Field and laboratory measurements of shear wave velocity in unsaturated soils

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Abstract. Shear wave velocity measurements in soil are important for assigning site soil profiles to seismic site classes and for calculating other dynamic soil properties. The seismic cone penetration test (SCPT) is commonly used to determine shear wave velocity profiles in the field. In the laboratory, bender elements provide an easy means to measure shear wave velocity of soil specimens from discrete depths. In this study, shear wave velocity measurements obtained from unsaturated soil profiles in the field and on field samples in the laboratory under similar stress conditions were analyzed and compared. Additionally, the influence of seasonal changes on the behavior of shear wave velocity was investigated. Comparisons of shear wave velocities from the field and laboratory were favorable for similar moisture and stress conditions. However, results showed that as the degree of saturation increases and suction decreases the shear wave velocity can decrease significantly.

1 Introduction

1.1 Background

Shear wave velocity is an important dynamic soil measurement used for assigning site soil profiles to seismic site classes that govern geotechnical and structural design. It is also used to calculate the small strain shear modulus of the soil, which is an essential parameter for geotechnical and earthquake engineering design. Various methods exist to measure the shear wave velocity in the field and the lab. The seismic cone penetration test (SCPT) is a common method used to determine the shear wave velocity in the field with the added benefit of providing other useful cone penetration test parameters. During a SCPT, arrival times of shear waves generated at the ground surface are determined after halting the cone penetration at discrete depths and taking measurements. In this way, average shear wave velocity between SCPT measurement depths can be determined. In the laboratory, bender elements are commonly used to measure the shear wave velocity of samples from discrete depths.

The SCPT also provides nearly continuous measurements of cone tip resistance, sleeve friction and pore water pressure in the case of a piezocone (SCPTu). This information is extremely useful for geotechnical analysis, in addition to the shear wave velocity determinations. However, a limitation of the SCPT is the lack of soil sampling during testing. This is a problem since soil samples are needed for laboratory testing to compare with the results from the field. Generally, the availability of comparisons between field- and lab-measured shear wave velocity is limited in the published literature. Although, some studies have examined the accuracy of shear wave velocity measurements in the field using measurements done in the laboratory [1-3]. Valsson et al. [3] investigated the differences in shear wave velocity between the field and the laboratory for one site consisting of a 30 m thick clay layer. The plasticity index (PI) and water content of the soil profile ranged between 30-45% and 40-80%. The SCPT was conducted in the field to measure the shear wave velocity at 1 m intervals. In the laboratory, the shear wave velocity was measured using a triaxial cell equipped with bender elements. Soil samples in the lab were tested at similar moisture and stress conditions to the field. Valsson et al. observed a good agreement between the field and lab shear wave velocity determinations. On the other hand, Landon et al. [1] measured the shear wave velocity in Boston Blue Clay (BBC) soil. The tested site consisted of a 16 m thick BBC layer with the water table located at a depth of 1.7 m. The PI ranged between 24-30%, and the water content ranged between 40-55% for the tested site. The shear wave velocity was measured in the field using the SCPT and a set of portable piezoelectric bender elements. The bender elements were used to measure the shear wave velocity of the block clay samples extruded in the field. Results showed that shear wave velocities measured using the SCPT were higher than those from bender element measurements on block samples. This may have been due to the fact that samples tested using the bender elements were not subjected to confining stresses.

Another limitation of the SCPT arises during testing in unsaturated soils. In an unsaturated soil profile, the

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shear wave velocity measurements depend on the moisture content and suction in the soil at the time of testing. If testing is done during a drier weather period, then soil conditions during the SCPT may not portray the worst conditions of the soil profile needed for geotechnical design. Some studies have investigated the influence of moisture content and suction on CPT parameters [4-7]; however, research into the effect of seasonal moisture changes on shear wave velocity measured with the SCPT is limited. Lehane et al. [4] investigated the effect of seasonal changes on in situ parameters at one site using SCPT measurements. The tested site consisted of a 12 m slightly moist aeolian siliceous sand layer. To account for seasonal changes, the SCPT was conducted once during the wet season and once during the dry season. Lehane et al. found that shear modulus, and hence shear wave velocity, varied during wet and dry seasons; higher shear modulus was observed during the dry season. Additionally, the shear modulus was measured in the lab using the bender element method under various saturations. Similar trends were found between shear modulus measurements taken in the field and the lab; as water content increases, shear modulus decreases.

This paper present results of an investigation involving three unsaturated soil profiles, where shear wave velocities determined from field and lab testing were compared. Results from the SCPT were compared to those obtained in the lab from bender element tests on thin-walled tube specimens from the field. Additionally, the influence of wetting and drying was investigated in the laboratory by changing the moisture conditions of the field specimens and determining corresponding shear wave velocity using bender elements.

1.2 Scope of research

The SCPT was performed at three sites across the state of Oklahoma, USA. During testing, the cone was halted at selected depths and shear wave arrival times were determined for shear waves generated at the ground surface. Using this information, shear wave velocities for soil layers in between the measurement depths were calculated. At each test site, moisture and suction conditions were determined by collecting soil samples from various depths on the same day the SCPTs were conducted. Soil samples were subjected to laboratory testing to determine the water content and total suction. Similarly, on the same day, thin-walled tube (Shelby tube) samples were collected at each site from depths of interest. These were used to determine shear wave velocity in the lab using bender element testing.

Shear wave velocities in tube samples were determined in the lab at in-situ moisture conditions (as-sampled), near saturation, and near dry conditions, using a modified bender element cell equipped to control the total confining stress on the sample. After bender element testing on samples at the in situ condition, the samples were wetted and dried using the vapor equilibrium method, and bender element testing was again conducted at near saturated and near dry conditions. The collection of shear wave velocity data at various moisture conditions is being used to build a framework for interpretation of shear wave velocity in unsaturated soil profiles considering moisture conditions at the time of field testing and changes due to seasonal wetting and drying.

2 Field and laboratory testing

2.1 Field testing

At each test site, the SCPT was conducted by pushing the cone into the ground at a rate of 2 cm/s and halting the cone at 1 m depth increments to conduct shear wave velocity testing. With the cone at the desired depth, a metal plate anchored at the ground surface was struck by a 2.3-kg hammer, and shear waves were detected by geophones sensors in the cone; sensor measurements were collected using a data acquisition system. During penetration the cone tip resistance and sleeve friction were obtained as well in between seismic test depths. However, this tip resistance and sleeve friction data is not discussed in the current paper.

Additionally, a companion test boring was conducted on the same day as SCPTs to collect disturbed and relatively undisturbed soil samples for laboratory testing. Relatively undisturbed Shelby tube samples were obtained for shear wave velocity measurements using the bender elements method, and disturbed samples were used for index property testing, water content and suction measurements.

2.2 Laboratory testing

For laboratory testing, moisture content, suction, and shear wave velocity measurements were conducted on the collected soil samples. Additionally, undisturbed soil samples were subjected to wetting and drying using the vapor equilibrium suction control method [8, 9]. This method uses the osmotic potential of a chemical solution to create an atmosphere of constant relative humidity corresponding to a desired suction in a sealed container as shown in Figure 1.

To start the wetting and drying cycles, Shelby tube samples were trimmed to a 1:1 diameter-to-height ratio and specimens were placed in the glass chambers. Each test specimen was placed in the chamber with a companion sample which was used to measure the suction and water content along the wetting and drying paths. Samples were initially subjected to a wetting cycle followed by a drying cycle.

Figure 1 Vapor equilibrium chambers used to impose the total suction on the soil samples along the wetting and drying paths.

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Once the desired water content was reached, the soil sample used for shear wave velocity measurement, and the companion soil sample were removed from the chamber to conduct the water content, suction, and shear wave velocity measurements.

Soil suction was measured using the WP4-T chilled mirror dew point hygrometer. Suction was initially measured at in-situ conditions, then samples were allowed to wet/dry and suction measurements were taken again near saturated/dry conditions.

The shear wave velocity measurements were conducted using a bender element system as shown in Figure 2. This system consists of:

1) modified triaxial cell equipped with an air pressure control system to apply the desired confining stresses on the test specimens,
2) piezoelectric ceramic plates (bender elements) attached to sender and receiver platens,
3) a function generator used to excite waves through the soil samples, and
4) an oscilloscope used to receive and display the waves generated using the function generator.

For each sample, a confining stress similar to the estimated average in-situ stress was applied on the sample before testing. To determine the sufficient consolidation time, a near saturation sample was allowed to consolidate and shear wave velocity was measured at 1, 5, 15, 30, and 60 minutes. Negligibly small differences were found between shear wave velocity measurements after 15 minutes of consolidation. Therefore, during testing, samples were left to consolidate for 15 minutes followed by shear wave velocity measurements. The same process was repeated for in-situ, near saturation, and near dry moisture conditions.

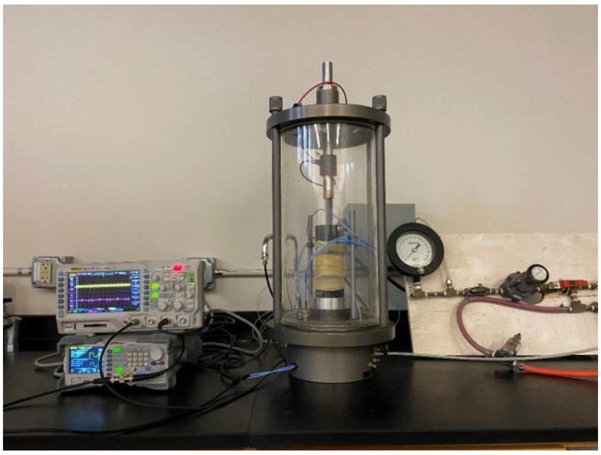

Figure 2 Bender element system consisting of a modified triaxial cell, air (cell) pressure control system, bender element platens, function generator, and an oscilloscope.

3 Test Sites

3.1 Site properties and soil profiles

Three sites were tested across the state of Oklahoma, USA. For each site, the site number, location, and site coordinates are shown in Table 1. The soil property profiles including the USCS group symbol, water content, plastic limit, liquid limit, and percent of fines are shown in Figures 3-5. In general, soil profiles consisted of a mixture of lean clay and silty soils.

Table 1 Site number, location, and coordinates of tested sites.

Site	Location	Coordinates
1	Oklahoma city	35°27’52’’N 97°31’50’’W
2	Norman	35°11’41’’N 97°22’04’’W
3	Tuttle	35°19’47’’N 97°51’45’’W

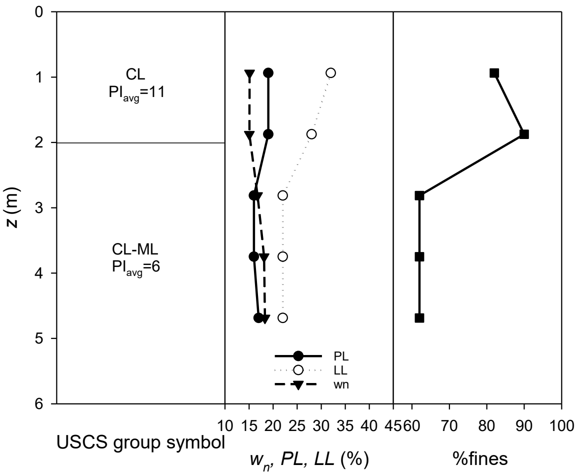

Figure 3 Soil profile for Site 1 including USCS, water content, plastic limit, liquid limit, and percent of fines.

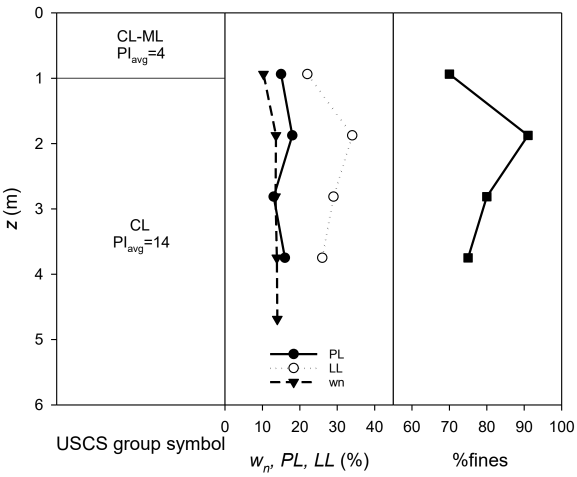

Figure 4 Soil profile for Site 2 including USCS, water content, plastic limit, liquid limit, and percent of fines.

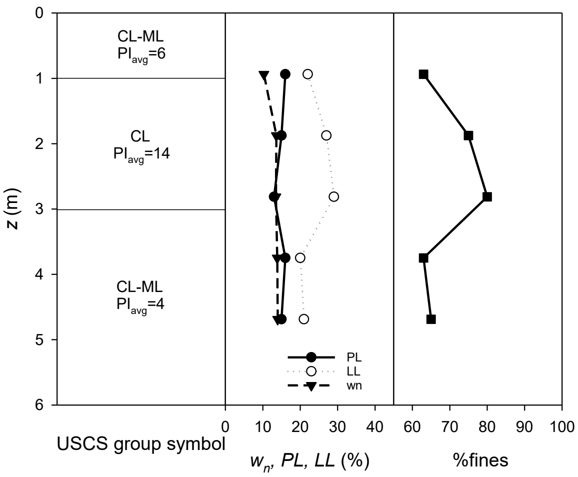

Figure 5 Soil profile for Site 3 including USCS, water content, plastic limit, liquid limit, and percent of fines.

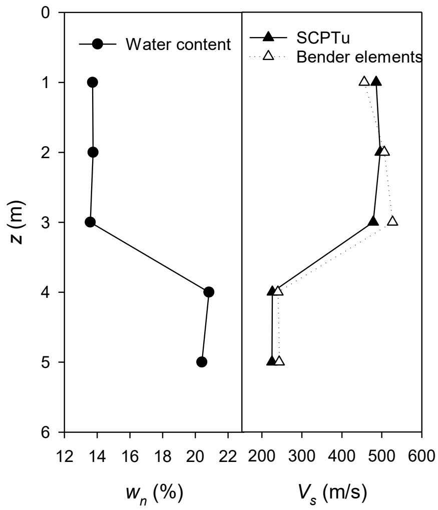

Figure 6 Water content and shear wave velocity results for tests conducted at Site 1. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

4 SCPT and bender elements shear wave velocity results

4.1 SCPT and bender element comparison results

Shear wave velocity results and water content measurements are shown in Figures 6-8. Shear wave velocity determinations from the SCPT and the bender element method are plotted side by side for comparison. Values from the SCPT represent the average shear wave velocity value for the 1-meter layer above the plotted point, whereas the values from the lab were determined on a 75-mm long sample from the test depth. Thus, the comparison is not exact in that it involved averages over different soil depths. For each site, SCPT measurements are shown using closed triangle symbols and bender element measurements are shown using open triangle symbols. Water content data correspond to the values at the test depths on the SCPT testing date, which was determined using soil samples collected in the field on the testing date.

Results in Figures 4-6 show that there was a variation in the water content along the soil profile. Also, shear wave velocities measured using the SCPT varied along the tested soil profiles in a manner that mirrored the water content profile.

Moreover, SCPT and bender element shear wave velocity measurements were nearly identical along the soil profile for Sites 1 and 2. For Site 3 small differences were found in the results between SCPT measurements and bender element measurements, where the first measurement was higher using the SCPT while the rest of the measurements were slightly higher using the bender element method. For the shallowest depth, this is likely due to fact that SCPT values represent the average for the first 1 m of soil where water content variations were probably relatively larger in the case of Site 3. The remaining differences may also be attributed to the differences in measurement depth ranges involved in each of the test methods, and natural variability in the soil profile.

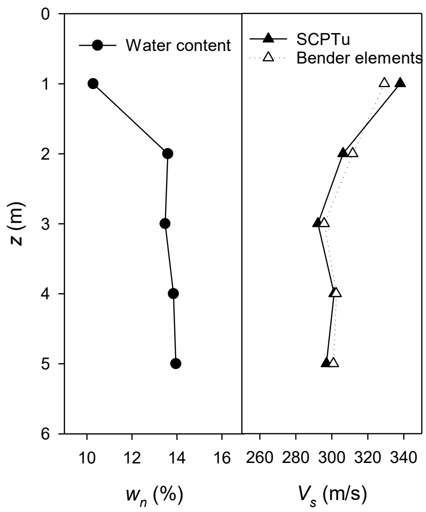

Figure 7 Water content and shear wave velocity results for tests conducted at Site 2. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

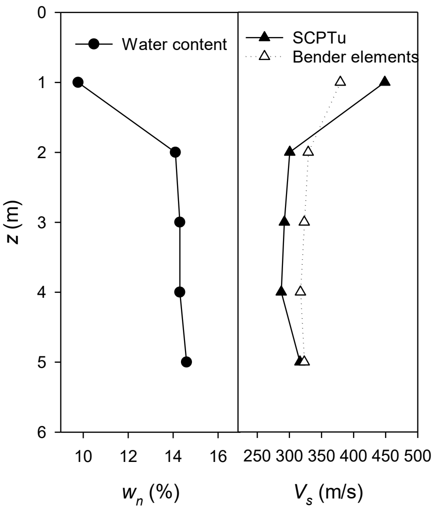

Figure 8 Water content and shear wave velocity results for tests conducted at Site 3. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

4.2 Bender element results for wet and dry samples

Water content, suction, and shear wave velocity measurements for soil samples tested at various moisture conditions are shown in Figures 9-11. Closed circles, open circles, and closed triangles were used to represent in-situ, dry, and wet conditions, respectively.

Results show a variation in water content, suction, and shear wave velocity as degree of saturation changes. For all three sites, the shear wave velocities under dry conditions were higher than in-situ and near saturated conditions. Hence, as water content decreases and suction increases, shear wave velocity increases. Additionally, results show that in-situ conditions were closer to wet conditions, which indicates that the SCPTs were conducted during a wetter season.

It was noticed that there was a major difference between measurements taken during wet and dry conditions. For example, for Site 2 the wet shear wave velocity was around 280 m/s along the soil profile while dry shear wave velocity was around 630 m/s. This is an important observation since the change between wet and dry conditions may affect the seismic site class of the tested soil, i.e., soil moved from class D to class C as soil dried. However, the actual seismic site class would depend on the shear wave velocity in the upper 30.5 m of the soil profile. Thus, the seismic site class may not change from D to C due to drying, but it could, depending on the average seismic velocity for the 25.5 m of soil underneath the 5 m deep profile considered here. Thus, it is important to consider the moisture conditions when investigating the shear wave velocity using the SCPT in unsaturated soil profiles.

During testing, the dry unit weight of the soil samples was obtained by determining their volume and computing the unit weight based on the total weight and measured water content. It's worth noting that the changes in water content have a significant impact on dry unit weight due to shrinking and swelling. Changes in dry unit weight, in turn, can have a significant effect on the shear wave velocity of the soil. As dry unit weight increases, the stiffness of the soil also increases, leading to a corresponding increase in the shear wave velocity. Conversely, as dry unit weight decreases, the soil becomes less stiff, resulting in a decrease in the shear wave velocity. Table 2 presents the results of the measurements of the dry unit weight of the soil tested for Site 1. Similar results were observed for the other test site soils.

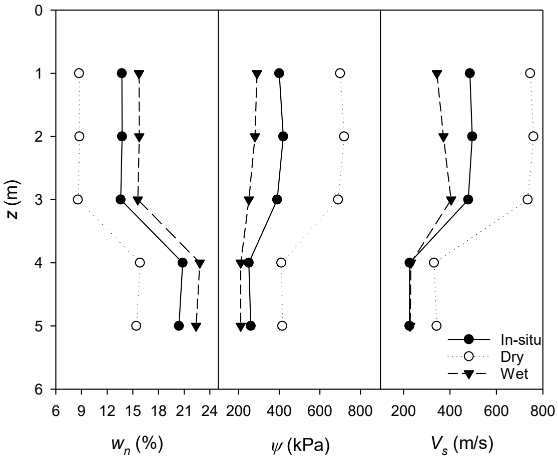

Figure 9 Soil profile showing water content, suction, and shear wave velocity results for Site 1 under in-situ, dry, and wet saturation conditions.

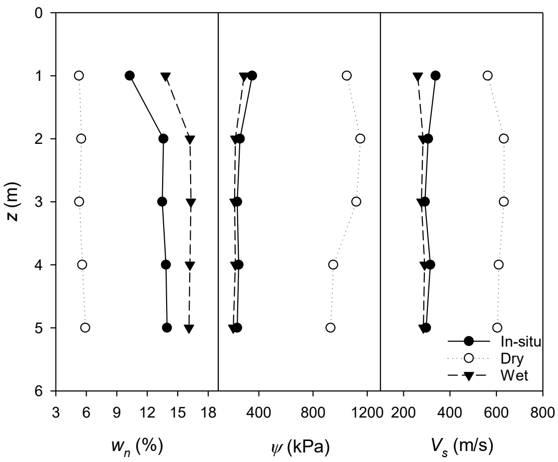

Figure 10 Soil profile showing water content, suction, and shear wave velocity results for Site 2 under in-situ, dry, and wet saturation conditions.

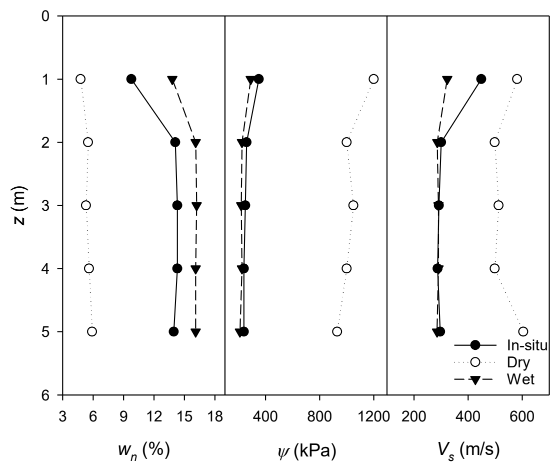

Figure 11 Soil profile showing water content, suction, and shear wave velocity results for Site 3 under in-situ, dry, and wet saturation conditions.

Table 2 Dry unit weight for soils tested at Site 1 at in situ, dry, and wet conditions.

Depth (m)	Soil type	Dry unit weight (in situ condition) (kN/m^3)	Dry unit weight (Dry condition) (kN/m^3)	Dry unit weight (Wet condition) (kN/m^3)
1	CL-ML	15.44	15.99	15.06
2	CL	14.94	15.21	14.58
3	CL	15.04	15.29	14.67
4	CL	14.87	15.54	14.28

5 Discussion and conclusions

In this study, various aspects related to the determination of shear wave velocity in unsaturated soil profiles have been investigated. Shear wave velocity was determined at three sites using the SCPT and bender element testing methods. Shear wave velocity measurements from the field and the laboratory were compared to investigate any differences in the two methods. Laboratory measurements were subjected to confining stresses similar to the in-situ overburden pressure to replicate the stress conditions in the field. Results showed that shear wave velocity measurements taken using the SCPT and the bender elements were in good agreement as shown in Figures 6-8 for the sites investigated. These results validate the accuracy and dependability of the field shear wave velocity measurements from the SCPT.

Additionally, the influence of seasonal changes on the behavior of shear wave velocity was investigated. To do so, undisturbed soil samples collected in the field were placed in glass suction control chambers where relative humidity was controlled using chemical salt solutions. Shear wave velocity, moisture content, and suction measurements were taken for the tested samples at various saturation conditions. Results showed that as the saturation decreases, the shear wave velocity increases. Hence, shear wave velocities measured in dry seasons are higher than those measured during the wet season. It follows given the agreement between field and lab measurements, that shear wave velocities determined with the SCPT would be similarly sensitive to moisture content changes.

The results from this study show that SCPT is a reliable means of conducting shear wave velocity measurements in the field. Also, it is extremely important to consider the soil moisture conditions during field testing in unsaturated soil profiles. Tests conducted in drier seasons could lead to an overestimation of the shear wave velocity compared to wetter seasons, and hence seismic site class and performance of designed structures could be adversely affected.

References

1. M.M. Landon, D.J. DeGroot, J. Jakubowski, Comparison of shear wave velocity measured in situ and on block samples of a marine clay, in Proceedings of the **57th** Canadian Geotechnical Conference, Que, Quebec City, (2004)
2. K. Markowska-Lech, M. Lech, A. Szymanski, Estimation of shear modulus from seismic tests on Pliocene clays, in Proceedings of the 10th International Symposium on Numerical Models in Geomechanics (NUMOG X), Rhodes, Greece, (2007)
3. S.M. Valsson, , M. Dahl, E. Haugen, S.A. Degago, Estimating shear wave velocity with the SCPTu and Bender element, in IOP Conference Series: Earth and Environmental Science, vol. **710**, IOP Publishing, (2021)
4. B.M. Lehane, M. A. Ismail, M. Fahey, Seasonal dependence of in situ test parameters in sand above the water table, Géotechnique **54**, (2004)
5. G.A. Miller, N.K. Tan, R.W. Collins, K.K. Muraleetharan, Cone penetration testing in unsaturated soils, Transportation Geotechnics **17** (2018)
6. R. Collins, G.A. Miller, Cone penetration testing in unsaturated soils at two Instrumented test sites, in Unsaturated Soils: Research & Applications, CRC Press, (2020)
7. G.A. Miller, R.W. Collins, K.K. Muraleetharan, T.Z. Abuawad, Application of in situ tests in unsaturated soils to analysis of spread footings, Soils and Rocks **44** (2021).
8. D.Tessier, Experimental study of the organization of clay materials, hydration, swelling and structuring during dessication and rewetting, PhD dissertation, Marseille, France (1984)
9. J.A. Blatz, C. Yu-Jun, L. Oldecop, Vapour equilibrium and osmotic technique for suction control, in Laboratory and field testing of unsaturated soils, Springer, Dordrecht, (2008)