798. Correlation of shear-wave velocities and cone resistance of quaternary glacial sandy soils defined by Seismic Cone Penetration Test (SCPT)

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Abstract. The derivation of dynamic geotechnical parameters of soil are of primary importance in designing specific structures. Direct measurements are expensive and time-consuming. In this study the correlation between the seismic wave velocities and cone resistance was derived from seismic cone penetration testing (SCPT) of Quaternary glacial sandy soils in Lithuania. The close relationship was obtained for sandy soils indicating wide range of cone resistance and seismic wave velocities. The correlation is as high as $R = 0.80$. The derived regression equation could be reasonably used in assessing dynamic geotechnical and seismic parameters in Lithuania and other territories characterized by similar geological conditions using conventional cone penetration testing (CPT) method. It enables consistent geotechnical and seismic zoning of sandy soils.

Keywords: seismic cone penetration test (SCPT), cone resistance, shear wave velocity, dynamic soil properties, seismic soil properties.

Introduction

The assessment of soil-structure interaction is an essential objective in modern geotechnical designing. The soil deformation parameters should be investigated in order to asses this interaction [13, 26]. The prognosis of soil behavior when subjected to dynamic loading is one of the essentially complex targets in constructing specific structures. The information on the dynamic properties of the soil is very important when planning structures that are going to be affected by artificial dynamic loads or potential seismic events. The effect of dynamic forces on structures such as nuclear power plants, wind meals, offshore petroleum platforms, etc. subject to vibration should be evaluated, including forces produced by earthquakes, wind, sea waves. The liquefaction parameters are essential in this kind of studies [2, 25].

Important dynamic geotechnical parameters of soil are the shear modulus G, the maximum shear modulus G_{max} and the shear modulus G_0 of very small strains, also the Poisson's ratio ν. Based on elasticity theory the shear modulus G depends on the soil bulk density ρ and the shear wave velocity v_s [15, 28]:

$$G = \rho \cdot v_s^2 \qquad (1)$$

Shear wave velocity directly depends on soil properties, such as soil density, void ratio, effective stress that, in turn, are the result of geological evolution of a site, i.e. soil age, cementation rate, sin- and post-depositional stress history, over consolidation ratio (OCR). Therefore seismic wave velocity provides information on dynamic geotechnical properties and is one of basic parameters in assessing the construction site in terms of evaluation of seismic hazard or dynamic soil-structure interaction required by Seismic Design Criteria [8].

Shear wave velocities v_s can be measured in laboratory using resonant column, cyclic torsion shearing, bender elements, and triaxial test under very small strains ($<10^{-3}$-10^{-4} %) of the sample, in its centre [14, 23, 24, 29] that, however, leads to partial destruction of sample integrity.

During the past decades, the geophysical methods such as downhole test (DHT), crosshole test (CHT), suspension logging, seismic reflection, seismic refraction, spectral analysis of surface waves (SASW), also geotechnical field tests, e.g. seismic cone penetration test (SCPT), seismic dilatometer test (SDMT) became increasingly effective in measuring shear wave velocities v_s of the soil [3, 20].

Methodology of seismic cone penetration test (SCPT)

Based on world-wide experience of engineering geology studies the cone penetration test (CPT) provides most valuable information compared to other field tests. Data collected by using this method enables identification of architecture of soil layering, definition of soil types, and calculation of a number of geotechnical parameters of the soil. Data derived from CPT are directly employed in geotechnical designing. Compared to other field and laboratory methods used for measuring geotechnical parameters of the soil the CPT is the most economically effective [16, 18].

In case of simple geological structure, where the foundations could be immediately designed based on CPT data this method becomes the major approach, even compensating the need for the drilling information, while at a site of more complex geological conditions it provides the baseline information for application of other methods. CPT can be applied for investigation of soils that are impossible to measure using other field test methods, or sampling is not possible [12].

The modification of this method to seismic cone penetration test (SCPT) was implemented in geotechnical studies several decades ago [2, 27]. The same equipment used in CPT is employed in the SCPT test, with the addition of the hammer trigger, recording system and the seismic cone electrometer (Fig.1). It was originally developed by Robertson P. K. et al. in 1986 [19]. The geophones, fit inside the cone body, are mounted in three orthogonal planes *X*, *Y*, *Z*. A shear wave is generated by means of a hammer blow and simultaneously the seismograph is triggered and subsequently the seismic wave arrivals at the geophone array are recorded.

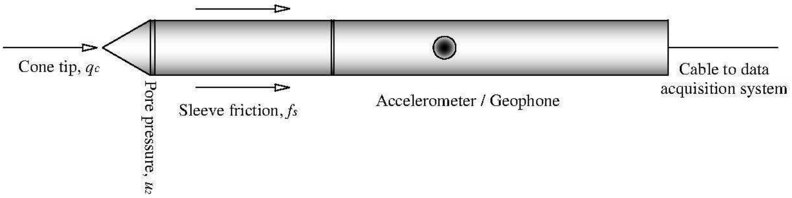

Fig. 1. Scheme of SCPT penetrometer

The cone is penetrated to measure cone tip resistance, sleeve friction and pore water pressure, which are used to calculate the strength of the soil and identify the soil type profile. Besides, the shear (and compression, in some cases) wave velocities are measured. At certain intervals (commonly at 0.5 m spacing) the cone penetration is stopped and the seismic excitation is produced on the surface to make seismic waves propagate to the seismic device and then return to the surface where they are registered by special equipment. The principal scheme of the seismic CPT test is indicated in Fig. 2.

In this case shear wave v_s velocities are measured at particular intervals. It is also possible to measure v_p compression wave velocities. This method allows employment of the same penetration technique, equipment and data registration system that are used in conventional cone penetration tests. In addition, seismic wave excitement source is required, i.e. plates, hammer, seismic module comprising exciter and receiver to register data.

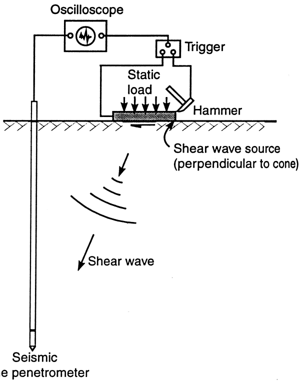

Fig. 2. Scheme of seismic cone penetration test [2]

Empirical equations relating cone resistance and local sleeve friction to shear wave velocity

The dual application of the cone penetration test described above has been used in different regions and resulted in accumulation extensive database as regards the relationship of conventional geotechnical parameters (q_c and f_s) to shear wave velocities (v_s). The derived relationships (equations) between q_c, f_s and v_s are conventionally allowed for usage in estimating soil dynamic properties based on CPT data, in case the alternative SCPT technique is not available at a site. Some relationships defined for sandy soils of particular regions are presented in Table 1.

Table 1. Shear wave velocity correlation equations for sandy soils derived from different regions based on SCPT data

No.	Soil type	Equations	References
1	Sand	$v_s = 277 \cdot (q_t)^{0.13} \cdot (\sigma'_{vo})^{0.27}$	Baldi et al., 1989 [1]
2	Sand	$v_s = 13.18 \cdot (q_t)^{0.192} \cdot (\sigma'_{vo})^{0.179}$	Hegazy & Mayne, 1995 [7]
3	Alluvial sand	$v_s = 0.70 \cdot q_c + 218$	Iyisan, 1996 [9]
4	Marine sand	$v_s = 50 \cdot \left(\left(\frac{q_c}{p_a} \right)^{0.43} - 3 \right)$	Paoletti et. al., 2010 [17]
5	Sand	$v_s = 12.02 \cdot (q_c)^{0.319} \cdot (f_s)^{-0.0466}$	Trevor et al., 2010 [22]

here:
v_s – shear wave velocity, m/s;
q_t – corrected (by pore pressure, u_2 (in MPa)) cone resistance, MPa:

$$q_t = q_c + u_2 \cdot (1 - a);$$

q_c – measured cone resistance, MPa;
f_s – sleeve friction, kPa;
σ'_{vo} – effective overburden stress, (σ_{vo}-u_0), kPa;
σ_{vo} – total overburden stress, kPa;
p_a – atmospheric pressure, 100 kPa.

SCPT study results of quaternary glacial sandy soils of Lithuania

Seismic cone penetration tests were performed by JSC ”Geotestus” in north-east Lithuania. Two L-form plates were used to excite shear waves. A special hammer was applied to the plates (Fig. 3). In total, 21 penetration sites were measured. Penetration depth reaches 25 m.

Fig. 3. Plate used for excitation of shear waves

The depth spacing of seismic velocity measurements was 0.5-1.0 m. The vertical seismic velocity profiles were compiled based on penetration test data (Fig. 4).

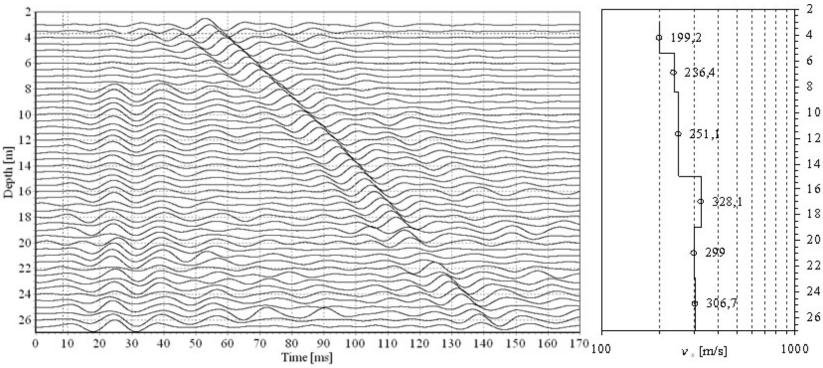

Fig. 4. Sample of shear waves propagation to a depth (left hand figure) and diagram of alteration of shear wave velocity to a depth (right hand figure), Lithuania, JSC “Geotestus“

Data were processed using express software; the data processing was carried out by software “GeoTech SCPT Analysis”. It is important to note that the latter programme allows removal of seismic noise that inevitably disturbs the registered signal. The seismic velocities were calculated applying backward polarization and cross-correlation approaches.

Results

The surface of Lithuania is composed by Quaternary deposits that accumulated mainly during the last glaciation and postglacial stages [6]. A soil profile is represented by intercalation of sandy and clayey (e.g. moraine) sediments. The present study is focused on glacial sandy soils of glaciofluvial and glaciolacustrine type. Sandy soils range in grain-size composition and density. Only soil layers bellow the ground water level were studied. The Quaternary succession is commonly of highly complex architecture. Sands varying from coarse-grained to very fine-grained were unified into a single sandy soil group. Different layers characterized by specific average cone resistance and share wave velocities were defined based on SCPT data and associating drilling information (Fig. 5).

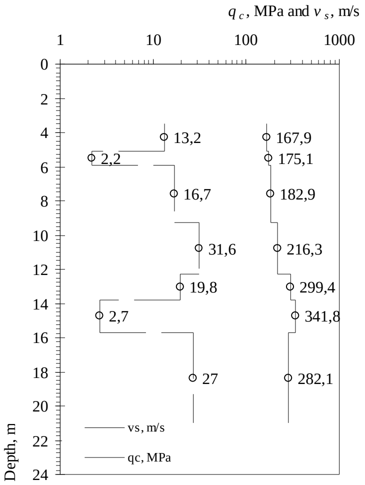

Fig. 5. Comparison of profiles of averaged cone resistance and seismic wave velocities

Such combination of different data types enabled compilation of the common database that provided a base for comparative analysis of shear wave velocities, v_s and soil strength parameter represented in form of cone resistance, q_c. The regression analysis was applied to derive the correlation between those two parameters.

The depth of analyzed sandy layers is in the range of 3-25 m. In total, 70 averaged values were derived. The layer-averaged seismic wave velocities range from 110 m/s to 540 m/s that associate with the wide range in cone resistance varying from 2 MPa to 35 MPa. Such a wide interval of measured values assures consistency of defined correlation between those two parameters.

The correlation is as close as R = 0.80. The regression equation (2) linking the shear wave velocities to cone resistance (Fig. 6) was derived:

$$v_s = 10.8 \cdot q_c + 90 \tag{2}$$

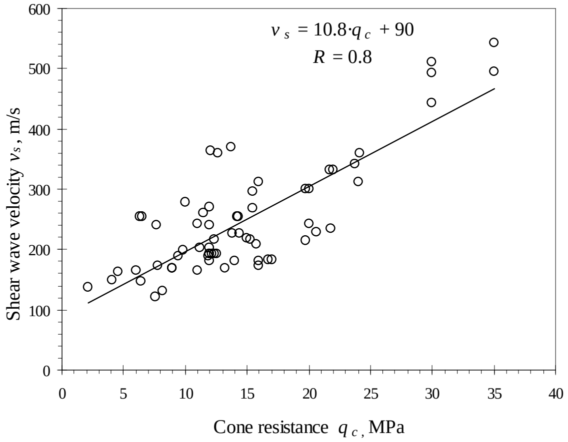

Fig. 6. Plot of cone resistance q_c vs shear wave velocities v_s of studied sandy soils

The correlation between shear wave velocities and cone resistance defined for Lithuanian sandy soils differ somewhat from those defined in other areas (Fig. 7). For instance, comparison of Lithuanian data and relationship provided by Baldi et al. (1989) [1] (see Table 1) indicates that the latter underestimates cone resistance of Lithuanian quaternary glacial sands by about 0.77. This misfit can be primarily related to different soil behavior type [21, 11] of quaternary sandy soils of Lithuania and those studied in other regions.

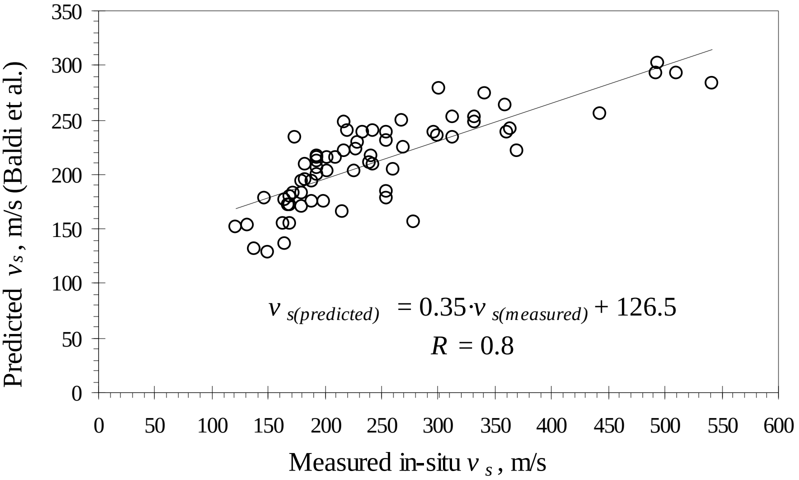

Fig. 7. Measured shear wave velocities ($v_{s(measured)}$) of Lithuanian sandy soils vs shear wave velocities predicted ($v_{s(predicted)}$) by Baldi et al. (1989) equation

Conclusions

The correlation between the cone resistance and shear wave velocity was defined for quaternary glacial sandy soils of Lithuania using SCPT method. It provides a base for geotechnical and seismic microzoning of areas characterized by similar geological conditions using conventional CPT data. In the case of seismic zoning the equivalent shear wave velocities, i.e. velocities as weighted average of shear wave velocities of soil layers in the top 20-30 m, can be estimated for quaternary sandy soils by converting widely available CPT data. Equivalent shear wave velocities are commonly used in evaluating the design earthquake characteristics on the ground surface [4, 5, 10].

The obtained correlation between the cone resistance and shear wave velocities is as high as $R = 0.80$. The equation of correlation of cone resistance with shear wave velocity obtained for quaternary sandy soils of Lithuania and those defined in other regions are somewhat different that can be related to different soil formation history of sands of various regions. It is therefore crucial to define region-specific correlation equations for application of CPT data in determining seismic and dynamic properties of soils. Application of correlation equations defined in other regions having different geological setting may lead to considerable inconsistencies in microzoning of particular areas.

Acknowledgements

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References

[1] **Baldi G., Belloti R., Chionna V. N., Jamiolkowski M., LoPresti D. C. F.** Modulus of sands from CPTs and DMTs. Proc. of the 12th Internat. Conf. on Soil Mechanic and Foundation Engineering, Vol. 1, Rio de Janeiro, Brazil, 13-18 August 1989, p. 165 – 170.

[2] **Campanella R. G., Robertson P. K., Gillespie D.** A seismic cone penetrometer for offshore applications. Proc. of the Internat. Conf. on Oceanology (Oceanology International'86), Vol. 6, Brighton, U. K., 4-7 March 1986, p. 479 – 486.

[3] **Campanella R. G.** Field methods for dynamic geotechnical testing: an overview of capabilities and needs. Dynamic Geotechnical Testing II, ASTM Special Technical Publication No. 1213, Eds. Ebelhar R. J., Drnevich V. P., Kutter B. L., American Society for Testing and Materials, Philadelphia, USA, 1994, p. 3 – 12.

[4] **Dobry R., Borcherdt R. D., Crouse C. B., Idriss I. M., Joyner W. B., Martin G. R., Power M. S., Rinne E. E., Seed R. B.** New site coefficients and site classification system used in recent building seismic code provisions. Journal of Earthquake Spectra (EERI), Vol. 16, Issue 1, 2000, p. 41 – 67.

[5] Eurocode-8. BS-EN 1998-1:2004, Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization, Brussels, 2004.

[6] **Guobytė R.** A brief outline of the quaternary of Lithuania and the history of its investigation. Quaternary Glaciations – Extent and Chronology, Part I, Eds. Ehlers J., Gibbard P. L., Amsterdam, Holland: Elsevier, 2004, p. 245 – 250.

[7] **Hegazy Y. A., Mayne P. W.** Statistical correlations between v_s and CPT data for different soil types. Proc. of 1st Internat. Symposium on Cone Penetration Testing (CPT'95), Vol. 2, Swedish Geotechnical Society, Linköping, Sweden, 4-5 October 1995, p. 173 – 178.

[8] IAEA. Seismic Design and Qualification for Nuclear Power Plants. Safety Standards Series No. NS-G-1.6, Vienna, Austria, 2003.

[9] **Iyisan R.** Correlations between shear wave velocity and in-situ penetration test results. Chamber of Civil Engineers of Turkey, Teknik Dergi, Vol. 7, Issue 2, 1996, p. 1187 – 1199.

[10] **Kanli A. I., Tildy P., Pronay Z., Pinar A., Hermann L.** V_s^{30} mapping and soil classification for seismic site effect evaluation in Dinar region, SW Turkey. Geophysical Journal International, Vol. 165, Issue 1, April 2006, p. 223 – 235.

[11] **Karray M., Lefebvre G., Ethier Y., Bigras A.** Influence of particle size on the correlation between shear wave velocity and cone tip resistance. Canadian Geotechnical Journal, Vol. 48, Issue 4, 2011, p. 599 – 615.

[12] **Lunne T., Robertson P. K., Powell J. J. M.** Cone Penetration Testing in Geotechnical Practice. London, UK: Blackie Academic & Professional, 1997.

[13] **Massarsch K. R.** Deformation properties of fine-grained soils from seismic tests. Keynote Lecture, International Conference on Site Characterization (ISC'2), Porto, Portugal, 19 – 22 September 2004, p. 133 – 146.

[14] **Mayne P. W.** Cone Penetration Testing: State-of-Practice. Final Report, NCHRP Project 20-05, Task 37-14, Georgia Institute of Technology, Atlanta, GA, Transportation Research Board Synthesis Study, 2007.

[15] **Mayne P. W., Rix G. J.** G_{max}-q_c relationships for clay. ASTM Geotechnical Testing Journal, Vol. 16, Issue 1, 1993, p. 54 – 60.

[16] **Mayne P. W.** The 2nd James K. Mitchell Lecture: Undisturbed sand strength from seismic cone tests. Geomechanics and Geoengineering: An International Journal, Vol. 1, Issue 4, 2006, p. 239 – 247.

[17] **Paoletti L., Hegazy Y., Monaco S., Piva R.** Prediction of shear wave velocity for offshore sands using CPT data – Adriatic sea. Proc. of 2nd International Symposium on Cone Penetration Testing (CPT'10), Vol. 2, Huntington Beach, CA, USA, 9-10 May 2010, p. 361 – 368.

[18] **Prakoso A. W.** Correlation of cone resistance and shear wave velocity for residual soil. Proc. of 2nd International Symposium on Cone Penetration Testing (CPT'10), Vol. 2, Huntington Beach, CA, USA, 9-10 May 2010, p. 425 – 430.

[19] **Robertson P. K., Campanella R. G., Gillespie D. G., Greig J.** Use of piezometer cone data. Proc. of the ASCE Specialty Conference (In-Situ'86): Use of In Situ Tests in Geotechnical Engineering, Blacksburg, VA, USA, 23-25 June 1986, p. 1263 – 1280.

[20] **Schneider J. A., Hoyos L. Jr., Mayne P. W., Macari E. J., Rix G. J.** Field and laboratory measurements of dynamic shear modulus of Piedmont residual soils. Behavioral characteristics of residual soils. Proc. of the Sessions of the Geo-Congress'99, Geotechnical Special Publications No. 92, ASCE, Charlotte, NC, USA, 17-20 October 1999, p. 12 – 25.

[21] **Suzuki Y., Sanematsu T., Tokimatsu K.** Correlation between SPT and seismic CPT. Geotechnical site characterization. Proc. of the 1st International Conf. on Site Characterization (ISC'98), Vol. 2, Atlanta, Georgia, USA, 19-22 April, 1998, p. 1375 – 1380.

[22] **Trevor F., Paisley J. M., Mayne P. W.** Cone penetration tests at active earthquake sites. Proc. of 2nd International Symposium on Cone Penetration Testing (CPT'10), Vol. 2, Huntington Beach, CA, USA, 9-10 May 2010, p. 519 – 526.

[23] **Woods R. D., Henke R.** Seismic techniques in the laboratory. ASCE Journal, Geotechnical Engineering Division, Vol. 107, Issue GT10, 1981, p. 1309 – 1325.

[24] **Woods R. D.** Laboratory measurement of dynamic soil properties. Dynamic Geotechnical Testing II, ASTM Special Technical Publication No. 1213, Eds. Ebelhar R. J., Drnevich V. P., Kutter B. L., American Society for Testing and Materials, Philadelphia, USA, 1994, p. 165 – 190.

[25] **Youd T. L., Idriss I. M.** Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geo-Environmental Engineering ACSE, Vol. 127, Issue 10, 2001, p. 297 – 313.

[26] **Long M.** Design parameters from in situ tests in soft ground – recent developments. Geotechnical and geophysical site characterization. Proc. of the 3rd Int. Conf. on Site Characterization (ISC'3), Taipei, Taiwan, 1–4 April, 2008, p. 89 – 116.

[27] **Campanella R. G., Howie J. A.** Practical Applications of the Cone Penetration Test. A Manual on Interpretation of Seismic Piezocone Test Data for Geotechnical Design, Civil Engineering Department, June 2005, 305 p.

[28] **Sully J. P., Campanella R. G.** In situ shear wave velocity determination using seismic cone penetrometer for evaluating soil anisotropy. Proc. of the 10th World Conf. on Earthquake Engineering, Madrid, Spain, 19-24 July 1992, p. 1269 – 1274.

[29] **Anderson N., Croxton N.** Introduction to Geotechnical Geophysics, Geophysical Methods Commonly Employed for Geotechnical Site Characterization. Transport Research Board, Washington, July 2008, 44 p.