Correlations between shear wave velocity obtained from PS Logging and pressuremeter test data in silty sands

Corrélations entre la vitesse de l'onde de cisaillement issue des diagraphies PS et les essais pressiométriques en sables limoneux

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ABSTRACT

The pressuremeter is a versatile ground investigation equipment that is used to test any type of soil or rock in situ, quantifying in-situ stress, stiffness and strength. However, for the seismic design, the shear wave velocity up to a depth of 30 m below the foundation level is required. To determine the shear wave velocities of the soil, typically a seismic refraction survey is conducted. The seismic refraction surveys are quick and relatively inexpensive tests. However, they require the expansion of geophones which is equal to three times the depth from which information is required. So, even for a structure resting directly on the surface, to get the shear wave velocities of the strata up to a depth of 30 m depth, you must spread the geophones linearly on the surface extending to 90 m. Specially in urban environment, this can be impossible for most cases. So, one option is to conduct geophysical tests such as PS logging, but these tests are relatively expensive and time consuming, because after you drill the site investigation borehole to the desired depth, you must clean the borehole of debris and ensure it is free of obstructions. Then a casing is often necessary to ensure the stability of the borehole to provide a clean and consistent path for the shear wave signals and finally the geophones and seismic sources are installed in the borehole. Although there is little literature available, the existing studies indicate that a good correlation may exist between the E modulus determined from pressuremeter test and the shear wave velocity. In this paper case studies from various international projects have been selected where both PMT and PS logging tests have been conducted at the same boreholes providing a unique opportunity to compare the results and empirical relations between two methods. This empirical relationship correlates the Menard modulus to the shear velocity with the regression value of $R^2 = 0.77$ which is much better than previous studies regarding the parameters mentioned.

RESUME

Le pressiomètre est un équipement d'investigation du sol polyvalent qui est utilisé pour tester tout type de sol ou de roche in situ, en quantifiant la contrainte, la rigidité et la résistance in situ. Cependant, pour la conception sismique, la vitesse des ondes de cisaillement jusqu'à une profondeur de 30 m sous le niveau de la fondation est nécessaire. Pour déterminer les vitesses des ondes de cisaillement du sol, une étude de sismique réfraction est généralement effectuée. Les études de sismique réfraction sont des tests rapides et relativement peu coûteux. Cependant, elles nécessitent l'expansion des géophones qui est égale à trois fois la profondeur à partir de laquelle les informations sont requises. Ainsi, même pour une structure reposant directement sur la surface, pour obtenir les vitesses des ondes de cisaillement des strates jusqu'à une profondeur de 30 m, vous devez étendre les géophones linéairement sur la surface jusqu'à 90 m. Surtout en milieu urbain, cela peut être impossible dans la plupart des cas. Une option consiste donc à effectuer des tests géophysiques tels que la diagraphie PS, mais ces tests sont relativement coûteux et prennent du temps, car après avoir foré le trou de forage d'investigation du site à la profondeur souhaitée, vous devez nettoyer le trou de forage des débris et vous assurer qu'il est exempt d'obstructions. Ensuite, un tubage est souvent nécessaire pour assurer la stabilité du trou de forage afin de fournir un chemin propre et cohérent pour les signaux d'ondes de cisaillement et enfin les géophones et les sources sismiques sont installés dans le trou de forage. Bien qu'il existe peu de littérature disponible, les études existantes indiquent qu'une bonne corrélation peut exister entre le module E déterminé à partir du test pressiométrique et la vitesse de l'onde de cisaillement. Dans cet article, des études de cas de divers projets internationaux ont été sélectionnées où des tests de diagraphie PMT et PS ont été effectués dans les mêmes trous de forage, offrant une occasion unique de comparer les résultats et les relations empiriques entre les deux méthodes. Cette relation empirique corrèle le module de Menard à la vitesse de cisaillement avec une valeur de régression de $R^2 = 0.77$, ce qui est bien meilleur que les études précédentes concernant les paramètres mentionnés.

Keywords: PS Logging Test, shear wave velocity, Pressuremeter Test, Silty sand

1. Introduction

In situ Geotechnical and Geophysical tests are the two main methods used in practice to obtain the soil strength and soil deformation properties and to assess the in-situ stress state of a soil deposit. In situ tests are often preferred to laboratory tests as they reveal more realistic and reliable results since they are carried out without soil disturbance.

Pressuremeter test (PMT) is one of the widely used in-situ tests carried out to estimate the soil properties. Statistical correlations based on PMT results are vital and important for many geotechnical engineering projects. In practice, in situ tests and correlations derived between the tests results are very important because not only do they provide a cross-check, but also because sometimes due to several factors some in-situ tests might not be available or applicable.

PMT is a unique device amongst the different in situ devices that has the potential to derive the full stress-strain curve. The test is also unique considering the range of materials it could be used in, compared to other tests. Namely, PMT could be used in sandy formations, soft to firm clays and even in rocks.

On the other hand, geophysical tests such as PS logging or cross hole tests are important tests specially to obtain parameters for seismic design. The average shear wave velocity of the top 30 m depth of soil $(V_s)_{30}$ is a parameter that is used to represent the contribution of the subsoil conditions to the behavior of the superstructure and provides insight into the strength properties of the soil and rock. However, often difficulties are experienced during the geophysical tests to determine the $(V_s)_{30}$ value. Sometimes the necessary equipment like PS logging is not available, or the cost of the tests is very high. The least expensive in-situ test to determine the $(V_s)_{30}$ is the seismic refraction method. However, sometimes the site is not long enough for surficial measurements to be conducted properly up to the required depths. Literature also cites that the seismic refraction results may not be as precise as for example PS Logging measurements. Haque et al. (2013), Cheshomi, A. & Khalili, A (2021) and Akkaya et al (2019) compared the geophysical test results obtained from MASW (Multichannel Analysis of Surface Waves) and PS logging tests and concluded that the most reliable and precise $(V_s)_{30}$ results are obtained from PS Logging tests which is conducted as a suspension downhole test. Figure 1 shows the comparison results as a chart.

Letif and Bahar (2024) report one of the most recent research projects for the relationship between Menard modulus and shear wave velocity including both clayey and silty sand soils. They also provide a correlation for predicting shear wave velocity from Menard modulus for silty sand soils (Figure 2). Considering the regression value they obtained for the correlation, empirical relations in silty sandy soils can be considered of satisfactory magnitude. However, according to theoretical evaluations and the derivation provided in Reiffsteck et al. (2022), the general form of the correlation between shear wave velocity and Menard modulus is expressed as $Vs = a\, Em^b$ and is not of linear nature as shown in Letif and Bahar (2024). It is our opinion though, that the empirical relationship between Vs measurements obtained from PS logging test presents more realistic results compared to those obtained from seismic refraction tests which were used in previous studies

A study reported by Reiffsteck et al. (2022) gives correlations between shear wave velocity and Menard modulus for different types of soils as can be seen in Figure 3. According to the findings given in this study, PS logging tests provide more reliable values in comparison to MASW test results. However, the authors acknowledge that there is a big scatter in the data which can be due to the different methods which might have been implemented to determine the shear wave velocity of the corresponding layers.

Therefore, it seems inevitable to search for empirical equations which can help geotechnical engineers to obtain shear wave velocity from different test results, for example from Menard modulus values since pressuremeter test is a very reliable test representing in-situ soil conditions in a precise manner. Numerous empirical correlations for the soil or rock units have been proposed in the literature that are based on V_s. However, due to the high reliability of the pressuremeter, providing correlations between PMT and shear wave velocity (V_s) as an alternative can be very beneficial.

In this study a set of test data from an international project during our geotechnical consultancy have been gathered specially where Pressuremeter and PS Logging tests have been conducted within the same location as part of the geotechnical investigation campaign.

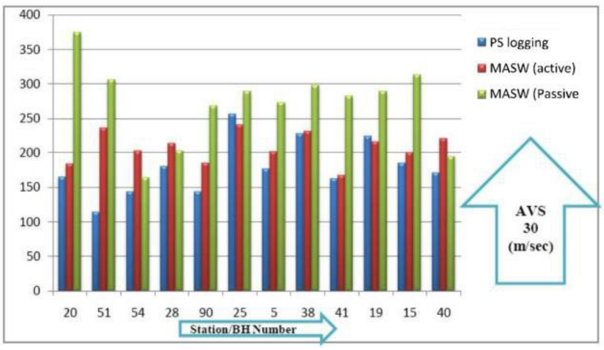

Figure 1. Comparing the $(V_s)_{30}$ results obtained from PS Logging and seismic refraction tests (Haque et al, 2013)

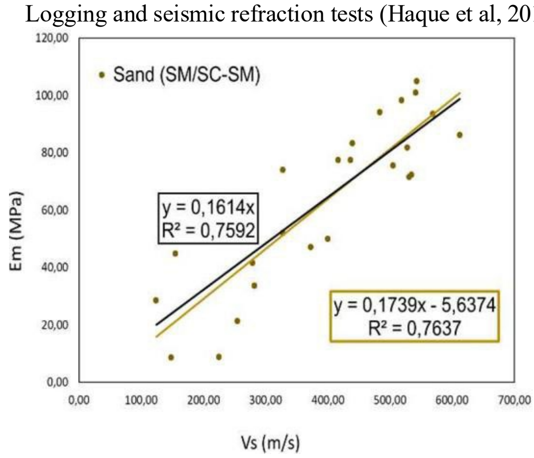

Figure 2. Empirical relationship obtained for sand (Letif and Bahar, 2024)

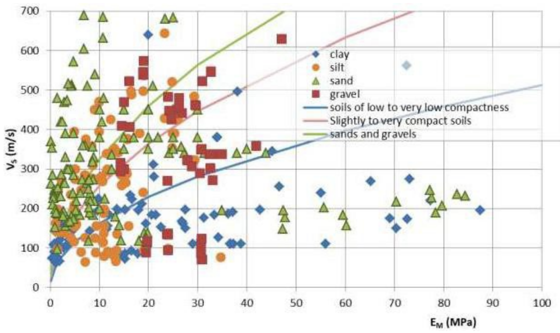

Figure 3. Correlation of the shear wave velocity and the Menard modulus for all soil (Reiffsteck et al., 2022)

Figure 4. Conducting Pressuremeter test at the same location

Figure 5. Conducting PS Logging test at site

2. Methodology and Equipment Used to Obtain Data

The data used for this study was collected from two detailed soil investigation campaigns. One study was conducted for the construction of the Ashgabat New International Airport project in Turkmenistan. As part of this study 6 boreholes were explored within the scope of the geotechnical investigation plan of Ashgabat international airport project. Project area is located in the Ashgabat Municipality. Ashgabat is the capital and largest city of Turkmenistan, a country in Central Asia, and is situated between the Kara Kum desert and the Kopet Dag mountain range, about 19 miles (30 kilometers) from the Iranian frontier. The investigation area is located on the Upper Pliocene aged, continental marine, deposits which mainly consists of Silty SAND. Furthermore, the area is covered with Eolian sand and sand dunes, which are constantly eroded from one place and sedimented to another by wind. Also, cross-beddings of the eolian sands are visible on the surface of the working area. Project Area is 2.300.000 m^2 including a runway and other structures. According to the factual reports of these projects, soil unit consists of silty sand and clayey silt. The silt ratio varies on average from 40% to 90% with depth and the sand consists of fine sized grains. These deposits were sedimented in a low-energy environment and consequently coarse sized sand grains or gravels are not present. Investigated boreholes were drilled up to 60 m depth where pressuremeter tests were conducted within 3-4 m intervals (Figure 4). After completion of pressuremeter tests PS logging tests were performed within the same boreholes (Figure 5) which could help to analyze the relationship between geophysical and PMT data in a detailed manner.

Same comparison has been made for another site in Iraq, Basra. The soil on this site consisted of silty sands and clayey soils. Since it is known from literature that the relation between shear wave velocity and pressuremeter testing is dependent on the soil type, only the data which came from silty sands have been used in this study. Project site is located at the city of Faw which is a city of Basra province in Southern Iraq. The soil investigation for this project has been conducted by ALMAMAAS Company within the scope of the geotechnical investigation campaign for service berth project at Al Faw Port in Iraq.

At both sites Menard GA type pressuremeter with BX and NX types of probes were employed to carry out pressuremeter tests. Tests were executed according to the ASTM D 4719-87 at the Iraq site and according to ASTM D 4719-87 and GOST 20276-99 standards at the Turkmenistan site. The probe is lowered into the borehole and is inflated with compressed carbon dioxide gas and radial displacements at test depth are recorded with every 0.5 and 1 minute at each pressure level. Menard GA and probes of 76 mm diameters were used for testing. The tests in Turkmenistan were conducted by STFA (2013) and reported in New Ashgabat Airport project factual report. The pressuremeter tests in the Iraq site were conducted by Almamas Company in 2023.

Shear wave measurements were conducted by means of PS Logging tests after completion of pressuremeter tests at the same borehole. The suspension PS logging method has gained acceptance since the 1990's and is widely used for determining seismic velocities. The method is based on the double sensors recording seismic waves with three axial geophones generated by the source which was lowered into borehole via armored suspension cable. Later these seismic recordings are processed and seismic velocities determined for each measuring level. Suspension P-wave and S-wave velocity logging instrument is a lower frequency acoustic probe. It is exclusively possible to obtain high resolution P and S waves towards depths. Reliable P and S-wave velocities can be assessed down to depths which were almost impossible from surface methods. PS Logging tests were conducted by Iyisan and Çevikbilen (2013) and reported in the technical reports of the relevant sites.

3. Correlation Results

Relationship between Menard modulus and shear wave velocity was investigated according to the data from these two geotechnical investigations in Turkmenistan and Iraq. Since both PS logging test and pressuremeter tests were conducted within the same boreholes, highest compatibility was provided regarding the analysis of soil type, in-situ stress conditions and depth. Totally 34 data pairs of Em –Vs from same soil type (silty Sand) were analyzed. Empirical results obtained from this study are given in Figure 6 which has a relatively good correlation coefficient of R^2 = 0.77. The correlation formula is as:

$$Vs = 75\ Em^{0.5}$$

where V_s is the shear wave velocity in m/s and E_m is the Menard Modulus in MPa.

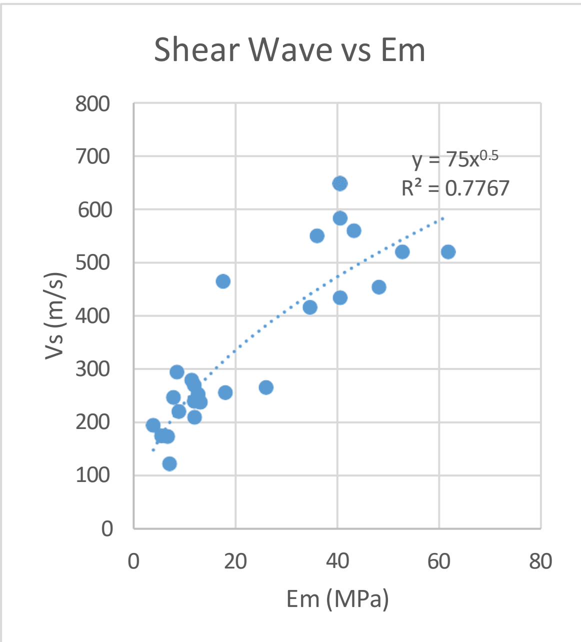

Figure 6. Relationship between E_m and V_s for silty sands

4. Conclusions

This study explored an empirical relationship between Menard modulus and shear wave velocity obtained from PS logging test for silty sand soils. Due to the availability problems of seismic testing instruments, especially PS logging test which can be assumed as an expensive in-situ experiment in some regions, a correlation which could assist geotechnical engineers obtaining shear wave velocity from Menard modulus seems profitable. The proposed model shows a good regression ratio between the obtained tests results. Based on the findings of this study a correlation for silty sands can be given as $Vs = 75\ Em^{0.5}$. However, it should be noted that the same correlation might not be valid for clayey soils. Some studies have been conducted previously by other researchers for clayey soils and empirical equations have been presented. However, additional data from different types of soils can be beneficial to improve the correlation.

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