

From the field measurements and empirical correlations, the shear-wave velocity V_S was estimated and dynamic elastic moduli (*Go*, *Eo* and *Er*) based on that velocity were calculated, Fig. 11, 12, 13. In the calculation of the shear modulus *Go* (Eq. 2), the Young's modulus *Eo* (Eq. 4) and the reference Young's modulus *Er* (Eq. 6), the

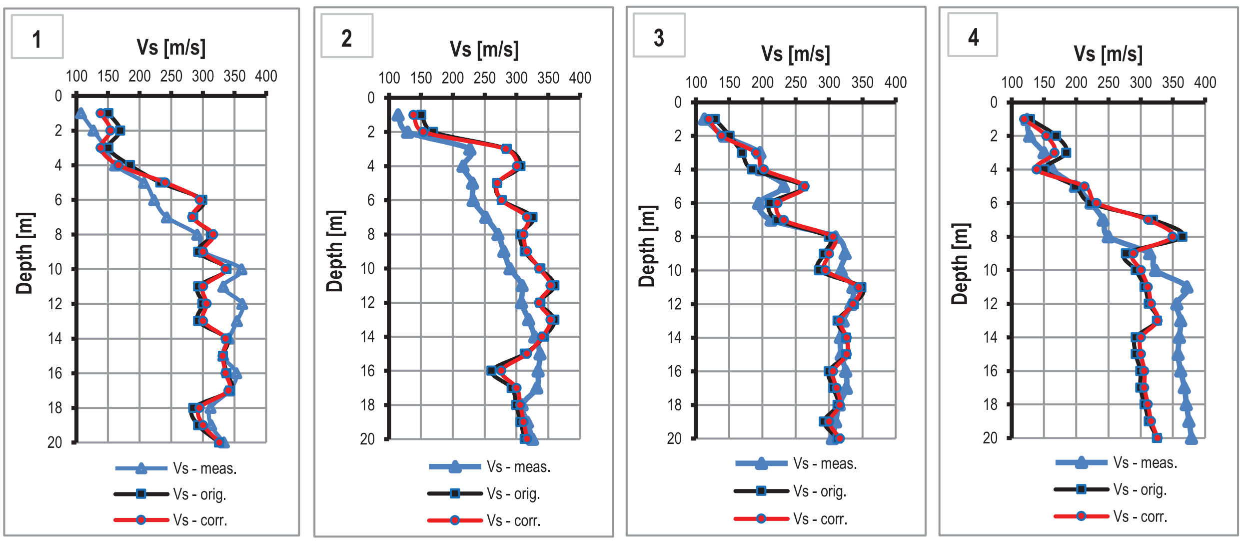

Figure 10. Comparison between measured V_S (blue: $V_{S,meas}$), V_S estimated from N_{DPH}^{ORIG} (black: $V_{S,orig}$) and V_S estimated from N_{DPH}^{CORR} (red: $V_{S,corr}$).

soil density was evaluated using Eq. 3, while Poisson's ratio with values of $\upsilon = 0.20$ and $\upsilon = 0.45$ for dry and soil under the water table was used. From Fig. 11, 12 and 13 the shear modulus *Go* varies from 20 MPa (MN/m^2) to 292 MPa, the Young's modulus *Eo* varies from 49 MPa to 846 MPa, and reference Young's modulus *Er* varies from 9 MPa to 158 MPa for the Varaždin region.

The estimated elastic moduli *Go*, *Eo* and *Er* were cross-checked at low (MASW) and high (DPH) strains and they made a good match (especially for test location 3. Zagreb street). High deviated results (test locations 1. Landfill, 2. Water well and 4. Motičnjak) can be explained by a number of factors pertaining to local soils, such as the particle distribution, plasticity, soil texture, loose soil, sticking cone into the boulder, etc., and thus the V_S - N_{DPH} correlation should be used with caution.

Two different approaches (low vs. high strain) were compared, and the results found to be in good agree-

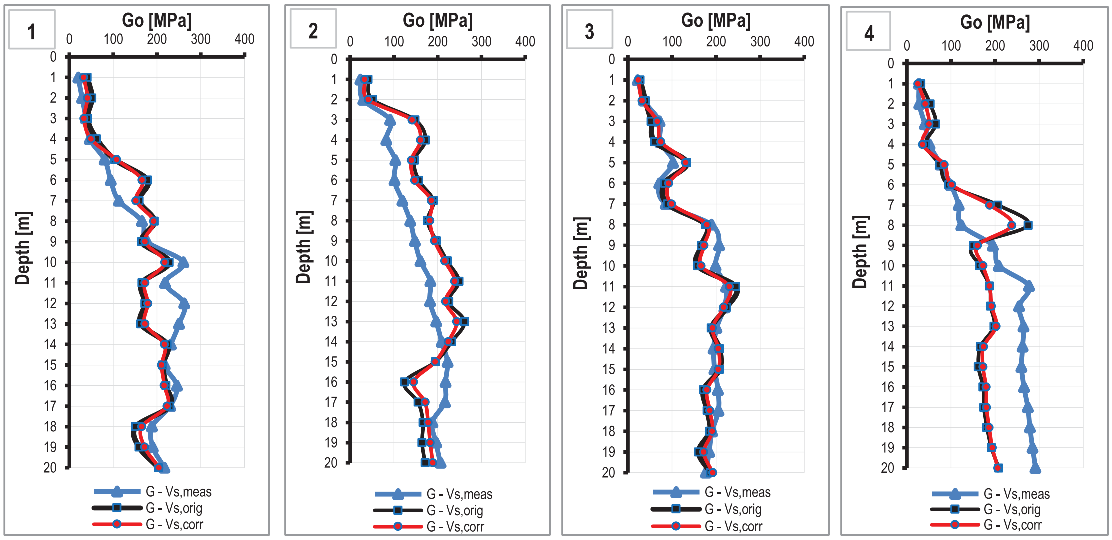

Figure 11. Shear modulus *Go* (low strain) calculated from measured V_S (blue: $V_{S,meas}$), V_S estimated from N_{DPH}^{ORIG} (black: $V_{S,orig}$) and V_S estimated from N_{DPH}^{CORR} (red: $V_{S,corr}$).

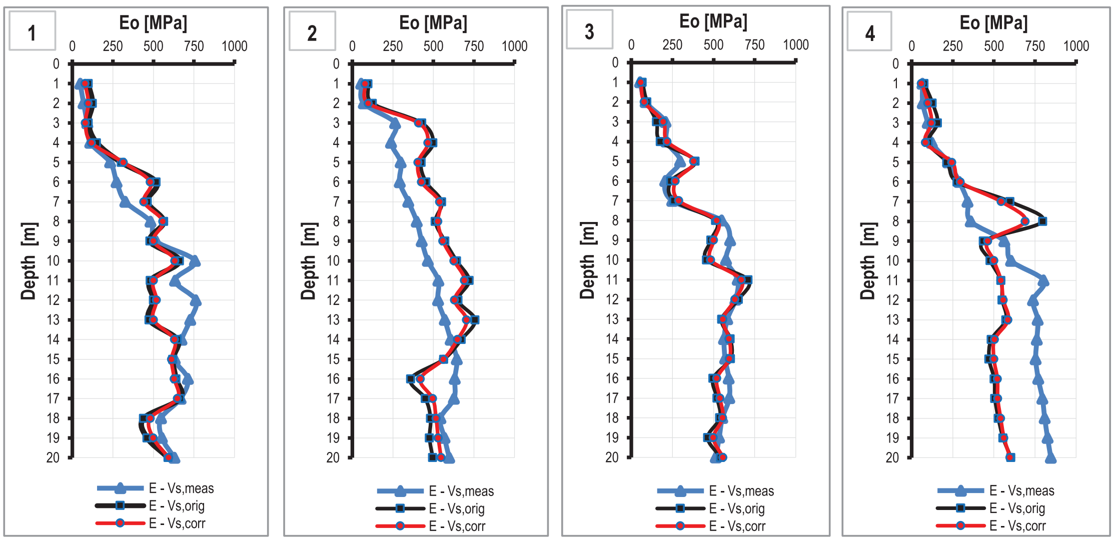

Figure 12. Young's modulus *Eo* (low strain) calculated from measured V_S (blue: $V_{S,meas}$), V_S estimated from N_{DPH}^{ORIG} (black: $V_{S,orig}$) and V_S estimated from N_{DPH}^{CORR} (red: $V_{S,corr}$).

ment when the relative difference between the velocities is small and smooth, Fig 14.

The relative difference of velocities (RD(o/m) or RD(c/m)) is defined as the ratio of the absolute difference between the measured and estimated velocity and the measured velocity for some depth:

$$RD = \frac{abs\left(1 - V_{S,estimated}\right)}{V_{S,measured}} \qquad (7)$$

One can find that the local extremes of the RD curves, Fig. 14, match the local extremes of the *N - DPH* curves, Fig. 7. Moreover, if the relative difference of the velocities is small and the curve is smooth, Fig. 14 location 3, then the local RD maximum indicates a local *N - DPH* minimum, and vice versa. When there is a significant spike in the *N - DPH* data we can expect a significant dispersion of the V_S - N_{DPH} data, Fig. 14 location 4.

Regardless of the field measurements, at low (MASW) or high (DPH) strains, it is necessary to evaluate the

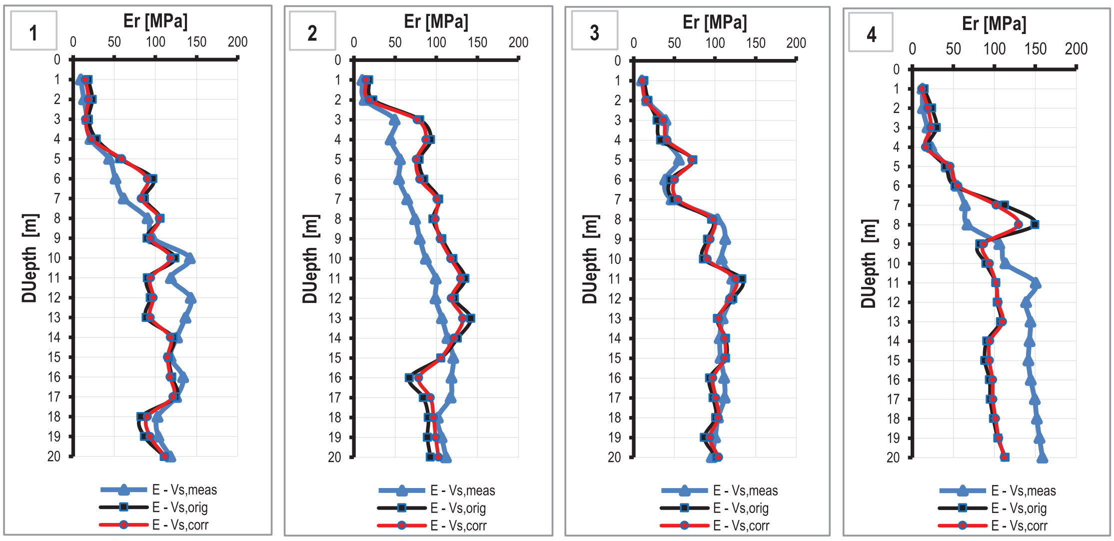

Figure 13. Young's modulus *Er* (high strain) calculated from measured V_S (blue), V_S estimated from $N_{DPH}{}^{ORIG}$ (black) and V_S estimated from $N_{DPH}{}^{CORR}$ (red).

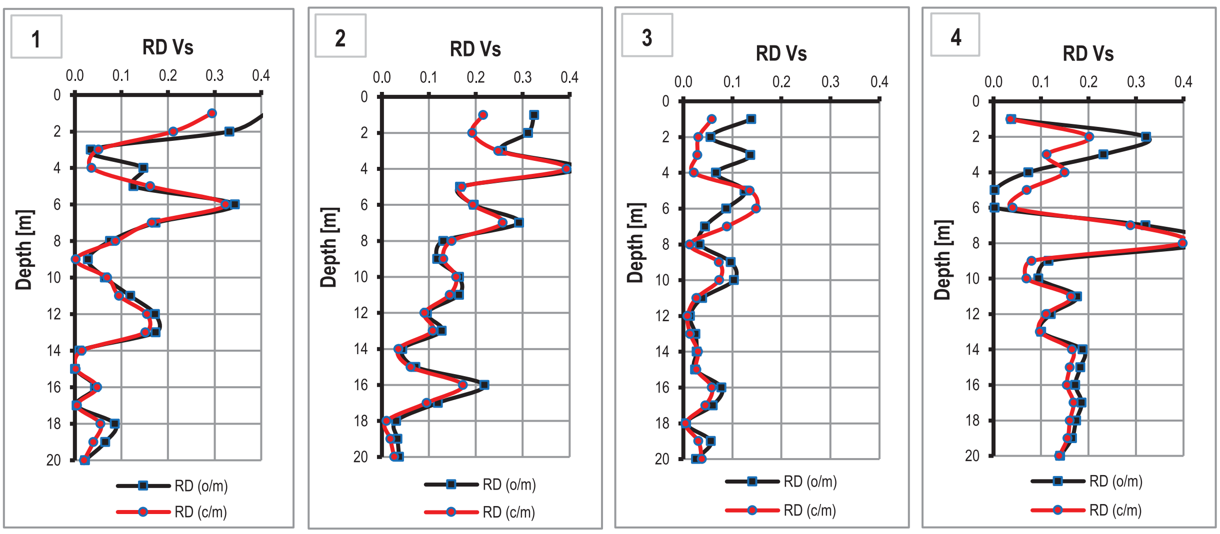

Figure 14. Relative difference between the estimated and measured velocities. RD(o/m or c/m) is a relative difference of V_S estimated from $N_{DPH}{}^{ORIG}$ or V_S estimated from $N_{DPH}{}^{CORR}$ and measured MASW velocity V_S (black and red line respectively).

appropriate dynamic properties of the materials in the soil deposit. A precise determination of the dynamic soil properties is a somewhat difficult task when solving geotechnical engineering problems. It is clear that the choice of technique depends on the problem to be solved. Dynamic properties play a vital role in the design of earthquake-resistant structures or structures subjected to dynamic loads.

6 CONCLUSION

In this paper we present empirical correlations between the shear-wave velocity V_S and the dynamic probing test (DPH) for s case study in a site-specific region of Varaždin. The geological characteristics of Varaždin are quaternary alluvial soft sediments of the Drava river basin (Fig. 2). Field measurements (low strain - MASW, high strain - DPH) were carried out at four different test locations inside and outside the city of Varaždin. Since Varaždin sits on alluvial soft sediments, the penetration resistance of the N_{DPH} groundwater-level correction was taken into consideration. An empirical correlation was developed between the measured shear-wave velocity V_S and the raw (original) N_{DPH}^{ORIG} and groundwater-level-corrected N_{DPH}^{CORR} data. The results of the developed empirical correlation (Fig. 9) for N_{DPH}^{ORIG} and for N_{DPH}^{CORR} were:

$$V_S = 97.839 \cdot N_{DPH}^{0.395};\ R^2 = 0.723,$$

$$V_S = 92.998 \cdot N_{DPH}^{0.363};\ R^2 = 0.815.$$

The groundwater-level correction was found to be effective in "statistically enhancing" the empirical correlations, which can be seen in Fig. 10. There is a very small difference between $V_{S,\mathrm{orig}}$ estimated from N_{DPH}^{ORIG} and $V_{S,\mathrm{corr}}$ estimated from N_{DPH}^{CORR}. These developed empirical correlations proved to be sufficient for rough estimations of V_S from N_{DPH} and the groundwater-level correction can be applied in order to lower the statistical error, but a correlation with raw (original) data can also be effective in a good way for estimating V_S from N_{DPH}.

The shear-wave velocity V_S is one of the most important parameters for a determination of the dynamic soil properties and the ground response analysis. From the field measurements and empirical correlations, the shear-wave velocity V_S, the dynamic elastic moduli of the shear modulus (*Go*) (Eq. 2) and the Young's modulus (*Eo* and *Er*) (Eq. 4 and 6) were estimated (Fig. 11, 12, 13). Two different approaches (low vs. high strain) were compared, and the results found to be in good agreement when the relative difference between the velocities is small and smooth, Fig 14.

The measured dynamic soil properties (V_S, *Go*, *Eo*, *Er*) can be used for the seismic design of structures based on Eurocode 8 [17, 18, 19], site response studies [2], settlement analysis and V_S is also widely used in liquefaction assessments [1].

Preliminary seismic tests proved that dynamic probing tests are effective when looking at a discrete point of interest in a large field area. The suggested correlation V_S - N_{DPH} can be used to make rough estimations of V_S from N_{DPH} (they are site-specific, and so not applicable worldwide). It should not be used as a substitute for seismic measurements, but used as a comparison and verification of the measured shear-wave velocity and dynamic probing test for site-specific dynamic soil properties. In this way very useful information about the dynamic soil properties can be extracted for ground-response analyses and the study of local site effects, particularly for preliminary studies and/or noncritical projects that are under consideration.

REFERENCES

[1] Kramer, S.L. 1996. Geotechnical Earthquake Engineering. Prentice Hall, New Jersey.

[2] Reiter, L. 1990. Earthquake Hazard Analysis. Columbia University Press, New York.

[3] Barton, N. 2007. Rock Quality, seismic velocity, attenuation and anisotropy. Taylor & Francis Group, London.

[4] Hanumantharao, C., Ramana, G.V. 2008. Dynamic soil properties for microzonation of Delhi, India. J. Earth Syst. Sci. 117 S2, 719-730.

[5] Marto, A., Soon, T.C., Kasim, F. 2013. A correlation of shear wave velocity and standard penetration resistance. EJGE, 18, 463-471.

[6] Jafari, M.K., Shafiee, A., Razmkhah, A. 2002. Dynamic properties of fine grained soils in south of Tehran. Soil Dyn. and Earthquake Eng. 4, 25-35.

[7] Uma Maheswari, R., Boominathan, A., Dodagoudar, G.R. 2010. Use of Surface Waves in Statistical Correlations of Shear Wave Velocity and Penetration Resistance of Chennai soils. Geotechnical and Geology Engineering 119–137.

[8] Kuo, C.H., Wen, K.L., Hsieh, H.H., Chang, T.M., Lin, C.M., Chen, C.T. 2011. Evaluating Empirical Regression Equations for V_S and Estimating VS30 in Northeastern Taiwan. Soil Dyn. and Earthquake Eng. 31, 431-439.

[9] Akin, M.K., Kramer, K.L., Topal, T. 2011. Empirical Correlations of Shear Wave Velocity (VS) and Penetration Resistance (SPT-N) for Different Soils in an Earthquake prone Area (Erbaa-Turkey). Engineering Geology 119, 1-17.

[10] Anbazhagan, P., Kumar, A., Sitharam, T.G. 2013.

Seismic Site Classification and Correlation between Standard Penetration Test N Value and Shear Wave Velocity for Lucknow City. Indo-Gangetic Basin. Pure and Applied Geophysics 170, 299-318.
[11] Iyisan, R. 1996. Correlations between Shear Wave Velocity and In-Situ Penetration Test Results. Digest. 96, 371-374.
[12] Mayne, P.W., Schneider, J.A. 1999. Small and large strain soil properties from seismic flat dilatometer tests. Proc. Pre-failure Deformation Characteristics of Geomaterials, Jamiolkowski et al. editors, Torino, 419-426.
[13] Aki, K., Richards, P.G. 2009. Quantitative Seismology. University Science Book, California.
[14] Mavko, G., Mukerji, T., Dvorkin, J. 2003. The Rock Physics Handbook. Cambridge University Press, Cambridge.
[15] Ohsaki, Y., Iwasaki, R. 1973. Dynamic shear moduli and Poisson's ratio of soil deposits; Soils and Foundn. 13, 61-73.
[16] Burns, S.E., Mayne, P.W. 1996. Small and high strain soil properties using the seismic piezocone. Transport. Research Record 1548, National Acad. Press, Wash. DC, 81-88.
[17] CEN 2004. Eurocode 8 - design of structures for earthquakes resistance. Part 1 - general rules, seismic actions, design and rules for building. European standard EN 1998 -1, December 2004, European Committee for Standardization, Brussels.
[18] Hrvatski zavod za norme, 2011a. HRN EN 1998-1:2011 hr, Eurokod 8: Projektiranje potresne otpornosti konstrukcija -1. dio: Opća pravila, potresna djelovanja i pravila za zgrade (EN 1998-1:2004+AC:2009). HZN - Oglasnik za normativne dokumente 6/2011.
[19] Hrvatski zavod za norme, 2011b. Nacionalni dodatak za niz normi HRN EN 1998 - 1:2011/NA:2011, Eurokod 8: Projektiranje potresne otpornosti konstrukcija - 1.dio: Opća pravila, potresna djelovanja i pravila za zgrade.
[20] Markušić, S., Herak, M. 1999. Seismic zoning of Croatia. Natural Hazards 18, 269 - 285.
[21] Prelogović, E., Velić, J. 1988. Quaternary tectonic activity in western part of the Drava depression. Geološki vjesnik 41, 237 - 253.
[22] Babić, Ž., Čakarun, I., Sokač, A., Mraz, V. 1978. On geological features of quaternary sediments of Drava basin on Croatian territory. Geološki vjesnik 30(1), 43 - 61.
[23] Urumović, K. 1971. On quaternary aquifer complex in Varaždin area. Geološki vjesnik 24, 183 - 191.
[24] Urumović, K., Hlevnjak, B., Prelogović, E., Mayer, D. 1990. Hydrogeological conditions of Varaždin aquifer. Geološki vjesnik 43, 149 - 158.
[25] Nazarian, S., Stokoe II, K.H. 1984. In situ shear wave velocity from spectral analysis of surface waves, 8th World Conference on Earthquake Engineering Proceedings, 31-38.
[26] Stokoe II, K.H., Nazarian, S. 1983. Effectiveness of ground improvement from spectral analysis of surface waves, 8th Euro. Conf. on Soil Mech. and Found. Engin. Proceedings, 91-94.
[27] Stokoe II, K.H., Wright, G.W., Bay, J.A., Roesset, J.M. 1994. Characterization of geotechnical sites by SASW method, in Geophysical characterization of sites, ISSMFE Technical Committee #10, edited by R.D. Woods, Oxford Publishers, New Delhi.
[28] Park, C.B, Xia, J., Miller, R.D. 1998b. Imaging dispersion curves of surface waves on multichannel record, 68th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1377-1380.
[29] Xia, J., Miller, R.D., Park, C.B. 1999. Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave: Geophysics 64, 691 - 700.
[30] Park, C.B, Miller, R.D, Xia, J. 1999. Multichannel analysis of surface waves. Geophysics 64, 3, 800-808.
[31] Park, C.B., Miller, R.D., Xia, J., Hunter, J.A., Harris, J.B. 1999. Higher mode observation by the MASW method: Technical Program with Biographies, SEG, 69th Annual Meeting, Houston, TX, 524-527.
[32] Xia, J., Miller, R.D., Park, C.B., Hunter, J.A., Harris, J.B. 1999. Evaluation of the MASW technique in unconsolidated sediments: Technical Program with Biographies, SEG, 69th Annual Meeting, Houston, TX, 437-440.
[33] Miller, R.D, Xia, J., Park, C.B., Ivanov, J.M. 1999. Multichannel analysis of surface waves to map bedrock. Leading Edge 18, 12, 1392-1396.
[34] http://www.masw.com/DataAcquisition.html/ <1.12.2014.>
[35] Waschkowski, E. 1982a. Dynamic Probing and Site Investigation. Proc. ESOPT 2, Amsterdam.
[36] Waschkowski, E. 1982b. Dynamic Probing and Practice. Proc. ESOPT 2, Amsterdam.
[37] Hack, R., Azzam, R., Charlier, R. 2004. Engineering geology for infrastructure planning in Europe: a European perspective. Springer, Berlin.
[38] EN ISO 22476 - 2: 2005: Geotechnical Engineering - Field testing - Part 2: Dynamic probing.
[39] DIN 4094: 2002: Subsoil - Field Investigations. Part 3: Dynamic probing.
[40] BS EN 1997 - 2: 2007. Eurocode 7 - Geotechnical design - Part 2: Ground investigation and testing, London.
[41] Stenzel, G., Melzer, K. J. 1978. Soil Investigations by Penetration Testing According to DIN 4094. Tief bau 20, 155-160, 240-244.
[42] Czado, B., Pietras, J.P. 2012. Comparison of the cone penetration resistance obtained in static and dynamic field test. AGH Journal of Mining and Geoengineering 36, 1, 97-105.