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A proposed correlation between downhole shear wave velocity and unconfined compressive strength for weak sedimentary rock formations: insights from Dubai's geology

Une proposition de corrélation entre la vitesse des ondes de cisaillement en fond de trou et la résistance à la compression non confinée pour les formations rocheuses sédimentaires faibles: aperçus de la géologie de Dubai

Muhammad M. El-Sherbiny
Senior Geotechnical Engineer, Dar Al-Handasah (Shair and Partners), Cairo, Egypt, mohammed.elsherbiny@dargroup.com

Ayman L. Fayed
Professor, Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt

Ahmad A. Mousa
Senior Lecturer, School of Engineering, Monash University Malaysia, Selangor, Malaysia

ABSTRACT: Dubai has developed a robust business reputation and a conducive market that has attracted global trade over the last few decades. Construction of mega projects, with some of the tallest building embraced in the heart of the city, necessitates the use of geophysical testing. The coastal geology of Dubai comprised shallow marine sand and silts deposits generally underlained by sedimentary weak rock. The shear wave velocity (V_s) was used for this purpose. DST provides a direct and reliable measurement of V_s in rock. The available literature on correlating the unconfined compressive strength (UCS) of weak rocks to V_s, though limited, was also utilized for these three cases. The study developed a new correlation between the measured shear wave velocity from DST (V_{s-DST}) and the UCS. The proposed correlation has proven satisfactory statistical performance for the three sites despite the observed variation in rock quality. This could encourage relying on UCS of weak sedimentary rocks to confidently estimate their V_s in the absence of direct measurements. Finally, the developed correlation can assist with seismic site classification for these rocks formation.

RÉSUMÉ: Dubaï a développé une solide réputation commerciale et un marché propice qui a attiré le commerce mondial au cours des dernières décennies. La construction de mégaprojets, avec certains des bâtiments les plus hauts au cœur de la ville, nécessite l'utilisation d'essais géophysiques. La géologie côtière de Dubaï comprenait des dépôts de sable et de limon marins peu profonds généralement sous-tendus par des roches sédimentaires faibles. La vitesse de l'onde de cisaillement (V_s) a été utilisée à cet effet. DST fournit une mesure directe et fiable des V_s dans la roche. La littérature disponible sur la corrélation de la résistance à la compression non confinée (UCS) des roches faibles aux V_s, bien que limitée, a également été utilisée pour ces trois cas. L'étude a développé une nouvelle corrélation entre la vitesse de l'onde de cisaillement mesurée à partir de DST (V_{s-DST}) et l'UCS. La corrélation proposée s'est avéré une performance statistique satisfaisante pour les trois sites malgré la variation observée de la qualité des roches. Cela pourrait inciter à s'appuyer sur le SCU des roches sédimentaires faibles pour estimer en toute confiance leurs V_s en l'absence de mesures directes. Enfin, la corrélation développée peut aider à la classification des sites sismiques pour ces formations rocheuses.

KEYWORDS: Downhole seismic test, shear wave velocity, weak sedimentary rock, Dubai, seismic site class characterization.

1 INTRODUCTION

The United Arab Emirates (UAE) has experienced a significant economic growth in the last few decades. The accelerated schedule driven projects promote the use of geophysical in-situ tests for evaluation of seismic hazard (Irfan et al., 2012). This is particularly critical for the dominant high-rise building in Dubai. Downhole survey is one of the most efficient methods for near surface investigation to determine the weathering and sub-weathering thicknesses and velocities. A downhole survey normally involves taking shots on or near the surface and at a distance from the borehole, and using geophones/hydrophones to measure the arrival times (Agoha et al., 2015).

According to the uniform building code, UBC 1997, International Building Code IBC 2006, the seismic soil profile type is identified for the upper 100 ft (30m) below the foundation. In order to evaluate the soil profile type to retrieve the seismic parameters of the soil, seismic site classification need to be conducted depending on the standard penetration blow counts (N_{spt}), undrained shear strength (C_u) or shear wave velocity (V_s) of soil. V_s is considered one of the most common in-situ parameters for site characterization of soil and rock formations. Though correlations between the measured and predicted values of V_s do provide a convenient approach in geomechanics (e.g. Fayed and Mousa 2020), the direct measurement of V_s is inevitable for characterization of local geologies. Several reported correlations relate V_s to either the standard penetration blow counts or undrained/unconfined shear strength (UCS) - albeit in case of correlating rock formations with V_s typical uncertainties arise. The most common

Figure 1. Location map for the three sites considered in the study

practice considers the rock formation as a very dense cohesionless layer (i.e. using equivalent blow counts) to evaluate the seismic site class type, which in turn could lead to a very conservative design. Many reported correlations were created to investigate the rock properties using site measured V_s as a simplified approach in case of the absence of rock coring (Judd and Huber 1961, D'Andrea et al. 1965, Irfan and Dearman 1978, Koumantakis 1982, Tug˘rul and Zarif 1999, Kahraman 2001, Yasar and Erdogan 2004 and Diamantis et al. 2009). Mostly, these correlations relied on the measured P-wave velocities, whereas the attempts to correlate V_s with the rock properties are rather modest. (Diamantis et al. 2011, Diamantis et al. 2009 and Majstorovic et al 2019) managed to establish relationships between UCS and V_s for hard rocks.

This study embarks on characterization of the weak sedimentary rock formation using site measured shear wave velocity, which can be ultimately utilized for identifying the seismic site class. A reliable correlation between V_s and the UCS was developed for this purpose. The soft rock geology of Dubai, UAE, was a good candidate for this investigation. The proposed regression was developed using data collected from three different sites. The corresponding site class was accordingly interpreted considering the encountered rock head levels.

2 STUDY AREA

2.1 Site description

The study area comprises three different sites in Dubai. The sites are dispersed almost evenly apart from each other within Dubai bounds. Brief description of each site is stipulated below. Figure 1 depicts the location of the executed downhole seismic tests in these sites.

Jebel Ali - The project was aiming to founding a new residential community near the seashore. The ground investigation included geotechnical and geophysical tasks. Part of the campaign included drilling of fifteen (15) boreholes associated with performing downhole seismic tests (DST) at three (3) locations down to a depth of 40 m.

Ibn-Battuta Mall - The project incorporated construction of a high-rise building consisting of ground floor, four parking levels and a pool deck in addition to 50 story levels. Furthermore, the project consisted of an expansion of the existing mall including a ground floor for retails usage and three parking levels. The ground investigation campaign comprised drilling of Eight (8) boreholes with an average depth ranging between 30 to 50 m. One (1) DST was performed to a depth of 40 m below ground surface.

Creek Harbor Development - The project consisted of twin residential towers overlooking Dubai Creek and Creek Harbor Marina. The towers embrace 37 floors with a common podium that enclose retails, parking lots and MEP spaces at the ground floor. The geotechnical investigations involve the drilling of six (6) boreholes with depths of 60 m and 40 m, in addition to, two (2) downhole seismic tests were carried out to a depth of 60 m below ground surface.

2.2 Site geology

The geology of the different project locations is a part of the geology of Arabian Peninsula Gulf, as shown in Figure 1, that is limited by four tectonic boundaries:

1- The Red Sea and the Dead Sea rift system on the west and northwest bounds.
2- The Thrust zone from the Alpine Orogeny on the north.
3- The mobile belt of Zagros and Oman Mountains on the east and southeast.
4- The wrench fault associated with Owen Fracture zone on the south.

The coastal region of the United Arab Emirates and the floor of the Arabian Gulf is an area of extensive carbonates sedimentation near to surface. Aeolian dune sand, Sabkha and evaporation deposits of Holocene to Pleistocene age dominate the geology of the western region of UAE. The dune sand deposits typically comprise fine grained silty calcareous sand. The degree of cementation generally increases with depth, (such that the variably cemented sand grades to predominantly calcareous sandstone). Very silty Gypsiferous Sabkha and evaporate layers are commonly encountered within the Aeolian sand deposits. Sabkha layers, where recent, tend to occur from surface of shallow depth. Surficial Sabkha deposits are found throughout the coastal belt of the Arabian Gulf, and far inland in the western and southern part of the United Arab Emirates. Sabkha is local name, used to describe relatively fine grained hyper saline, silt and sand deposits, which are commonly saturated with brine, and salt encrusted. Various formations are included below the Sabkha, Beach and Dune Sand deposits and Bioclastic Limestone and Milolite Sandstone. The Sandstone layers are followed by Conglomerate, Limestone, Calcisiltite and Siltstone.

2.3 Subsurface conditions

Commonly, all the sites are characterized by the presence of weak rock formations consisting of Calcisiltite, Calcarenite, Siltstone, Conglomerate and Sandstone. Specific subsurface conditions with the corresponding field and lab tests are summarized below for the different sites.

Jebel Ali – Subsurface conditions were consisting of manmade ground Sand with an average thickness of 4 m overlying a very weak to weak sandstone/conglomerate with an average thickness of 4 m underlain by an extending very weak to moderately weak calcisiltite layer. Lab tests comprised index properties, and rock strength tests (i.e. UCS: 39 test, UCS/E: 50 test and Point load index: 27 test) while the field tests included packers, pressuremeters and downhole tests.

Ibn-Battuta Mall – The prevailing ground conditions at this location were mainly covered by a top 1.5 m of fine to medium sand layer overlying a very loose to very dense sand of an average thickness 6.5 m underlain by extremely weak to weak sandstone/calcarenite with an average thickness of 11 m followed by an extremely weak to weak siltstone/claystone interbedded with gypsum which extends to the end of boreholes. Lab tests included index properties, and rock strength tests (i.e. UCS: 52 test, UCS/E: 9 test and Point load index: 10 test) while the field tests involved permeability packers and downhole tests.

Creek Harbor Development – The generalized geological strata at the harbor location was mainly encompassing a top 1 m of slightly gravelly to gravelly sand layer overlying a medium dense to dense turning to very dense sand with an average thickness of 15 m underlain by extremely weak to weak sandstone/calcarenite with an average thickness of 40 m. Lab tests comprised index properties, and rock strength tests (i.e. UCS: 22 test, UCS/E: 34 test and Point load index: 44 test) while the field tests involved permeability packers and downhole tests.

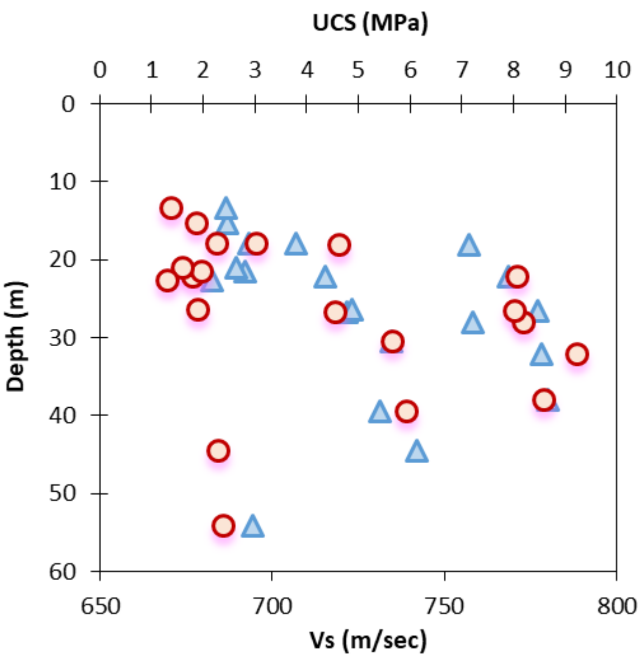

Figure 2. Profiles of unconfined compressive shear strength (UCS) and Shear wave velocity (V_s) for the three sites

3 ROCK PROPERTIES

3.1 *Unconfined compressive strength*

Within the presence of rock formations, numerous parameters counted as vital measures in capturing the performance and durability of this formation (i.e. RQD, RMR, UCS, etc.). Field tests provide a more realistic approach to classify the overall quality of the rock formations, albeit, the intact strength of rock is hardly to be interpreted precisely. On such terms, lab tests, namely unconfined compressive strength and point load index tests, are considered the most common measures to provide the factual strength of the rock.

The unconfined compressive strengths were collected for weak rock from the three different sites (Figure 2). Values of the unconfined compressive strength vary between 1 and 9 MPa, signifying weak rock formations extending to deeper depths.

The rock formation across the different sites was categorized mainly with RQD values ranging from 0% to 99%, RMR falling between 51 and 60 while the bulk densities were ranging between 1.80 and 2.4 t/m^3.

3.2 *Downhole seismic test*

Downhole Seismic tests (DST) were executed in order to investigate the seismic properties of the sites. Propagation of the S- and P- waves in the rock strata was monitored. Figure 2 depicts the variation of the shear wave velocities (V_S) corresponding to the same depths of the executed UCS tests for a better evaluation of the relationship between UCS and V_S.

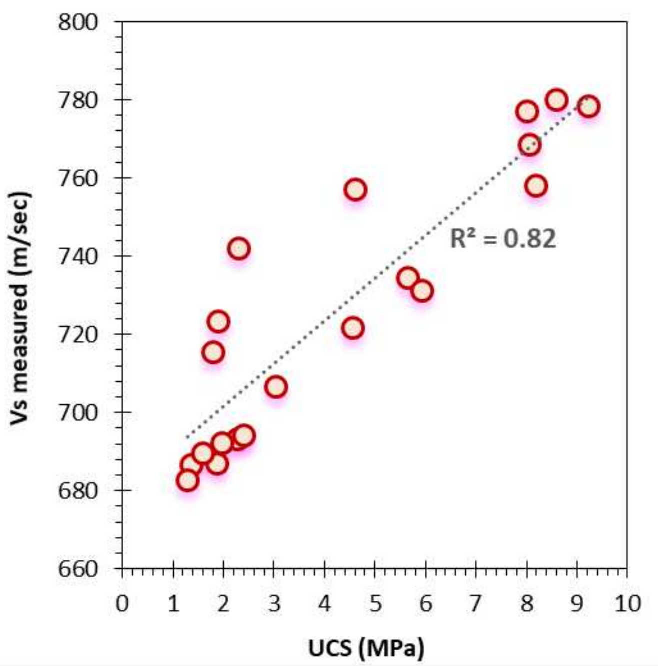

Figure 3. Measured shear wave velocities and the corresponding UCS tests for the three sites

4 REGRESSION ANALYSIS

The number of data points (i.e. 20 points) collected from the three different sites was sufficient to investigate the relation between (V_S) and (UCS). The unconfined compressive strength versus the corresponding measured shear wave velocities are shown in Figure 3. Regression analyses were performed in order to investigate the relation between both measurements. A data analysis program was adopted to evaluate the best fitting correlation to describe the available data. DataFit Version 9.0.59,

(2008) is a program which includes a broad library of mathematical expressions, nonetheless linearity was found to be the best form to capture the trend of input data. The developed relationship can be expressed as Eq. 1, in conjunction with Figure 3:

$$V_s = 11UCS + 680 \qquad Vs;\ (m/sec),\ UCS;\ (MPa) \qquad (1)$$

The best fitting correlation yields a number of predicted shear wave velocities ($V_{s\ predicted}$) that approximately matches the measured ones. The quality of correlations was evaluated using the coefficient of determination (R^2). Figure 4 represents the linear zero intercept for the computed data plotted against the measured data. With R^2 value of 0.81, a very good correlation between the unconfined compressive strength and the shear wave velocity in this weak rock formation can be evident.

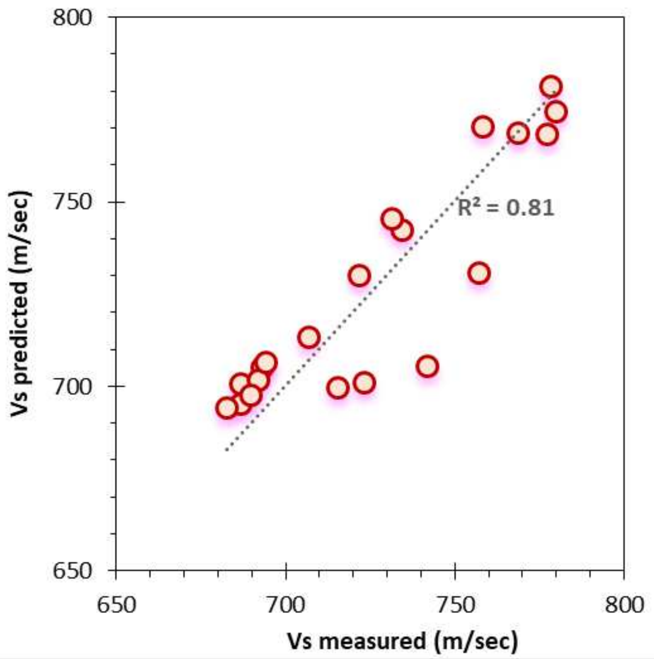

Figure 4. Measured versus predicted shear wave velocities

5 INTERPRETATIONS

5.1 *Comparison with reported correlations*

Numerous correlations were developed as an attempt to have the chance to characterize the mechanical rock properties in term of the P-wave velocities resulting from the field tests. Lack of literature was available correlating the shear wave velocity with the mechanical properties of rock generally and the unconfined compressive strength specifically. Through the literature review, the following equations were one of the few attempts to investigate the UCS with respect to the measured shear wave velocities. It is worth mentioning that the incorporated rock in these studies was very strong rock formations.

Table 1. Different correlations developed between UCS and Vs

Correlation	R^2	*Condition*	*Reference*
$UCS = 0.14V_s - 336.05$	0.8	Moderately hard to very hard formations	Diamantis et al., 2009
$UCS = 0.18V_s - 625.45$	0.83	hard to extremely hard formations	Diamantis et al., 2011
$UCS = 0.1121V_s - 153.58$	0.89	weak to hard formations	Majstorovic et al., 2019

In order to cross check the above correlations against the developed equation in this study, the UCS values collected from the three different site were utilized in these correlations to examine its adequacy level to simulate the weak rock properties from both sides; the strength and the shear wave velocity. Figure 5 is plotted to investigate the shear wave velocity values in terms of the unconfined compressive strength values of the weak rock considering the different correlations.

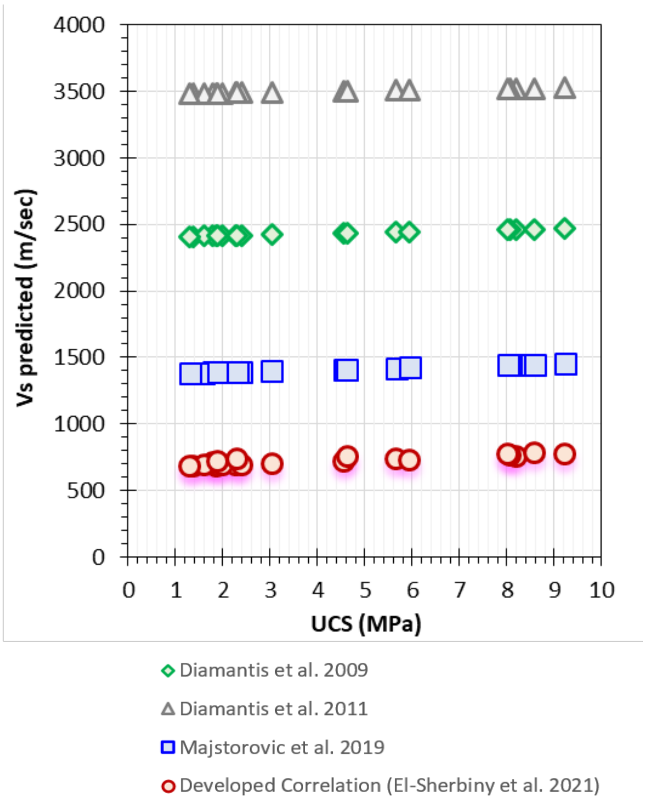

Figure 5. Shear wave velocities versus the unconfined compressive strength values of the weak rock using the developed equation in this study

According to the Unified Building Code (UBC 1997), the hard rock is classified to have a shear wave velocity higher than 1500 m/sec, while the normal rock should fall in the range between 760 and 1500 m/sec, whereas the soft rock formation characterized by a low shear wave velocities varying between 360 and 760 m/sec. As shown in Figure 5, the available correlations from the literature were investigating harder formations of the rock resulting in a higher values of shear wave velocities compared to the predicted ones from the developed equation in this study which principally originates from the weak rock strength parameters.

5.2 *Identifying seismic site class*

Reference to the data retrieved from the three different sites along Dubai, an exercise was performed to investigate the site class utilizing the common practical approach versus the correlated shear wave velocities, specifically for the rock formation, using the developed equation in this study. Relying on the borehole log profiles adopted at each site, by following the common practice approach, the seismic site class characterization was estimated to be S_D, which corresponds to a range of SPT numbers between 15 and 50 attributed to the UBC 1997.

By implementing the developed equation (i.e. Eq. (1)) for estimating the shear wave velocity relying on the weak rock compressive strength parameters (UCS), the resulting site class characterization was S_c, which corresponds to soft rock formations after the UBC 1997. Such variation in the estimated site classes has a major implications on the overall cost of the project as it entails stiffer elements for the superstructures to sustain the anticipated seismic activities.

5.3 *Effect of rock head level*

It was realized that each of three sites had a definite level of the rock head below the natural ground surface. For Jebel Ali site, the rock head level was encountered near ground surface. As for Ibn Battuta site, the rock head level was encountered at a depth of 10 m from the grade - underlying a medium dense to dense sand layer. For Creek Development site, the rock head level was encountered at an average depth of 16 m from the natural grade - underlying medium dense to dense sand formation. This study allowed to shed the light on the effect of the rock head level on the overall site class characterization.

Although, with such discrepancies in the rock head level below the ground surface, the estimated seismic site class for the three sites was S_c. The effect of the rock head level factor on the estimation of the seismic site class is fairly small.

6 CONCLUSIONS

The use of the shear wave velocity has proven to be very efficient for characterising the subsurface conditions and deciding upon the seismic site class in Dubai. Three different sites were slected for this study. The unconfined compressive strength of the soft rock formations were collected for the sites along with the corresponding shear wave velocities. Attempts to estimate the shear wave velocities using the correlations reported in the literature failed to provide realistic estimates. This can be attributed to the fact that these relations were developed for a wide range of rock formations. Dubai, however, rests on weak rock consisting of calcisiltite, calcarenite, siltstone, conglomerate, limestone and sandstone. As such, this study presents a regression analysis to develope an adequate correlation between the downhole shear wave velocity and compressive strength of the weak sedimentary rock.

The predicted shear wave velocites were compared against the measured values. The developed correlation ($Vs = 11UCS + 680$) yeilds a satisfacotry R^2 value of 0.81 The proposed correlation outperforms the reported regressions. This was evident for the three sites considered in this study. Obviously, the better estimates of the shear wave velocities can enhance our siesmic site classification and minimize the consequences of casual approches that are typically conservative in such weak formations. Rockhead level renders a minor effect on the site class characterizations, albeit a proper laboratory test for the rock strength evalution is crucial for confirmation.

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