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ANALYSIS OF SHEAR WAVE VELOCITY MEASUREMENTS USING SCPT

Roman BULKO[1,*]

[1] Department of Geotechnics, Faculty of Civil Engineering, University of Žilina, Univerzitná 8215/1, 01026 Žilina, Slovakia.
[*] corresponding author: roman.bulko@uniza.sk

Abstract

The article deals with the comparison of different CPT tests over time and the evaluation of shear wave velocity V_s using Seismic Cone Penetration Test (SCPTu). The measurements analyzed the cone resistances q_c, sleeve friction f_s, pore pressure u_2, and signals obtained from geophone records at different depths. The results were processed using several methods. The article describes wave arrival detection methods, including Peak-to-Peak, Start-to-Start, Cross-Correlation, and Reverse polarity methods. By comparing these approaches, the advantages and disadvantages of individual methods in processing real field signals were identified. The results indicate the need for further research aimed at optimizing data processing and improving the reliability of V_s determination. Future research tasks, such as the selection of an appropriate filter, sensitivity to signal quality, and anomalies in arrival times, were defined.

Keywords:

Cone Penetration Test;
Shear wave;
Wave arrival detection methods;
Peak to peak;
Start to start.

1 Introduction

Every geotechnical structure should be designed to meet the requirements for safety, usability, and durability. To ensure these requirements, we must correctly evaluate the characteristics of the soil. Laboratory tests and in-situ tests are used for this. One of the most widespread in-situ tests is the Cone Penetration Test - CPT. The CPT test has its roots in the 1930s, when the Dutch engineer P. Barentsen developed the first versions of the Cone Penetrometer in 1932 to assess the mechanical properties of soils. Over time, the CPT test evolved, and in 1948, the Dutch geotechnician Begemann improved the original design and introduced a mechanical penetrometer that measured the resistance at the tip q_c and the sleeve friction f_s. The test began to be referred to as CPTm - Cone Penetration Test with Mechanical Cone [1]. In the 1970s, electronic penetrometers were introduced, which allowed for more accurate and faster measurements. Sensors for measuring pore pressures were added (the test began to be referred to as CPTu), and knowledge of pore pressures helped to better identify layers of fine-grained soils and assess their degree of consolidation. During this period, various temperature sensors, electrical resistance sensors, or sensors measuring shear wave velocities V_s or pressure waves V_p began to be developed, which were added to the CPT test. In the 1980s and 1990s, the Seismic Cone Penetration Test (SCPTu) became one of the methods in geotechnical engineering, and its accessories are being developed practically to this day. The SCPTu test has established itself as a reliable tool for obtaining dynamic soil properties, which has led to its wide acceptance in geotechnical practice [2].

In the laboratory setting, Bender elements are used in geotechnical engineering to measure shear wave velocity. Bender elements operate on the basis of the piezoelectric effect, a physical phenomenon in which certain materials develop an electric charge in response to mechanical deformation, and conversely, these materials deform mechanically when an electric field is applied to them [3]. The first use of Bender elements dates back to the 1970s, when they were developed as a means of generating and detecting seismic waves in small soil samples. These piezoelectric elements, which bend when an electric voltage is applied, enabled accurate measurements of shear wave propagation velocity in the laboratory. In the 1980s and 1990s, Bender element technology was further improved, leading to its wider adoption in geotechnical research and practice. Modern Bender elements are capable of generating and detecting waves over a wide frequency range [4].

The measurement of shear wave velocity (V_s) is of key importance in geotechnical engineering as it is directly related to the stiffness of soils under small deformations. The stiffness of any material is the ability of the material to resist an applied load. The higher the stiffness, the lower the deformation under the same load. Soil, as a granular material that exhibits highly nonlinear and inelastic behavior, has its own specific range of deformations where its behavior is linear and elastic. Therefore, the stiffness will depend on the level of stress to which the material is subjected [5].

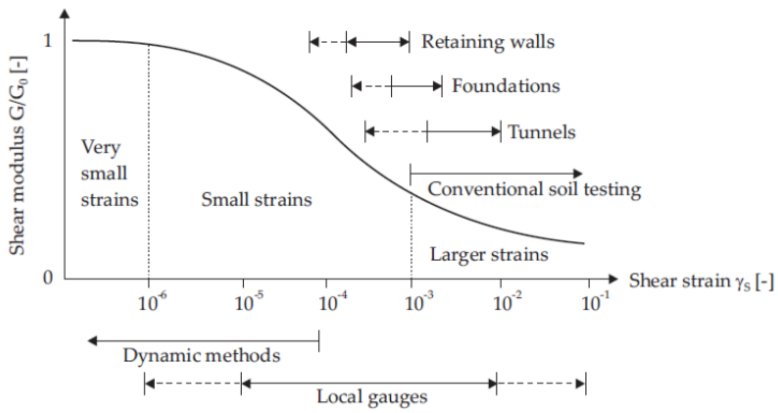

Fig.1: The range of deformations observed around geotechnical structures with stiffness degradation, proposed testing methods under the shear deformation axis [4, 5].

As shown in Fig. 1, at deformations of the order of < 0.001%, soils behave as linear elastic materials and G_{max} describes their stiffest behavior. By dynamic methods, including shear wave velocity measurement, we can derive the maximum shear modulus G_{max}, which we can express using the equation:

$$G_{max} = V_s^2 . \rho \quad (1)$$

where:
V_s is the shear wave velocity and
ρ is the bulk density of the soil.

These parameters, G_{max} as well as V_s, can be used as input parameters for various nonlinear soil behavior models in numerical modeling. Without the correct value of V_s, the results of numerical simulations may be inaccurate, especially when modeling dynamic effects.

2 Cone Penetration Test

The measuring cone is cyclically inserted into the soil using steel rods at a constant speed of 20 mm.s^{-1}. During penetration, values such as cone resistance q_c, sleeve friction f_s, and pore pressure u_1/u_2 are recorded as standard. With the seismic extension, signals that have passed through the given environment are recorded. We call them shear waves, S-waves, or primary waves, P-waves. Cone Penetration Test is divided according to the tip used into:

- CPTm – cone penetration test with a Begemann mechanical cone,
- CPTu – cone penetration test with piezocone,
- SCPT - cone penetration test with a seismic piezocone.

3 Test locality

The soil conditions at the site of the University of Žilina next to the Veľký Diel dormitories are thoroughly documented in works [6, 7]. At the tested site (Fig. 2), 6x core drilling, 24x CPTm, 24x CPTu, and 1x SCPTu were designed. Soil samples were taken for laboratory testing. Clay with medium plasticity F6/CI is found at the site. The clay layer is homogeneous with a relatively constant grain size, and has an average content of fine-grained particles of about 80%. The liquid limit ranges between 37-41% and the plastic limit ranges between 18-20.5%, the plasticity index ranges between 18-20%, and the water content in the soil fluctuates between 16-27.5%. A continuous image of the subsoil is shown (Fig. 3) according to the soil resistance at the tip. In the figure (Fig.3), we can see the influence of time and weather on the measured data. We can see that the first meter of depth varies significantly because they were measured at different times of the year with different weather conditions. The data was measured for CPTm in November, for CPTu in July, and for SCPTu in March.

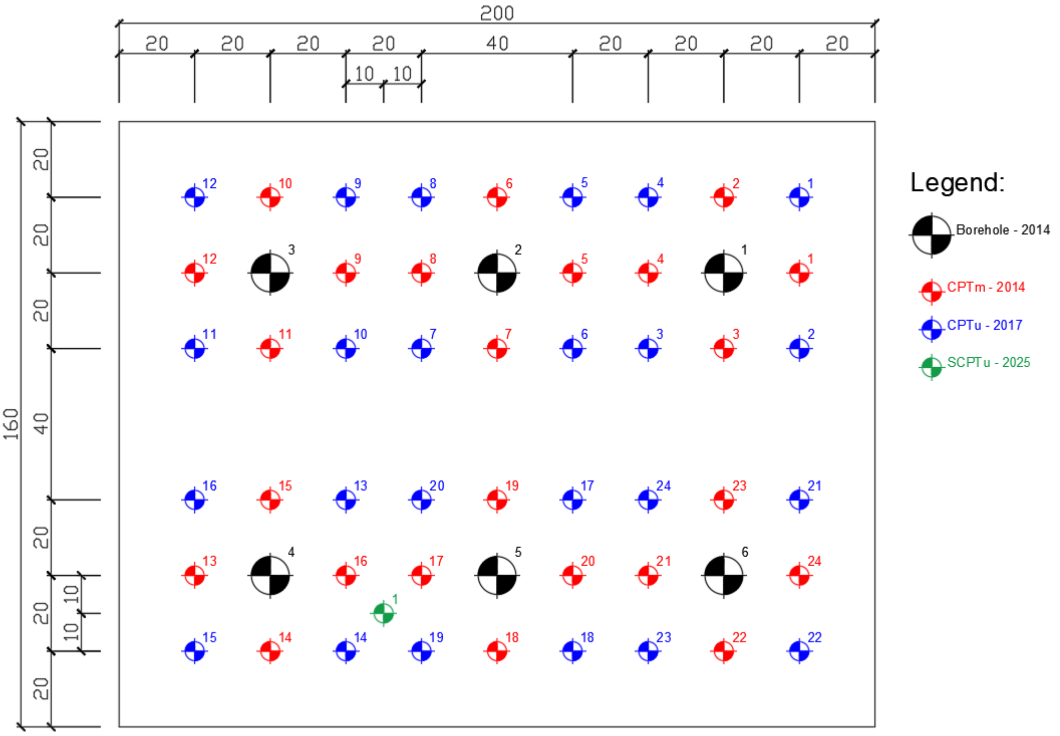

Fig. 2: Configuration of tests on the experimental field.

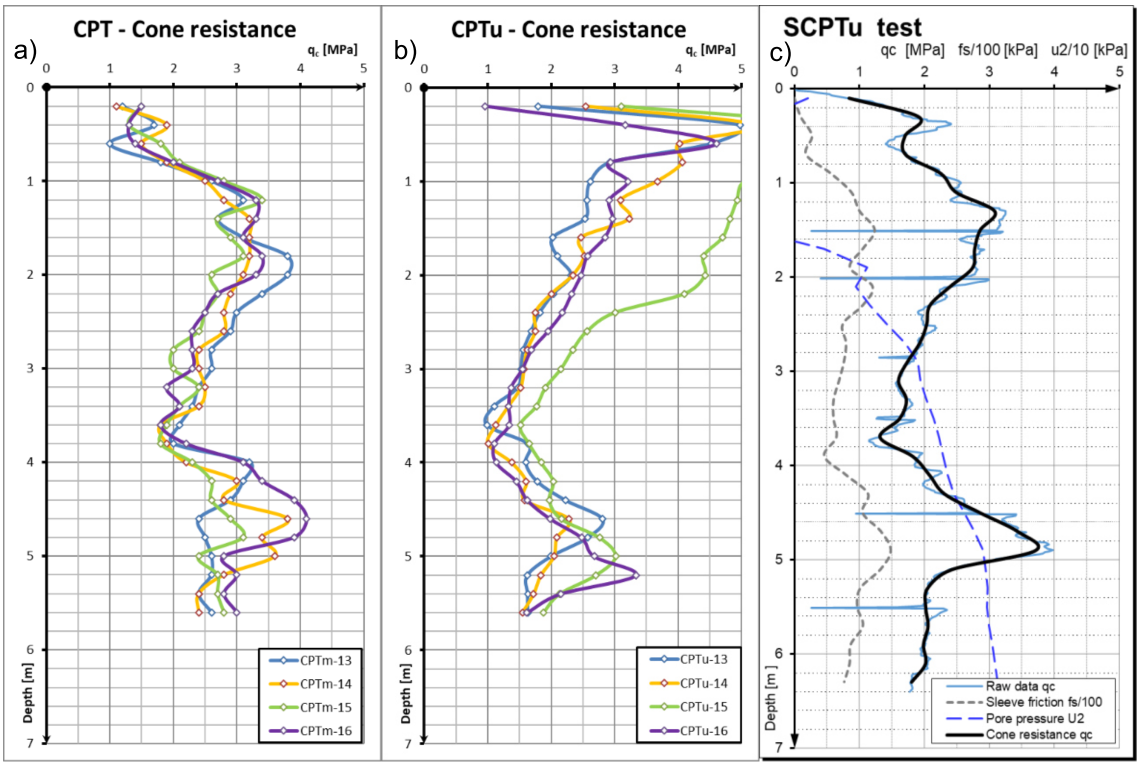

Fig. 3: a) Cone resistance of CPTm in 2014; b) Cone resistance of CPTu in 2017; c) SCPTu test in 2025.

In the history of CPT testing, indirect methods for evaluating the shear wave velocity V_s based on empirical equations have been presented by various authors. Some of them are selected in this paper. Robertson [8] presented equation (2) of the shear wave velocity from the values of the shear wave velocity coefficient avs, the normalized penetration resistance q_t, the vertical geostatic stress σ_v, and the atmospheric pressure p_a. The coefficient avs (3) is estimated based on the soil type boundaries I_c in the Robertson plot, and p_a is the atmospheric pressure.

$$V_s = [a_{vs}.(q_t - \sigma_v)/p_a]^{0.5} \quad (2)$$

$$a_{vs} = 10^{(0.55.I_c+1.68)} \quad (3)$$

Empirical equations for predicting the shear wave velocity V_s with small deformation from cone resistance for soils of different geological ages are presented in [9]. The variables considered in developing the equations include: cone tip and sleeve resistance (q_t), depth, overburden pressure, soil behavior type index (I_c), and geological age (ASF). The results suggested that geological age, as well as cementation, should be considered when predicting V_s from cone measurements.

$$V_s = 2.27.q_t^{0.412}.I_C^{0.989}.D^{0.033}.ASF \quad (4)$$

In [10], Mayne investigated the trends of various data on the tip resistance q_c and the sleeve friction f_s as a function of the shear wave velocity V_s. The data q_c and f_s depend on the soil type, strength, stress history, and index properties. While V_s is a function of the soil type I_c and its consistency. In the equation of shear wave is also total vertical stress σ_v and atmospheric pressure p_a. The shear wave velocity is calculated using the equation:

$$V_s = 0.0831.q_{cIN}.\left(\frac{\sigma'_{v0}}{p_a}\right).e^{(1.786.I_C)} \quad (5)$$

As we can see in equations (2,4,5) V_s from various authors, the soil type component of the soil, based on the Robertson graph, mainly enters. Therefore, it is important to correctly determine the soil type of soils. Equation (6) is used for this:

$$I_C = [(3.47 - \log q_{cIN})^2 + (\log F + 1.22)^2]^{0.5} \quad (6)$$

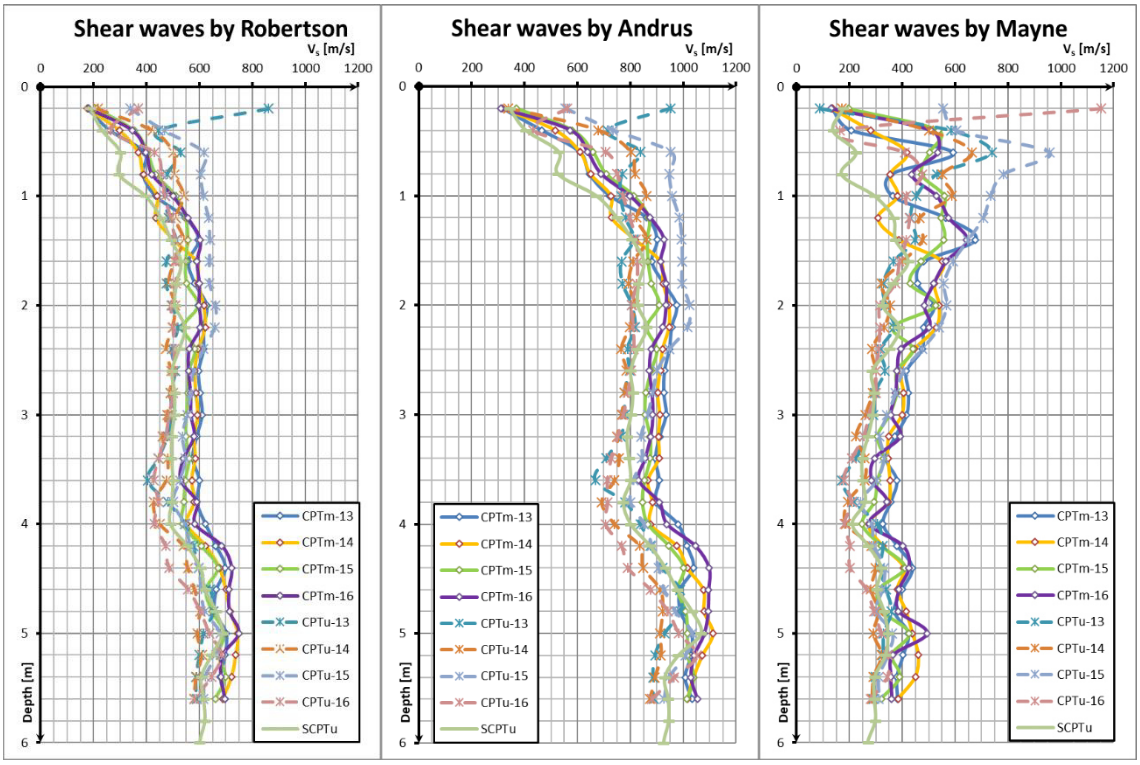

Fig. 4: Derived shear wave velocities according to individual authors and their equations.

Although the trend of the shear wave velocity V_s with depth is similar in both the Robertson and Andrus empirical models, a significant difference in absolute values is observed. This discrepancy may be attributed to the differences in the underlying assumptions of the models, the geological age of the soils, and the level of cementation. Andrus' equation incorporates geological age and overburden stress more explicitly, which tends to increase the predicted V_s in older or more cemented soils. In contrast, Robertson's model is more general and primarily based on the soil behavior type index Ic derived from CPT data.

4. Methods for processing shear wave velocity

There are several methods for calculating shear wave velocity. The most well-known are Peak to Peak (PtP), Start to Start (StS), Cross Correlation (CC), or Reverse Polarity Method (RPM).

The Peak to Peak method is one of the simplest and most widely used methods for determining the arrival time of shear waves when working with signals. The goal of the method is to determine the time interval between the sending and receiving of the signal in order to calculate the shear wave velocity V_s. PtP identifies the first significant peak in the received signal.

$$V_s = \frac{\Delta L}{\Delta t_{peak}} \quad (7)$$

The PtP method does not require complex algorithms or time/frequency domain analysis. In clean signals, the peaks are clearly visible. In distorted or noisy signals, there is inaccuracy in selecting the correct peak, since the frequency components propagate at different speeds, and the signal shape may change. However, this method can be used for quick estimates of V_s and basic comparison with other methods.

The Start to Start method is more accurate in signal processing, especially in determining the arrival time of shear waves. It focuses on detecting the beginning of the wave instead of tracking the peak of the signal. The arrival time of the first wave is determined, i.e., the moment when the received signal first shows a deviation from the zero line. The first zero crossing, or the point where the signal starts to visibly rise, is taken as the start.

$$V_s = \frac{\Delta L}{\Delta t_{start}} \quad (8)$$

The StS method is less affected by signal distortion (dispersion). It works even when peaks are not well identified. Determining the start of a signal can sometimes be difficult if the signal is noisy. Therefore, noise filtering should be performed before analyzing the arrival time. This method shows higher accuracy in determining V_s.

The Cross-Correlation method is used to accurately determine the arrival of a shear wave (S-wave) when processing signals from a seismic static penetration test (SCPT). The principle lies in correlating signals recorded at two different depths by geophones. The resulting correlation function reveals a time delay between the waves, which corresponds to the wave propagation time between two points. This time difference, combined with the known distance between the geophones, allows a reliable calculation of the shear wave propagation velocity:

$$V_s = \frac{L}{\Delta t} \quad (9)$$

The advantage of the method is its robustness to noise and the ability to work even with weaker signals, but it requires proper data preprocessing (e.g., filtering).

The Reverse Polarity Method in SCPT testing is one of the techniques used to more accurately determine the arrival time of shear waves V_s. Within SCPT testing, we often encounter the fact that it is difficult to clearly determine when exactly the wave arrived at the receivers (geophones). By exciting the signal from the right, I get normal polarity, and by exciting the signal from the left, I get the opposite polarity. RPM helps to clearly determine the arrival of the shear wave by comparing the opposite polarities - the signal from the second test will be mirror-inverted compared to the first. In other words, we are looking for a point where the two signals differ by exactly 180° - this is the exact identification of the arrival of the shear wave V_s. The method suppresses noise and other unwanted signals that could distort the results

The described methods determine the arrival times of individual signals. All equations have a common parameter, "distance" ΔL. The difference in the distance of the wave can be calculated from the geometry (Fig.5) as:

$$\Delta L = \sqrt{D_2^2 + d_x^2} - \sqrt{D_1^2 + d_x^2} \quad (10)$$

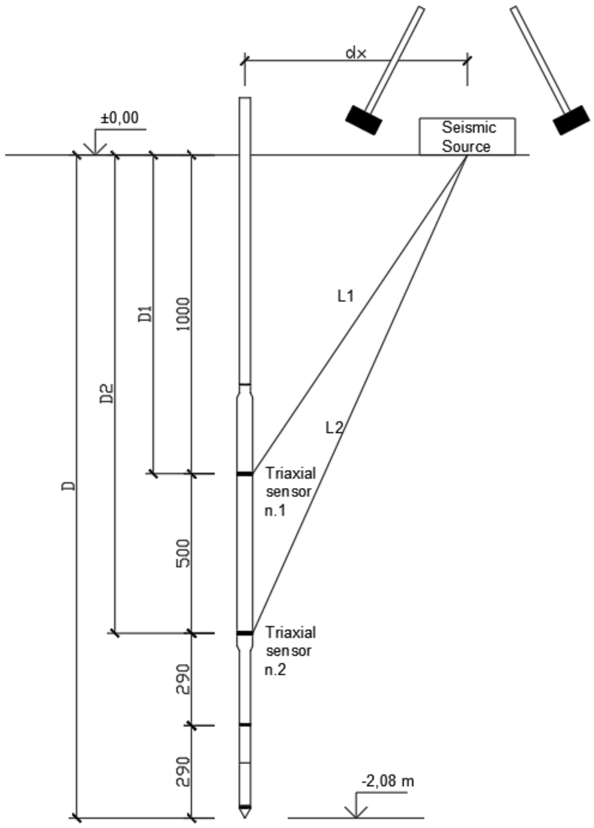

Fig. 5: Calculation of the source-sensor distance.

Table 1: Comparison of signal processing methods from SCPT.

Method	Application	Advantages	Note
Peak-to-peak	Alternative	For sinusoidal signals	Less conservative
Start-to-start	Most common	Simple, conservative	Most reliable for engineering purposes
Cross-correlation	For weak signals	Robust, less sensitive to noise	Often as a complementary method
Reverse Polarity Method	Detection of the first reflected wave	Highlights the change in polarity, suitable for low S/N ratio	Sensitive to correct adjustment of amplitudes and phases
Spectral analysis	Research, validation	Frequency information	Requires advanced processing

5. Interpretation of SCPT Test

The CPT field test is considered a standard method for assessing soil properties, so measurement errors can occur during the test. Some of them can be detected immediately at a glance, while others can be mistaken for real soil properties. One of the easiest ways to detect errors is to review the raw data. In Fig. 3c, we can see (Raw data q_c) significant drops occurring in connection with cone stops during the tests. Stops during the penetration test are due to the need to attach new rods and, at the same time, to perform seismic tests. These errors are caused by stops and often manifest as drops in cone resistance. In general, most of the data removed were errors caused by stops, and the final results are shown in Fig. 3c (Cone resistance q_c).

In Figure 4, we can see that the results of the Vs by Robertson and Andrus copy the trend cone resistance by index consistency. On the other hand, results by Mayne are significantly lower and do not follow the same trend, likely due to different empirical calibration based on soil type and reference stress conditions, which makes them more conservative in estimating shear wave velocity

5.1. Shear wave results from SCTU

The seismic signal was generated by hammer blows, with only one blow for each wave type. The first step in interpreting the results was to verify that the signal propagated in the correct direction with depth. The signals were processed in the MATLAB environment. The shear wave profiles can be seen in Fig. 6, with depths of 150, 200, 250, 350, 450, 550, and 650cm from top to bottom. Where the blue curves are the results from triaxial sensor no. 1 and the red curves are the results from triaxial sensor no. 2. In the V_s assessment, it can be observed that the deeper the triaxial sensors are, the weaker the signal, which was expected.

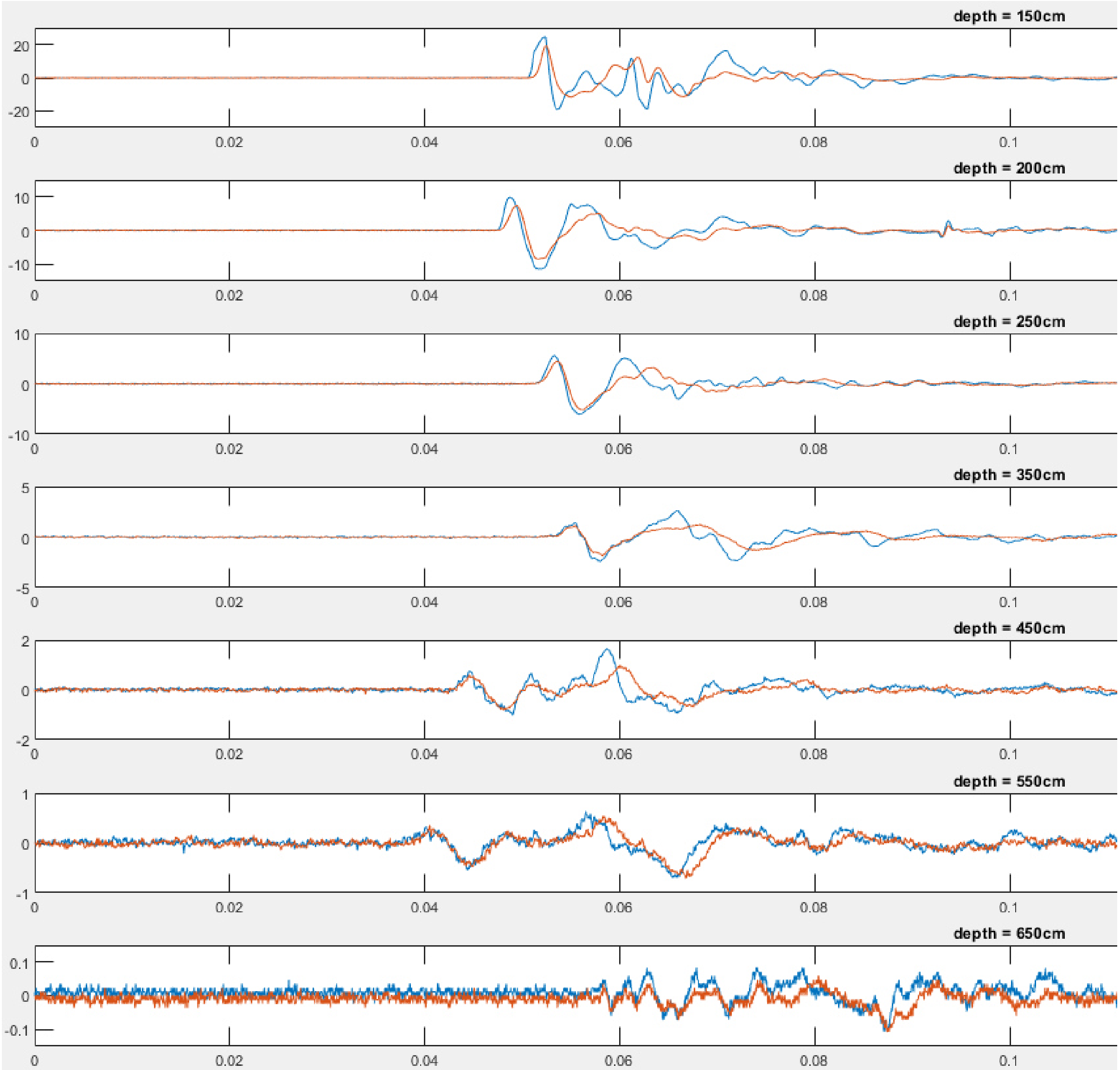

Fig. 6: Raw signals from SCPTu.

6. Discussion

In Fig. 6, we see the propagation of signals within individual depths. We can see certain anomalies, such as the beginnings of signals shifted in time at a depth of 150 cm versus 200 cm or 450 cm versus 350 cm. These discrepancies indicate the need for a more detailed analysis of the results of the SCPT test. In further research, we will focus on the influence of the distance of the seismic source from the rig, as well as on different types of pads under the source. When processing the signals, it will be important to correctly choose the appropriate type of filter and its parameters, such as the filter order or cutoff frequencies from which the signal needs to be cleaned. Future research will focus on refining the signal processing methodology, particularly in selecting and optimizing digital filters. A key step will be the evaluation of low-pass and band-pass Butterworth filters of different orders, as these significantly affect the signal-to-noise ratio and the clarity of shear wave onset. For example, articles [13, 14] suggest that incorrect filter settings can distort the wave shape or shift the apparent arrival time. Further, signal alignment and stacking techniques may be tested to enhance repeatability. It is also necessary that the results are validated with other types of tests, such as laboratory analysis using bender elements [4, 12] or in-situ analysis using surface-wave methods, MASW or geophysics [15,16] to assess scale effects and cross-method consistency. The evaluation of wave arrival time will also be deepened using comparative methods such as STA/LTA (short-term average / long-term average) energy detection, which has shown promising results in seismic event detection [17]. The verified results will be used in solving geotechnical problems using numerical methods [18, 19].

Conclusion

Engineering geological and geotechnical investigation using in-situ tests such as CPT is considered a standard method for assessing soil properties. The CPT test is suitable for determining soil properties continuously down to the subsoil. The results of the CPT test showed that it provides valuable information; it was found that soil resistivities change over time only in the surface area based on weather. The results of the SCPTu testing demonstrate that the applied signal processing methods significantly affect the calculated values of shear wave velocity. The results of shear waves from different authors were also compared. Methods for processing shear wave propagation were compared, and future research was defined. Future research will focus on systematically evaluating filter types and their parameters, which influence the shape and onset of the shear wave signal. Comparative analysis using automatic energy-based detection methods, such as STA/LTA, may improve arrival time detection and consistency. Further validation of SCPTu-derived Vs profiles using laboratory methods such as Bender Element testing or surface wave techniques like MASW is planned. This will allow for assessment of scale effects and help calibrate field measurements. Additionally, the relationship between observed waveform anomalies and the geological structure will be examined to improve interpretation accuracy.

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References

[1] LUNNE, T. – POWELL, J. J. – ROBERTSON, P. K.: Cone penetration testing in geotechnical practice. CRC Press, 2002. DOI: 10.1201/9781482295047.

[2] ROBERTSON, P. K. – CAMPANELLA, R. G. – GILLESPIE, D. – RICE, A.: Seismic CPT to measure in situ shear wave velocity. Journal of Geotechnical Engineering, 112(8), 1986, pp. 791-803. DOI: 10.1061/(ASCE)0733-9410(1986)112:8(791).

[3] NASH, D. – SUKOLRAT, J. – GREENING, P. – BENAHMED, N.: Comparison of shear wave velocity measurements in a soft clay specimen using time and frequency domain techniques. Riv Ital Di Geotec, 25, 2007, pp. 56-68.

[4] PANUŠKA, J. – FRANKOVSKÁ, J.: Regression Analysis of Small Strain Shear and Constrained Modulus Measurements on Sands with Fines: Effect of Different Void Ratio Functions Used. Slovak Journal of Civil Engineering, 26(4), 2018, pp. 11-19. DOI: 10.2478/SJCE-2018-0023.

[5] CLAYTON, C. R. I.: Stiffness at small strain: research and practice. Géotechnique, 61(1), 2011, pp. 5-37. DOI: 10.1680/GEOT.2011.61.1.5

[6] BULKO, R.: Analýza vplyvu parametrov vybraných konštitučných modelov zemín určovaných statickou penetráciou na presnosť numerických modelov (Analysis of the influence of parameters of selected soil constitutive models of soils determined by Cone Penetration on the accuracy of numerical models). Disertation thesis, 2016.

[7] GAGO, F.: Určovanie parametrov konštitučných modelov zemín in-situ testovaním (Determining parameters of constitutive models of soils by in-situ testing). Disertation thesis, 2020.

[8] ROBERTSON, P. K.: Interpretation of cone penetration tests—a unified approach. Canadian Geotechnical Journal, 46(11), 2009, pp. 1337-1355. DOI: 10.1139/T09-06.

[9] ANDRUS, R. D. – MOHANAN, N. P. – PIRATHEEPAN, P. – ELLIS, B. S. – HOLZER, T. L.: Predicting shear-wave velocity from cone penetration resistance. Proceedings of the 4th international conference on earthquake geotechnical engineering, Thessaloniki, Greece, Vol. 2528, 2007.

[10] HEGAZY, Y. A. – MAYNE, P. W.: A global statistical correlation between shear wave velocity and cone penetration data. Site and Geomaterial Characterization, 2006, pp. 243-248. DOI: 10.1061/40861(193)3.

[11] ILIESCU, A. I. – GERON, J.: Seismic Cone Penetration Test. Experimental results in onshore areas. Geotechnical Investigation. 2012.

[12] PANUŠKA, J. – FRANKOVSKÁ, J.: Effect of a void ratio on the small strain shear modulus Gmax for coarse-grained soils. Procedia Engineering, 161, 2016, pp. 1235-1239. DOI: 10.1016/J.PROENG.2016.08.554.

[13] SANTOS, R. S. – SAUVIN, G. – PARK, J. – VANNESTE, M.: Assessment of seismic cone penetration tests uncertainty: equipment set-up, processing, and interpretation workflows. SUT Offshore Site Investigation and Geotechnics, 2023. DOI:10.3723/IZTT5056.

[14] BOL, E.: A new approach to the correlation of SPT-CPT depending on the soil behavior type index. Engineering geology, 314, 2023, pp.106996. DOI: 10.1016/j.enggeo.2023.106996.

[15] BRIXOVÁ, B. – MOSNÁ, A. – PUTIŠKA, R.: Applications of shallow seismic refraction measurements in the Western Carpathians (Slovakia): case studies. Contributions to Geophysics and Geodesy, 48(1), 2018, pp. 1-21.

[16] PUTIŠKA, R. – MOJZEŠ, A. – BEDNARIK, M. – MATYS, M. – VYBÍRAL, V.: Geological models of landfills in Slovakia. Contributions to Geophysics and Geodesy, 35(4), 2005, pp. 429-439.

[17] DONOHUE, S. – GAVIN, K. – TOLOOIYAN, A.: Geophysical and geotechnical assessment of a railway embankment failure. Near Surface Geophysics, 9(1), 2011, pp. 33-44. DOI: 10.3997/1873-0604.2010040.

[18] VU, V. T.: Assessment of Slope Stability with the Assistance of Artificial Neural Network and Differential Evolution. Civil And Environmental Engineering, *19*(1), 2023, pp. 288-300. DOI: 10.2478/cee-2023-0026.

[19] WAHEED, M. – ASMAEL, N.: Study immediate and consolidation settlement of shallow foundations. Civil And Environmental Engineering, 19, 2023, 318-327. DOI: 10.2478/cee-2023-0028.