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Correlation between PMT & CPT after dynamic compaction in reclaimed calcareous sand

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ABSTRACT

Regardless of the reclamation technique that is used, sand reclamations are placed in a loose state, and are potentially subject to settlement under self-weight, insufficient bearing capacity and excessive settlements under loads. Dynamic compaction has proven to be a suitable ground improvement technique for the treatment of reclaimed sands, whether with silica or carbonate mineralogy. The pressuremeter test (PMT) has been systematically used in many dynamic compaction projects, but occasionally other tests such as the Cone Penetration Test (CPT) are used for quality control and verification purposes, and it would advantageous to be able to compare the results of the CPT with previously published projects that have used the PMT. While there are publications that have correlated CPT to PMT, the authors are not aware of any such publications for calcareous sands. In this paper, after a brief review of dynamic compaction, previous PMT and CPT correlations will be presented, and two projects in Qatar and UAE in which reclamation was done by hydraulic filling of calcareous sand will be discussed. The loose fills were improved by dynamic compaction, and CPTs and PMTs were carried out for testing purposes. This study suggests that PMT-CPT correlations derived in the two projects are in the same order, and do not appear to be dependent on depth. A relationship is proposed for estimating the elasticity modulus of improved calcareous sand using CPT cone resistance.

Keywords: dynamic compaction, PMT, CPT, reclamation, correlation

1 INTRODUCTION

1.1 Dynamic Compaction

Dynamic compaction was invented and promoted as early as 1969 by the late French engineer, Louis Menard, but it was not until 29 May 1970 that he officially patented his invention. The concept of this technique is improving the mechanical properties of the soil by transmitting high energy impacts to loose granular soils. Impact energy is delivered by dropping a heavy weight or pounder from a significant height. The pounder weight is most often in the range of 8 to 25 tons, and drop heights are usually in the range of 10 to 20 m.

The impact creates body and surface waves that propagate in the soil medium. In non-saturated soils the waves displace the soil grains and re-arrange them in a denser configuration. In saturated ground the soil is liquefied and the grains are re-arranged in a more compact state. In both cases the decrease of voids and increase in inner granular contact will directly lead to improved soil properties (Hamidi et al., 2009).

1.2 Existing PMT-CPT Correlations

The pressuremeter test (PMT) is an advanced field test that can be used to determine ground settlement and bearing capacity by direct measurement of stress-strain (Menard modulus, E_M) and failure (limit pressure, P_{LM}) parameters. This test that has also been invented and patented by Louis Menard is very commonly used for quality control and quality assurance purposes in dynamic compaction projects. However, other tests such as cone penetration test (CPT) are also occasionally used when PMT is not available.

Baguelin et al. (1978) have reviewed, and interpreted a number of PMT – CPT correlations such as those published by Van Wambeke (1962), Cassan (1968, 1969), Jezequel et al. (1968) and Nazaret (1972) that were originally printed in French publications. Baguelin et al. note that while most correlations in technical publications are based on the ratio of CPT cone resistance, q_c, to PMT limit pressure, in spite of introducing uncertainties, the ratio of net values q^*_c/P^*_{LM} would be more representative. q^*_c and P^*_{LM} are respectively net CPT cone resistance and net limit pressure, and can be calculated from:

$$q^*_c = q_c - q_o \tag{1}$$

$$P^*_{LM} = P_{LM} - P_o \tag{2}$$

q_o= the total vertical stress

P_o= total at rest horizontal earth pressure at the test level at the time of the test

In general q^*_c/P^*_{LM} and q_c/P_{LM} are close because q_o and P_o are small compared to q_c and P_{LM}, but can be quite different at depth in soft clays.

Jezequel et al. (1968) studied the influence of depth on q^*_c/P^*_{LM} at the hydraulic fill dikes of a tidal power project in Rance, France. The fill used was composed of clean sand with dry density equal to 1.5 t/m^3. q^*_c/P^*_{LM} in the upper 1.5 m layer of fill was from 9.11 to 12.03. Even though q_c varied from 2 to 10 MPa, q^*_c/P^*_{LM} was about 6.7 throughout the remainder of the 20 m thick fill.

Nazaret (1972) did not observe the same independency of q^*_c/P^*_{LM} from q^*_c in his study on Loire sand, and reports a tendency of the ratio to increase with the increase of q^*_c.

Baguelin et al. interpret that the high values of q^*_c/P^*_{LM} near the ground surface are due to the differences between shallow and deep failure conditions. CPT has a small diameter, and rapidly reaches its critical depth. However, PMT has to reach an embedment depth of about 1 m in clays and 2 m in sands before the test is no longer influenced by the surface of the ground.

According to Baguelin et al. soil type has the greatest effect on q^*_c/P^*_{LM}, and for depths of about 5 to 20 m there seems to be a narrow correlation between q^*_c and P^*_{LM}. Baguelin et al. consider that reasonable averages of q^*_c/P^*_{LM} can be considered to be as presented in Table 1.

Table 1: q^*_c/P^*_{LM} for different soil types according to Baguelin et al (1978)

Soil Description	q^*_c/P^*_{LM}
Very soft to soft clays	close to 1 or from 2.5 to 3.5
Firm to very stiff clay	from 2.5 to 3.5
Very stiff to hard clay	from 3 to 4
Very loose to loose sand and compressible silt	from 1 to 1.5 and from 3 to 4
Compact silt	from 3 to 5
Sand and gravel	from 5 to 12

Baguelin et al. understand that it is very likely that dilatancy is a key factor in sands and gravels, and q^*_c/P^*_{LM} could prove to be a reliable indicator of the importance of dilatancy in the resistance of a particular soil. They conceive that a soil is probably non-dilatant or slightly dilatant if q^*_c/P^*_{LM} is about 5 to 6, and a ratio of 8 to 12 probably suggests a soil that is probably dilatant.

Campanella et al. (1979) also performed a study on the plastic silt and silty clay fluvial deposits of the Fraser River delta at Sea Island, Vancouver. Their study showed that q_c/P_{LM} is approximately 2.1 to 4 in the plastic silts, which is of the same magnitude as what Baguelin et al. had concluded.

Based on theoretical and experimental studies, Van Wieringen (1982) proposed that q_c can be correlated to P_{LM} using (3) and (4):

For clays $$q_c = 3P_{LM} \tag{3}$$

For sands $$q_c = 15(\tan\varphi')^{1.75}P_{LM} \tag{4}$$

φ'= effective internal friction angle

Briaud et al. (1985) collected 82 PMT borings data from various projects from 1978 to 1985, and proposed the correlations of Table 2 (Briaud, 1992).

Table 2: Correlation between PMT and CPT (Briaud et al., 1992)

Soil type	PMT parameter	Correlation to CPT
Clay	P_{LM}	0.2 q_c
	E_M	2.5 q_c
Sand	P_{LM}	0.11 q_c
	E_M	1.15 q_c

2 AL NAKHILAT SHIP REPAIR YARD

2.1 Project Description, Ground Conditions and Dynamic Compaction

Ras Laffan, located on the southern coast of the Persian Gulf and approximately 70 km north of Qatar's capital city, Doha, houses the onshore facilities of the world's largest gas field. Nakhilat Ship Repair Yard is part of Port of Ras Laffan's expansion programme, and has been hydraulically reclaimed from the sea.

Seabed level at the location of the project was variable from -9.1 m to -13.2 m CD (chart datum). Design (final platform) level was set at +3.5 m CD. It was recognised that the hydraulic fill would be placed in a loose state, ground improvement would be required, and the platform level would consequently drop. Hence the working platform was reclaimed to approximately +4.1 to +4.3 m CD with an allowance of about 0.6 to 0.8 m for ground subsidence.

Reclamation was carried out using the carbonate sand and gravel that was dredged from the sea for deepening the port. The fill's grain size was generally less than 75 mm, but stones as large as 500 mm in diameter were also present. The maximum fines content of the fill was mostly less than 10% on the upper elevations, but there were occasional lenses of silt at depth with thicknesses varying from 0.2 to 0.4 m. Carbonate content of the reclamation material was approximately 90% as $CaCO_3$.

CPT tests were carried out as part of the geotechnical investigation after reclamation. In areas DDR4 (57,064 m^2), DDR5 (35,643 m^2) and DDR6 (82,962 m^2) of the dry dockyards the soil in the upper 3 to 5 m was medium to very dense with q_c ranging from as low as 5 to more than 20 MPa. The soil then became loose to medium dense with q_c fluctuating between 1 to 7 MPa. Dense seabed was encountered at depths of 13 to 17 m, and CPT friction ratio was understood to be generally well below 1%.

While it was understood that less sensitive areas of the project would require lesser ground treatment, areas DDR4, DDR5 and DDR 6 with a total area of more than 175,000 m^2 were deemed to be sensitive, and project specifications stipulated that relative density in these areas had to be 60% based on the correlation of Baldi et al. (1986) for silica Ticino sand with a correction factor of 1.94 for carbonate content[1].

Ground improvement works was awarded to a specialist contractor who had proposed the application of dynamic compaction and alternative acceptance criteria based on bearing capacity and footing settlement requirements. Based on the fill thickness and the phase of dynamic compaction, soil improvement was carried out using a combination of 15, 25, 28 and 35 ton pounders. Hamidi et al. (2010) have described the ground treatment and testing of the project in more detail.

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[1] Relative density is an unreliable concept and criterion for ground improvement (Hamidi et al., 2013a, 2013b).

2.2 Verification and PMT-CPT Correlations

After execution of dynamic compaction in DDR5 using a maximum pounder weight of 28 tons (without ironing) it was decided to perform a dynamic compaction trial to study the improvement effects using a 35 ton pounder that was dropped by MARS. This process included 3 deep compaction phases and an ironing phase. 3 PMTs were carried out next to 3 CPTs.

The ratios of q_c/P_{LM}, q^*_c/P^*_{LM}, E_M/q_c and are shown in Figure 1. It can be observed that the average q_c/P_{LM} values for 21 tests points, which exclude the uppermost test points of PMT007 and PMT010 due to the differences in between the shallow and deep failure modes, are equal to 4.54 (the average q_c/P_{LM} value is 5.20 when the top two ratios of PMT007 and PMT010 are also included). The average q_c/P_{LM} value for the three correlations on Ras Laffan carbonate sand are 4.1, 5 and 5.3 excluding the mentioned uppermost points. Minimum and maximum q_c/P_{LM} values were respectively 2.9 and 9.1 for the 21 points. It can be observed that average q_c/P_{LM} value that was derived in this project is almost half of what Briaud et al. (1985) have suggested.

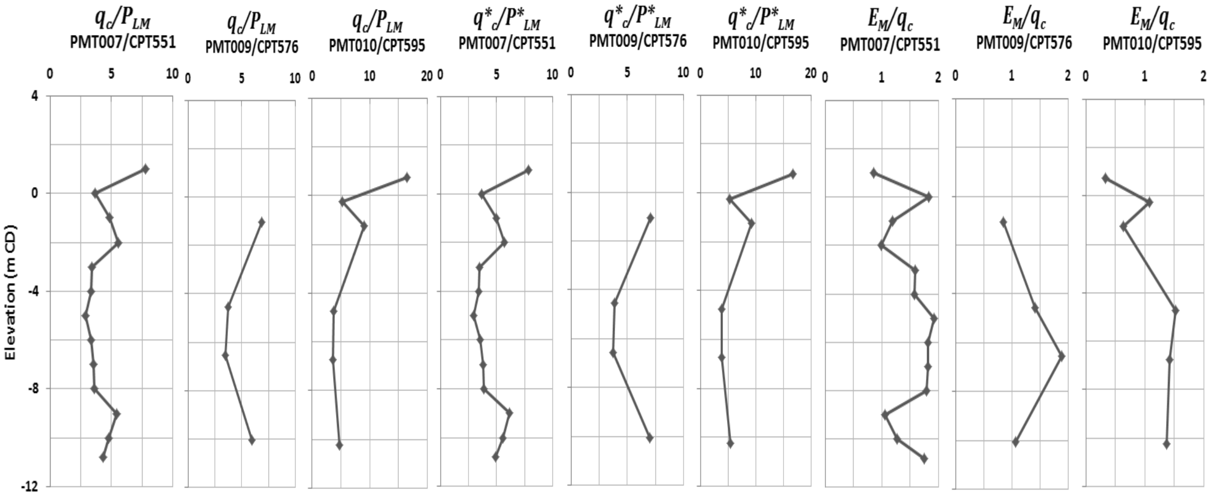

Figure 1. q_c/P_{LM} , q_c^*/P^*_{LM} and E_M/q_c for Ras Laffan carbonate sand

q^*_c/P^*_{LM} plots are identical in shape and very close in value to the q_c/P_{LM} ratios, and indicate that implementation of q_c/P_{LM} ratios has yielded the same results as q^*_c/P^*_{LM} in this saturated sand. The average q^*_c/P^*_{LM} value for the 21 tests points is equal to 4.82, which is just below the range of 5 to 12 that has been proposed by Baguelin et al. (1978). Average q^*_c/P^*_{LM} values for the three correlations are 4.3, 5.4 and 5.2 excluding the mentioned uppermost points. Minimum and maximum q^*_c/P^*_{LM} values for the 21 points were respectively 3 and 9.3.

E_M/q_c values of the two uppermost shallow points do not seem to correlate differently with the deeper points as the result of differences between the shallow and deep failure modes. The average E_M/q_c value for the 23 test points is 1.35. The average E_M/q_c values for the three tested locations were 1.5, 1.3 and 1.1. Minimum and maximum E_M/q_c values for the test points were respectively 0.3 and 1.91. The correlation factor that has been proposed by Briaud et al. (1985) is almost 85% of what has been measured in this project.

3 PALM JUMEIRA TRIAL

3.1 Project Description, Ground Conditions and Dynamic Compaction

Palm Jumeira has been reclaimed off the coast of Dubai in the United Arab Emirates, and consists of a tree trunk, a crown with 17 fronds, three surrounding crescent islands and two identical smaller islands on the sides of the trunk that are in the shape of the logo of The Palm. . The island itself is 5 km by 5 km, and has added about 78 km to Dubai's original 72 km coastline.

In total, 94 million m^3 of sand and 7 million m^3 of rock have been used in the construction of Palm Jumeira. Calcareous sand was dredged from the Persian Gulf using trailing suction hopper dredgers

(Dowdall Stapleton, 2008). When possible, the hopper was discharged by means of a big door located on the bottom of the hull, but when the water was shallow the dredger sprayed the sand and water mixture onto the reclamation by rainbow discharge.

In general, the reclamation was about 12 to 14 m thick of which about 3 to 4 m was above sea level. It was observed that the CPT cone resistance of the deposited calcareous sand above water level was very high and in the range of 20 to 40 MPa. The soil then became very loose in the rainbow discharged sand layer below water level with q_c as low as 1 MPa in the next 4 to 5 m of soil. Loose to medium dense sand with q_c varying from 4 to 8 MPa was encountered down to the depth of about 12 to 14 m where the soil became very dense. Carbonate content of the sand, measured as $CaCO_3$, varied from as low as about 60% to more than 90%.

After it was established that the reclamation was in a loose state the project's engineers stipulated that ground improvement had to be undertaken to increase the soil strength. Initially, the specifications required that relative density be at least 60%, and CPT q_c be at least 6 MPa to the depth of 4 m, at least 8 MPa in between depths of 4 to 8 m, and at least 10 MPa for depths greater than 8 m (Al Hamoud and Wehr, 2006), but later, in consideration of the carbonate content of the the specification was revised to $q_c \geq 6$ MPa for all depths.

In order to demonstrate the ability of dynamic compaction to satisfy this requirement, a trial was performed on of Frond N, renamed Al Naghal, using a 25 ton pounder that was dropped from 20 m.

3.2 Verification and PMT-CPT Correlations

q_c/P_{LM} and E_M/q_c correlations for in between prints, in prints and for average values at various testing depths are shown in Figure 2. It does not appear that q_c/P_{LM} is affected by the shallow and deep failure modes that were observed in Al Nakhilat Ship Repair Yard. As in Al Nakhilat project, q_c/P_{LM} does not seem to be influenced by depth.

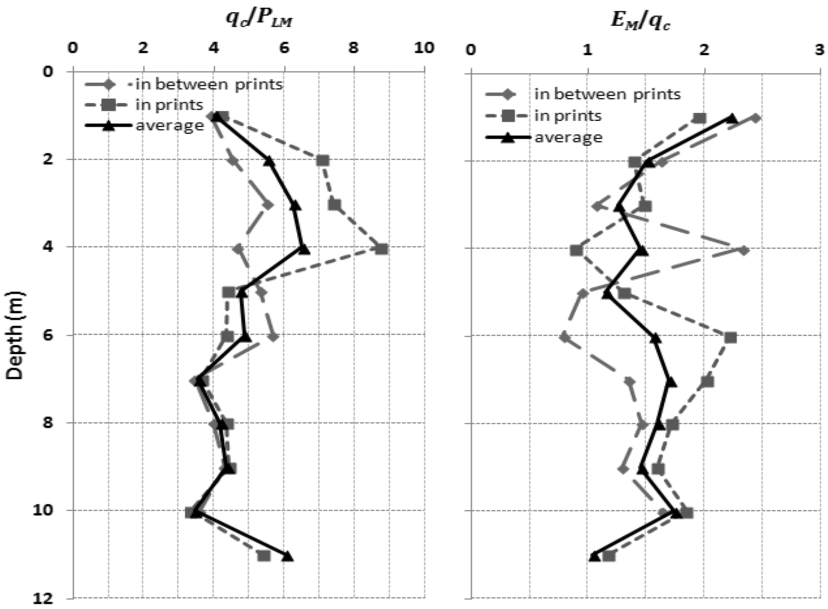

Figure 2. q_c/P_{LM} and E_M/q_c *correlations*

Average q_c/P_{LM} in between prints, in prints and for all tests, including tests carried out at the uppermost levels, can be calculated to be respectively 4.50, 5.20 and 4.86. These figures are either just below or just above the minimum q^*_c/P^*_{LM} value that has been proposed by Baguelin et al. (1978), but substantially less than the ratio that has been suggested by Briaud et al. (1985).

Baguelin et al. have related q^*_c/P^*_{LM} values to dilatancy, but as confirmed by the test results the treated sand in the trial was well compacted and a higher ratio should have been predicted. Noting that the location of the sands that were considered by Baguelin et al. are in a region where sands are not calcareous, with the available data it can be speculated that the low q_c/P_{LM} values originate from the soil mineralogy rather than compaction and soil dilatancy.

Standard deviations of these points were respectively 0.80, 1.75 and 1.08. Comparison of the overall q_c/P_{LM} average and standard deviation with Al Nakhilat suggests that, the difference between the average q_c/P_{LM} of the two studies is less than 8%.

E_M/q_c correlations at depth for in between prints, in prints and average values are also shown in Figure 2. E_M/q_c for the average of all points at the uppermost level seems to be greater than deeper points, but the deviation seems to be equal in magnitude to some deeper points of the in between prints and in print locations.

Average E_M/q_c of in between prints, in prints and all tests, including tests carried out at the uppermost levels, can be calculated to be respectively 1.49, 1.60 and 1.52. Standard deviations were respectively 0.54, 0.40 and 0.32. Comparison of the overall E_M/q_c average and standard deviation with Al Nakhilat Ship Repair Yard shows that the results of the two studies are compatible whereas there is less than 8% difference in the average E_M/q_c.

Similar to Al Nakhilat Ship Repair Yard, the average value of E_M/q_c in Palm Jumeira Trial is somewhat higher than what Briaud et al. (1985) have proposed.

4 CORRELATIONS FOR CALCAREOUS SANDS

q_c versus P_{LM} values of Palm Jumeira Trial and Al Nakhilat Ship Repair Yard have been plotted in Figure 3. Best fit linear, second and third degree polynomials and power curves were compared within the data range. Although these different mathematical functions produced non-coinciding curves, they appeared to be pseudo linear, which suggests that the best curve correlation can be assumed to be a linear function. By forcing the function to pass through the origin of the axes, the best curve can be expressed by (3).

$$q_c = 4.82P_{LM} \tag{3}$$

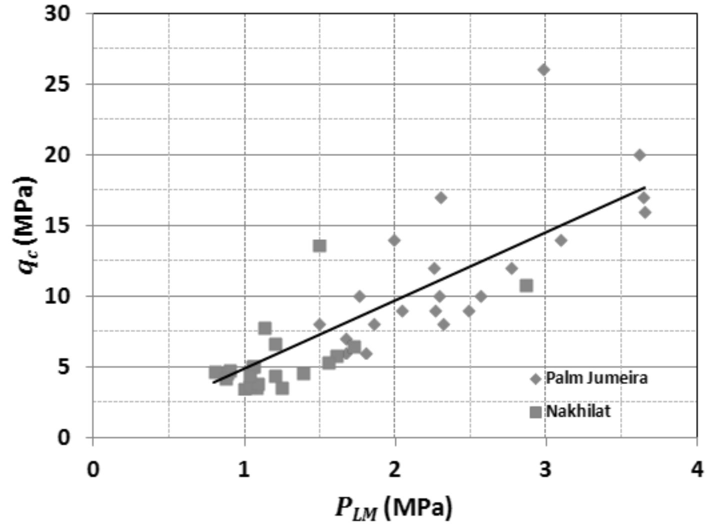

Figure 3. q_c versus P_{LM} values of Palm Jumeira Trial and Al Nakhilat Ship Repair Yard

E_M versus q_c values of Palm Jumeira Trial and Al Nakhilat Ship Repair Yard have been plotted in Figure 4. Best fit linear, second and third degree polynomials and power curves were compared within the data range. While the power curve also appeared to be pseudo linear, the polynomials slightly bent downwards towards the end of the range. In the studied range, the linear curve still seemed to be the best curve, and by forcing the function to pass through the origin, the best curve can be expressed as presented in (4).

$$q_c = \frac{E_M}{1.54} \tag{4}$$

The relationship between oedometer, E_{oed}, and Young, E_y, and moduli is:

$$E_{oed} = \frac{1-\nu}{(1+\nu)(1-2\nu)} E_y \tag{5}$$

Also, the relationship between E_{oed} and E_M is (Menard and Lambert, 1966):

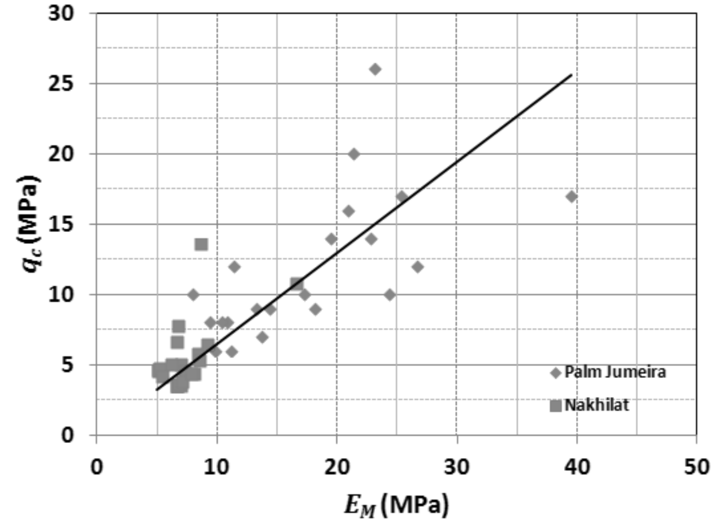

Figure 4. q_c versus E_M values of Palm Jumeira Trial and Al Nakhilat Ship Repair Yard

$$E_{oed} = \frac{E_M}{\alpha} \tag{6}$$

α= PMT rheological factor (Centre D'etudes Menard, 1975), which is 1/3 for sands with 7< E_M/P_{LM} <12

From (4) to (6), for the calcareous sands of Palm Jumeira and Al Nakhilat Ship Repair Yard:

$$q_c = \frac{\alpha}{1.54} \frac{1-\nu}{(1+\nu)(1-2\nu)} E_y \tag{7}$$

With an arbitrary value of v= 0.33, for saturated calcareous sands

$$E_y = 3.12 q_c \tag{8}$$

Lee and Salgado (2002) have cited from Schmertmann et al. (1978) and Robertson and Campanella (1989) that:

For young normally consolidated silica sand:

$$E_y = 2.5 q_c \tag{9}$$

For aged normally consolidated silica sand:

$$E_y = 3.5 q_c \tag{10}$$

For over consolidated silica sand:

$$E_y = 6 q_c \tag{11}$$

The factor of 3.12 in (8) is in between the factors for young normally consolidated and aged normally consolidated silica sands, and suggests that silica sand correlations are not suitable for carbonate sands.

5 CONCLUSION

The relationship between CPT and PMT parameters were studied for two sites that had been reclaimed from the sea using calcareous sands and treated by dynamic compaction. This study shows that q_c/P_{LM} for carbonate sand can be expected to be on the lower end of the range that has been suggested in other studies, and E_M/q_c was somewhat higher than suggested by Briaud et al. (1985). A relationship was also proposed for relating q_c to E_y in calcareous sands. In conclusion, while the authors believe that in principal any correlation between geotechnical parameters must be used with caution in any case, the range of q_c/P_{LM} from previous research and the analysis of the results of this research indicates that in particular the application of CPT-PMT correlations that have been developed for silica sands are not suitable to carbonate sands.

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REFERENCES

Al Hamoud, A. S. & Wehr, W. (2006). “Experience of Vibrocompaction in Calcareous Sand of UAE.” Journal of Geotechnical and Geological Engineering*,* 24, 3, 757-774.

Baguelin, F., Jezequel, J. F. & Shields, D. H. (1978). “The Pressuremeter and Foundation Engineering.” Aedermannsdorf, Trans Tech Publications, 617 pp.

Briaud, J. L., Noubani, A., Kilgore, J. & Tucker, L. M. (1985). “Correlation between Pressuremeter Data and Other Paramaters, Research Report.” Texas A&M University

Briaud, J. L. (1992). “The Pressuremeter.” Rotterdam, A A Balkema, pp.322.

Campanella, R. G., Berzins, W. E. & Shields, D. H. (1979). “A Preliminary Evaluation of Menard Pressuremeter, Cone Penetrometer and Standard Penetration Tests in the Lower Mainland, British Colombia.” Vancouver, University of British Colombia, 49.

Cassan, M. (1968). “Les Essais in Situ En Mécanique Des Sols.” Construction, 10 (October), 337-347.

Cassan, M. (1969). “Les Essais in Situ En Mécanique Des Sols.” Construction, 7-8 (July - August), 244-256.

Centre D'etudes Menard (1975). “The Menard Pressuremeter, D60.” Sols Soils, 26, 5-43.

Dowdall Stapleton, M. (2008). “Helping to Create a New Map.” Gulf News. Dubai.

Hamidi, B., Nikraz, H. & Varaksin, S. (2009). “A Review on Impact Oriented Ground Improvement Techniques.” Australian Geomechanics Journal, 44 (2), 17-24.

Hamidi, B., Varaksin, S. & Nikraz, H. (2010). "Treatment of a Hydraulically Reclaimed Port Project by Dynamic Compaction.” 3rd International Conference on Problematic Soils (PS10), Adelaide, 7-9 April, 113-120.

Hamidi, B., Varaksin, S. & Nikraz, H. (2013a). “Relative Density Concept Is Not a Reliable Criterion.” Ground Improvement*,* 166, GI2, 78-85.

Hamidi, B., Varaksin, S. & Nikraz, H. (2013b). "Relative Density Correlations Are Not Reliable Criteria.” Ground Improvement*,* 166, GI4, 96–208.

Jezequel, J. F., Lemasson, H. & Touzé, J. (1968). “Le Pressiomètre Louis Ménard: Quelques Problèmes De Mise En Oeuvre Et Leur Influence Sur Les Valeurs Pressiométriques.” *Bulletin de Liaison des Laboratoires des Ponts et Chaussées,* 32 (June - July), 97-120.

Lee, J. & Salgado, R. (2002). “Estimation of Footing Settlement in Sand.” *I*nternational Journal of Geomechanics, ASCE*,* 2, 1, 1-28.

Menard, L. & Lambert, P. (1966). "Etude Expérimentale D'un Massif De Fondation Soumis À Des Vibrations." Sols Soils, 17, 9-30.

Nazaret, M. (1972). “Influence Du Mode De Mise En Oeuvre De La Sond Pressiométrique.” Rapport De Recherche Du Laboratoire Régional Des Ponts Et Chaussées D'Angers, F.A.E.R 1.05.11.1.

Schmertmann, J. H., Hartman, J. P. & Brown, P. R. (1978). “Improved Strain Influence Factor Diagrams.” Journal of Geotechnical Engineering, ASCE*,* 104, GT8 (August), 1131-1135.

Van Wieringen, J. B. M. (1982). “Relating Cone Resistance and Pressuremeter Test Results.” 2nd European Symposium on Penetrating Testing, Amsterdam, 951-955.

Van Wambeke, A. (1962). “Méthodes D'investigation Des Sols En Place - Etude D'une Campagne D'essais Comparatifs.” Sols Soils, 2, September, 9-18.