Correlation between Menard pressuremeter modulus and shear wave velocity for various type of Algerian soils

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ABSTRACT: Soil deformation modulus is an important geotechnical parameter that characterizes the stiffness of soils. Menard Pressuremeter Test (MPT) is one geotechnical field test that analyzes the elasto-plastic soil behavior through its stress-strain curve results. MPT is a well-known expensive in-situ test that determines soil deformation modulus, known as Menard Pressuremeter Modulus (E_m). On the other hand, Shear wave velocity (Vs) is a geophysical parameter that characterizes soil stiffness more reliably and less costly. This study proposes correlation between E_m and Vs for sand, clay, marl, and all soils. Very few contributions have been made to investigate the relationship between E_m and Vs. This study provides an extensive database collected from different sites in central Northern Algeria. A comparison study was conducted between the proposed correlations in this study and those presented in the literature based on normalized consistency ratio (CR) values, revealing a good accuracy of the developed proposed models.

1 INTRODUCTION

Geotechnical and geophysical tests are common field methods used to investigate the engineering field soil properties that can potentially affect proposed civil engineering projects. Geotechnical in-situ tests consist of all of the Menard pressuremeter test (MPT), standard penetration test (SPT), cone penetration test (CPT), dilatometer tests (DMT) and others. Geophysical tests, on the other hand, include such as cross-hole, down-hole, Spectral Analysis Of Surface Waves (SASW), Multi-Channel Analysis Of Surface Waves (MASW), and Spatial-Autocorrelation Method (SPAC).

MPT method is one geotechnical field test that provides the strain-stress relationship at a specific depth level for different soil types, ranging from soft clays to weak rock. Through this test, different geotechnical parameters are obtained, namely, pressure limit (P_l), soil deformation modulus often called Menard pressuremeter modulus (E_m), sub-grade reaction modulus (K_s), and shear modulus (G). Menard pressuremeter modulus is a key engineering property as it can be used for different geotechnical purposes, such as determining the stiffness of soil or rocks, the ultimate bearing capacity, and the settlements of foundations in geotechnical projects. MPT method is an in-situ test that measures the stress-strain response of soils at a specific depth using an inflatable loading system (Bahar et al. 2012). Thus, E_m is obtained in response to changes in the cavity volume versus pressure increment. As the MPT is considered one of the most expensive and time-consuming field tests, it has been combined with different field tests, such as SPT and CPT results. Numerous empirical correlations expressing the main MPT parameters, i.e., P_l and E_m and based on SPT and CPT results, exist in the literature.

In other hand, the shear wave velocity (V_S) is a fundamental parameter required to define the dynamic properties of soils (Akin et al. 2011). It is useful in evaluating foundation stiffness, earthquake site response, liquefaction potential, soil density, site classification, soil stratigraphy, and foundation settlements. V_S is one geophysical parameter usually obtained from different geophysical field tests. Due to the dynamic nature of the shear wave velocity, several empirical relationships were investigated between V_S results and the dynamic SPT test.

Recently, researchers have shown an interest in exploring the correlation between MPT and V_S results. The first study was conducted by Akkaya et al. (2019). The authors developed three empirical equations among E_m, N_{60}, and V_S, respectively for low (CL) and high (CH) plasticity clay, based on total of 10 boreholes collected towards eastern side of Lake Van in The Turkey. Lately, Cheshomi & Khalili (2021) proposed a linear empirical equation between E_m and V_S based on a total of 94 MPT and V_S gathered on three sites intended for line 1 and 2 subway projects construction of Qom Mashhad cities in The Iran. Table 1 summarizes all proposed empirical correlation in literature.

From the literature review, less research has been conducted on developing an empirical relationship between E_m and V_S results. Additionally, site-dependent empirical models are considered more accurate than global models. Consequently, this study aims to proposed correlation between E_M and V_S results for different soil classification including sand (SM/SC-SM), clay (CH-CL) and marl (CH-CL) collected from different sites belonging to the Extension E Algiers Metro Line located in The Algiers region, northern Algeria.

Table 1. Existing correlation between E_m and V_S.

Authors	Correlation	Soil type
Akkaya et al. (2019)	$E_m = 0.1819V_S - 26.94$	Clay (CL and CH)
	$E_m = -39.32 + 2.46\ N_{60} - 0.637V_S$	
	$V_S = 1.4629N_{60} - 241.82$	
Cheshomi & Khalili (2021)	$E_m = 0.132V_S - 8.122$	Silty clay

2 GEOLOGICAL AND SISMOTECTONIS SOIL PROPERTIES

The data used for this study was collected from the Extension E of the Algiers Metro line (EEAML). This metro line is located in the Algiers region and consists of nine underground stations and ten ventilation shafts. The EEAML will run through the densely populated areas of the city and terminate at the new terminal of Houari Boumediene International Airport.

As part of this study, only eight sites belonging to the nine underground stations were explored to collect the whole of the datasets. A total of 56 boreholes were drilled to investigate the geological context of the sites. According to the drilling examination, most sites consist of Quaternary age deposits. This unit comprises of silty-clayey sand (Qs), silty clay (Qa) and sandy clay (Qa) soils. Some sites are composed in depth from 30 m to 60 m of Tertiary age deposits comprising fine to medium sand (TS) and marl (TM) soils. The groundwater level varied from site to site, mostly between 5 and 20 m. The study area is a tectonically complex zone accommodating part of the relative convergence between Africa and Eurasia. The Algiers area, is one active seismic zone in northern Algeria.

3 GEOTECHNICAL AND GEOPHYSICAL DESCRIPTION

As part of the soil investigation campaign in EEAML, various in-situ tests and laboratory tests were conducted to evaluate the engineering soil properties of sites. Forty-eight (48) MPT and 16 cross-hole tests were achieved at the eight sites. The shear wave measurement tests were conducted by means the cross-hole method. Both MPT and cross-hole measurements were taken at every 1m. Therefore, the results obtained for the breakdown of the MPT-Vs data pair are comparable and safe for establishing a relationship between these two tests. Figure 1 presents some of the MPT and Vs results recorded at each site. In the case of laboratory tests, grading size analysis and plasticity measurement are explored to indicate the different soil classifications encountered along the EEAML. Table 2 presents the statistical descriptive analysis, including mean, maximum, minimum, and standard deviation (std), and coefficient de variance (CV).

The MPT and cross-hole methods were drilled until 60 m for almost all sites (Fig. 1). The Em and Vs experiments vary significantly with depth, mainly because of different stratification. The dominant soil types observed in site 1 were mainly silty clay, sandy clay, silty sand, and fine to medium sand. Site 2 consists mainly of silty sand, clay, and clayey marl. Grave layers sometimes intercalate these formations. The main materials encountered in site 3 were silty sand, fine to medium sand, and clayey marl. Two principal units, namely clay and marl, were observed in site 4. In site 5, the subsoil consists mainly of sand and marl soils. At site 6, the soils are mostly made up of silty clay, silty sand, fine to medium sand, and marl. Grave layers sometimes intercalate these formations. The subsurface soil profiles encountered at site 7 consist of silty clay, sand and marl, and grave. In site 8, the study area comprises silty clay, clayey sand, and marl. All sites depict similar trend of E_m and V_s results. The upper values of Em and Vs correspond mainly to grave soil layers. However, the lower values were mainly related to different clayey soils. It should also be noted that the fine-grained soils, including clayey and marl soils, were distinguished as low to high plasticity (CL-CH), while sandy soils were SM/SC-SM, according to USCS.

Table 2. Statistical descriptive of E_m and V_s measured at each site.

Site	E_m (MPa)					V_s (m/s)				
	Max	Min	Mean	Std	CV	Max	Min	Mean	Std	CV
1	119.42	6.98	56.16	32.85	0.58	648.00	142.00	423.67	89.96	0.21
2	235.50	7.37	40.00	47.19	1.18	845.00	251.00	442.72	121.26	0.27
3	113.40	6.98	52.12	30.63	0.59	933.00	205.00	481.07	130.35	0.27
4	184.57	9.88	64.42	48.37	0.75	554.00	15.00	300.97	73.38	0.24
5	197.52	8.55	112.92	53.33	0.47	436.00	110.00	300.63	104.05	0.35
6	219.66	8.50	95.78	52.50	0.55	978.00	128.00	521.76	217.74	0.42
7	206.31	7.99	72.57	66.54	0.92	583.00	119.00	329.56	107.47	0.33
8	148.66	8.73	43.46	31.62	0.73	734.00	205.00	397.01	136.33	0.34

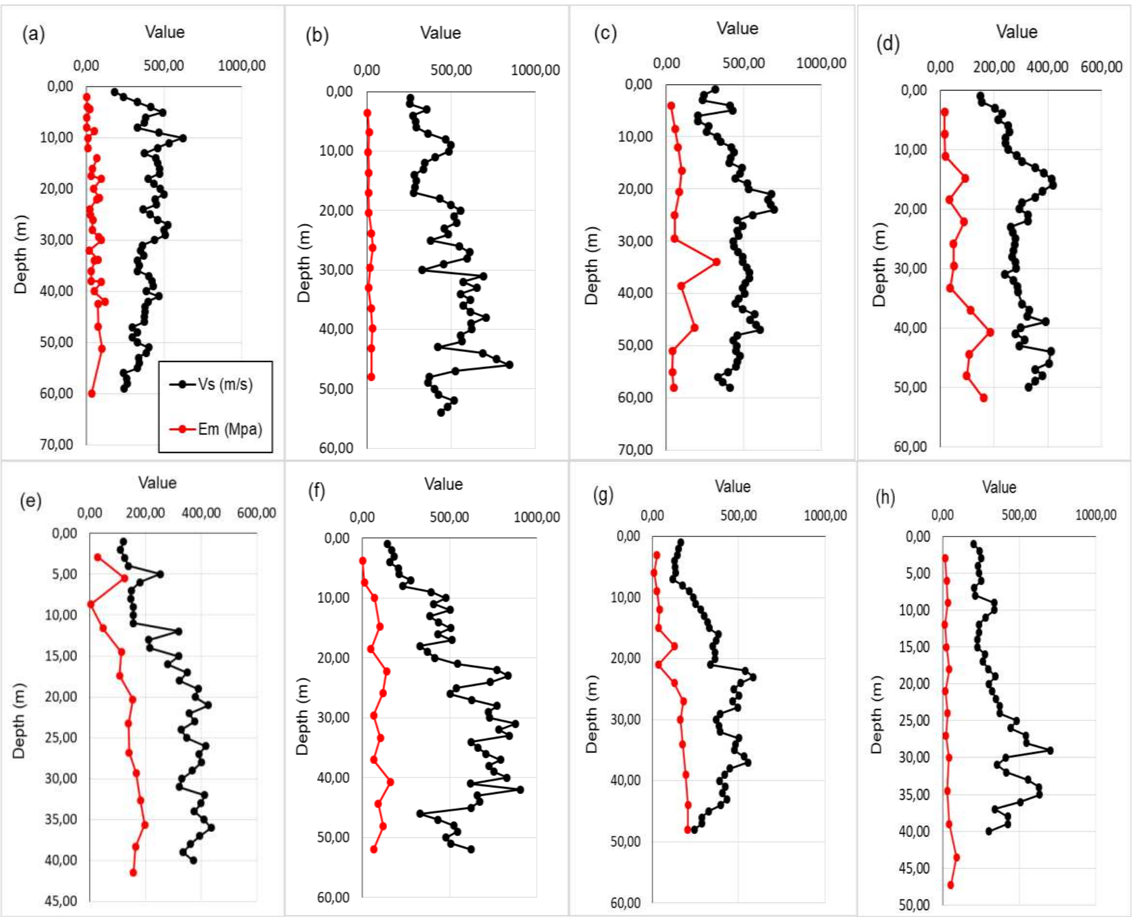

Figure 1. E_m and V_S values measured for (a) site 1, (b) site 2, (c) site 3, (d) site 4, (e) site 5, (f) site 6, (g) site 7, (h) site 8.

4 REGRESSION ANALYSIS RESULTS

In geotechnical engineering, simple regression analysis (SRA) is one common statistical method used to investigate the relationship between different geotechnical parameters. This study apply the SRA to develop empirical relationship between E_m and V_s. Before developing models, some data pair selection criteria should be considered to conduct a safe SRA. The data pairs of E_m and V_s were meticulously obtained at comparable level depth, soil type, and borehole locations between MPT and Cross-hole tests. In total, twenty-four (24) E_m-V_s data pairs of sandy soils (SM/SC-SM), 13 E_m- V_s data pairs of clayey soils (CL-CH), and 9 E_m- V_s data pairs of marly soils (CL-CH) were obtained. Different statistical models such as power, logarithmic, exponential, linear with intercept and without intercept functions were tested to investigate the most appropriate model. The best model is represented by high coefficient of correlation (R-square value). Table 3 presents the R^2 values generated from each sub-mentioned statistical formulas. As it is observed from Table 3, the most appropriate model based on R^2 for clay (CL-CH) is given by exponential form, for sand (SM/SC-SM) by linear form with intercept, for marl (CL-CH) by power formulas and for all soils by linear form with intercept. The linear model without intercept showed a weak R^2 values specifically for clay (CL-CH) and marl (CL-CH) soils. Figure 2 presents the relationship between E_m and Vs for each type of soil. The empirical correlations obtained in this study are expressed by Equations (5), (6), and (7) for sand (SM/SC-SM), clay (CL-CH), marl (CL-CH), respectively.

$$E_m = 0.174\,V_S - 5.637 \quad (R^2 = 0.764) \quad \text{sand (SM/SC-SM)} \tag{5}$$

$$E_m = 4.335\,e^{0.005V_s} \quad (R^2 = 0.641) \quad \text{clay (CL-CH)} \tag{6}$$

$$E_m = 2 \times 10^{-7} {V_S}^{3.258} \quad (R^2 = 0.704) \quad \text{marl (CL-CH)} \tag{7}$$

Accordingly, high coefficient correlations R^2 are obtained for the four empirical formulas, and two distinguished trend lines are proposed in this study. A linear function is developed for sandy soils (SM/SC-SM), while a non-linear function are proposed for clayey and marly (CH-CL) soils. When considering all data pairs, a linear fit is proposed. Equation 8 express correlation between E_m and V_S for all soils.

$$E_m = 0.207\,V_S - 25.113 \quad (R^2 = 0.685) \quad \text{all soils} \tag{8}$$

Table 3. Statistical coefficient (R^2) between E_m and V_S.

Soil type	Linear (y = ax + b)	Linear (y = ax)	Power	Exponential	Logarithmic
Clay (CL-CH)	0.636	0.509	0.594	0.641	0.565
Sand(SM/SC-SM)	0.764	0.759	0.636	0.649	0.711
Marl (CL-CH)	0.627	0.379	0.704	0.684	0.620
All soil	0.685	0.612	0.555	0.617	0.579

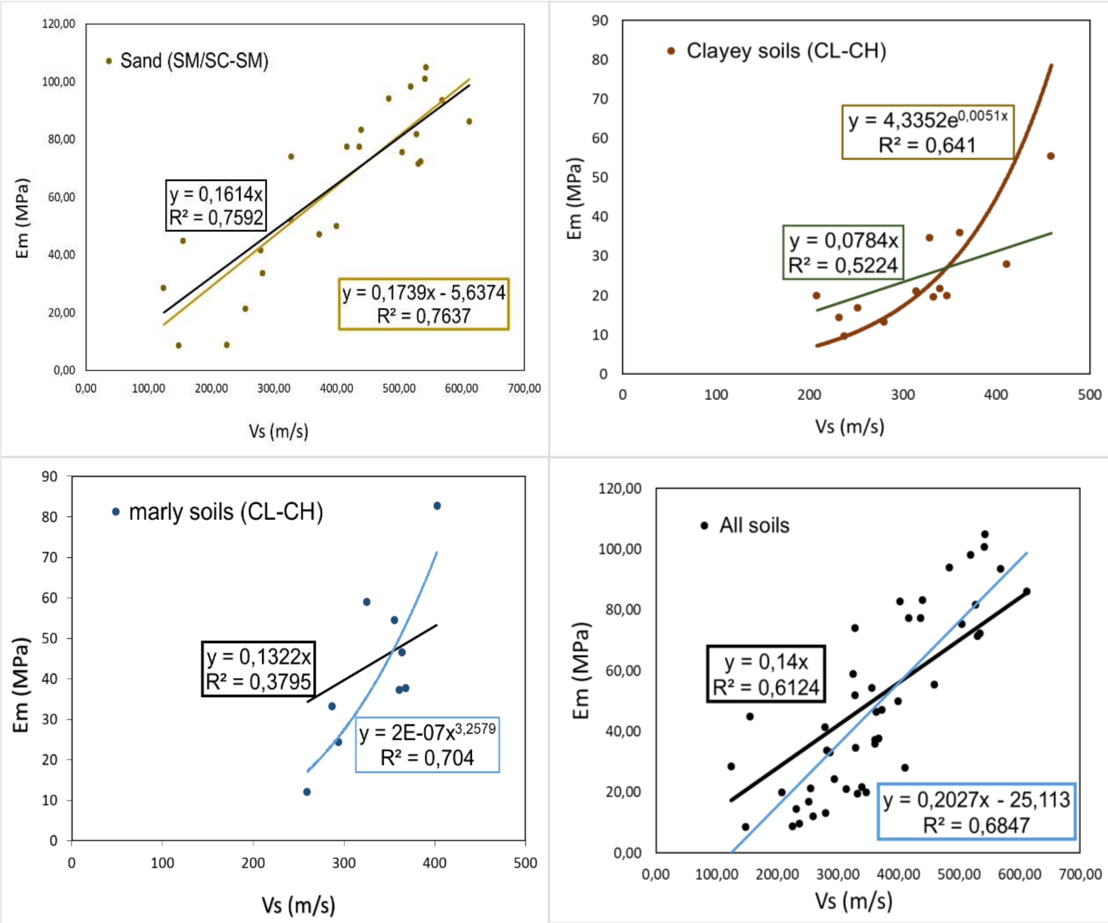

Figure 2. Relationship between E_m and V_S for sand, clay, marl and all soils.

5 DISCUSSION

This study develops a relationship between E_m and Vs for different types of soils. As only two studies exist in literature and have been conducted especially for clayey soils, this study compares only the developed model of clayey soils (CL-CH) in this study with two previous proposed models in the literature. Figure 3 presents the results of comparison study. The plotting comparative results depicts that there are a wide differences in the slope lines of the predicted values by the developed empirical model in this study with those proposed by previous works (Fig. 3a). Additionally, the major normalized consistency ratio (CR) variation according to the shear wave velocity values of this study are close to zero (Fig. 3b). It should note that the lower CR is the best-developed model. Thus, the proposed model of clayey soils in this study is more appropriate than the developed model of Akkaya et al. (2019) and Cheshomi and Khalili (2021). This comparison confirms the importance of the research of site-dependent empirical correlations. As few models exist between E_m and Vs, further studies are necessary to expand additional knowledge about the relationship between Em and Vs. This study presents four empirical equations intended for sandy soils (SM/SC-SM), clayey soils (CL-CH), marly soils (CL-CH), and all soils. Hence, we suggest other empirical formulas for sandy and marly soils based on an extensive database for further comparison.

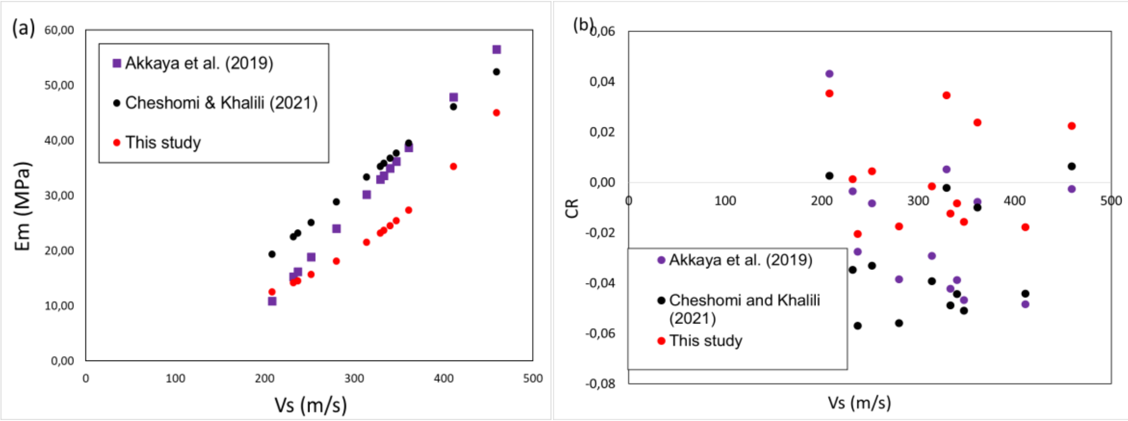

Figure 3. Comparison results of (a) Measured E_m and predicted E_m, and (b) CR variation of the developed model in this study and previous researchers for clayey soils.

6 CONCLUSION

This study express the Menard pressuremeter modulus (E_m) value based on shear wave velocity (V_S) measurements performed by cross-hole test. Different type of soils were collected, including sandy soils (SM/SC-SM), clayey, and marly (CL-CH) soils. Thus, the empirical correlations are proposed for these different type of soils. The mathematical formula of the developed model differs according to the soil type. The linear function is most appropriate for coarse-grained soil, while a non-linear fit is more accurate for fine-grained soils. The comparison study was conducted only for clayey soils and depicts the difference between the developed model in this study and precedent models. The models proposed in this study can be helpful for geotechnical engineers during soil investigation surveys for different purposes such as soil classification, foundation settlement, and bearing capacity calculation. These models are valid within the margin of Em and V_S variation, and further investigations are recommended.

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