# Correlations between CPT and PMT at a Dynamic Compaction Project

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ABSTRACT: In many ground improvement projects the preliminary field testing method is different from the tests that are carried out later. Hence, it may be necessary to correlate the two tests for comparative purposes.

Dynamic Compaction, using pounders weighing up to 35 tons, has been used to treat 175,000 $m^2$ of hydraulically reclaimed carbonate sands with a thickness of about 16 m for a port expansion project in Ras Laffan, Qatar. In this project CPT was used before and after ground improvement works. A number of Pressuremeter tests (PMT), some in the immediate vicinity of the CPT locations, were also carried out. This paper shall briefly describe the project and the ground improvement works. Previously published literature correlating CPT to PMT will be reviewed and the results of the two testing methods that have been carried out in Ras Laffan shall be correlated, and conclusions will be made based on the findings.

## 1 THE PROJECT: NAKILAT SHIP REPAIR YARD

Ras Laffan, located about 70 km north of Qatar's capital city, Doha, is one of the world's largest and fastest developing gas hubs. As shown in Figure 1 and as part of Port of Ras Laffan's expansion program it was decided to construct Nakilat Ship Repair Yard by hydraulically reclaiming its site from the Persian Gulf.

The land was reclaimed using the carbonate sand and gravel that was dredged for deepening the port. The material's grain size was understood to be generally less than 75 mm, but it was anticipated that stones as large as 500 mm in diameter could also be present. The maximum fines content (passing 63 μm sieve) of the fill was generally less than 10%.

The dense layer of seabed in the reclaimed area was variable from -9.1 m to -13.2 m CD (chart datum). Design (final platform) level was specified to be at +3.5 m CD.

While it was understood that other less sensitive areas of the project would require lesser treatment, three areas in the dry docks designated as DDR4, DDR5 and DDR 6 and shown in green in Figure 1 were deemed to require treatment by Dynamic Compaction (Menard, 1972-74). The surface areas of these regions were respectively 57,064 $m^2$, 35,643 $m^2$ and 82,962 $m^2$. Consequently, the total area was 175,669 $m^2$.

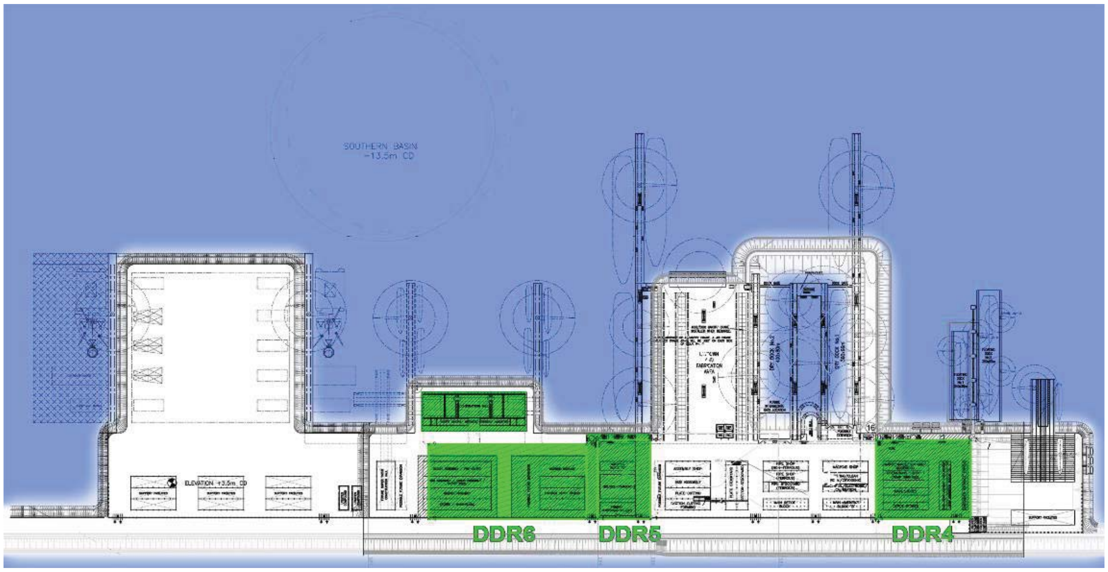


**Figure 1. Plan of Nakilat Ship Repair Yard (Dynamic Compaction areas shaded in green)**

With the assumption that the reclaimed ground would settle about 5% due to Dynamic Compaction (DC), reclamation was carried out 0.6 to 0.8 m higher than the design levels. Hence working levels varied from +4.1 to +4.3 m CD.

### 1.1 *Design and Acceptance Criteria*

It was the primary requirement of the project for the ground to possess a relative density, $D_r$, of 60% based on Baldi et al. (1986):

$$D_r = \frac{1}{2.41} \ln \left[ \frac{q_c}{157(\sigma'_{vo})^{0.55}} \right] \quad (1)$$

where $q_c$= CPT cone resistance (kPa) and $\sigma'_v$= effective vertical stress (kPa).

The correction factor to be applied to the cone resistance for carbonate sand was stipulated to be 1.94.

For the purpose of calculations it was specified that the saturated density, $\gamma_{sat}$, and unsaturated density, $\gamma_{unsat}$, were respectively 18.7 and 15.2 kN/m$^3$. Average groundwater level was assumed to be at +0.5 m CD.

As past experience indicated that this requirement would most probably not be met without ground improvement, it was foreseen that Dynamic Compaction would be carried out if the geotechnical investigation proved that this expectation was correct.

At the same time it was well understood that by implementing Dynamic Compaction the improvement of the upper layers of reclaimed ground would be much more than what was required. Consequently, the functionality of the project could have been achieved more affordably by also envisaging alternative criteria based on the design needs.

The alternative criteria specified that for an isolated footing carrying a 4000 kN load:

- Allowable bearing capacity: 200 kPa
- Maximum settlement: 50 mm

### 1.2 *Initial Ground Conditions*

The CPT tests that were carried out as part of the geotechnical investigation consistently demonstrated that the reclamation would not meet the criteria. In areas DDR4, DDR5 and DDR6 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. Then the soil 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. The CPT friction ratio was generally well below 1%.

## 2 GROUND IMPROVEMENT BY DYNAMIC COMPACTION

The project's schedule stipulated that mobilization, ground improvement and testing had to be completed according to the below milestones:

- DDR4: 154 days after issuance of notice to proceed.
- DDR5: 63 days after issuance of notice to proceed.
- DDR6: 91 days after issuance of notice to proceed.

Two specially equipped cranes were mobilized and utilized to meet the schedule.

Dynamic Compaction was carried out in areas DDR4, DDR5 and DDR6 using pounders weighing 35 tons, 28 tons, 25 tons and 15 tons. The 35 ton pounder was dropped in free fall from 25 m and without engagement to the winch and cabling system using the innovative MARS (Menard Automatic Release System) device that was used for the first time in 2004 during the ground improvement works of a loose fill with a maximum thickness of 28 m in Al Quoa'a, UAE (Varaksin, Hamidi and Aubert, 2005). Figure 2 shows the two Dynamic Compaction rigs. The front crane is dropping a 28 ton pounder and the back crane is dropping the 35 ton pounder using MARS.

**Figure 2. Dynamic Compaction using 28 ton and 35 ton pounders**

### 2.1 *Testing*

In order to verify that the project requirements had been satisfied 1 CPT was carried out per every 600 $m^2$ of improved ground. A number of PMT (pressuremeter) tests were also carried out for comparative purposes. This provided an opportunity to perform a number of CPT and PMT tests in the same locations and to correlate the results for carbonate sands.

## 3 CPT-PMT CORRELATION

### 3.1 *Literature Review*

Briaud et al (1985) collected 82 PMT borings data from various projects from 1978 to 1985. The result of this study proposed that the magnitude of correlation between $q_c$ and PMT parameters $P_l$, limit pressure, and $E_p$, pressuremeter modulus, is shown in Table 1.

**Table 1. Correlation between PMT and CPT according to Briaud et al. (1985)**

| Soil type | PMT parameter | Correlation to CPT |
|---|---|---|
| Sand | $P_l$ | $0.2q_c$ |
| | $E_p$ | $2.5\ q_c$ |
| Clay | $P_l$ | $0.11\ q_c$ |
| | $E_p$ | $1.15\ q_c$ |

Baguelin, Jezequel and Shields (1978) have reviewed and interpreted a number of CPT-PMT correlations such as Van Wameke (1962), Cassan (1968-69), Jezequel et al. (1968) and Nazaret (1972) that were originally printed in French publications.

Baguelin et al. note that although the correlation between CPT and PMT in most technical publications is based on the ratio of $q_c/P_l$, the ratio $q_c^*/P_l^*$ would be more representative ($q_c^*$ and $P_l^*$ are respectively the net cone resistance and net limit pressure and can be calculated from Equation 2 and Equation 3).

$$q_c^* = q_c - q_o \quad (2)$$
$$P_l^* = P_l - P_o \quad (3)$$

where $q_o$ and $P_o$ are respectively the in-situ vertical and horizontal total stresses. In general the ratios $q_c^*/P_l^*$ and $q_c/P_l$ are close because $q_o$ and $P_o$ are small compared to $q_c$ and $P_l$, but can be quite different at depth in soft clays.

The influence of depth on $q_c^*/P_l^*$ can be studied from the works of Jezequel et al. (1968) on the dikes of a tidal power project in Rance. The dikes were hydraulic fills composed of clean sand with dry density equal to 1.5 t/$m^3$. The ratio $q_c^*/P_l^*$ 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, $q_c^*/P_l^*$ was about 6.7 throughout the remainder of the 20 m thick fill.

Nazaret (1972) did not observe the same independency of $q_c^*/P_l^*$ 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 ratio values 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 a depth of embedment of about 1.5 m (1 m in clays, 2 m in sands) before the test is no longer influenced by the surface of the ground.

According to Baguelin et al. the soil type is the parameter that has the greatest effect on the ratio of $q_c^*/P_l^*$, and for depths of about 5 to 20 m there seems to be a narrow correlation between $q_c^*$ and $P_l^*$. Baguelin et al. summarize the $q_c^*/P_l^*$ ratio to be on average within the ranges shown in Table 2.

**Table 2. $q_c^*/P_l^*$ for different soil types according to Baguelin et al. (1978)**

| Soil Description | $q_c^*/P_l^*$ |
|---|---|
| Very soft to soft clays | close to 1 or 2.5 to 3.5 |
| Firm to very stiff clay | 2.5 to 3.5 |
| Very stiff to hard clay | 3 to 4 |
| Very loose to loose sand and compressible silt | 1 to 1.5 and 3 to 4 |
| Compact silt | 3 to 5 |
| Sand and gravel | 5 to 12 |

Baguelin et al. understand that it is very likely that dilatancy is a key factor and $q_c^*/P_l^*$ could prove to be a reliable indicator of the importance of dilatancy in the resistance of a particular soil. If $q_c^*/P_l^*$ is about 5 to 6 then the soil is probably non-dilatant or slightly dilatant. A ratio of 8 to 12 probably indicates a dilatant soil.

### 3.2 *CPT – PMT Correlation for Carbonate Sand in Port of Ras Laffan*

After execution of Dynamic Compaction in DDR5 using a maximum pounder weight of 28 tons (without ironing) it was decided to perform a DC 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 PMT tests were carried out next to 3 CPT tests in the below order:

- Before phase 1: PMT-007 and CPT-551 (in between impact points)
- After phase 1: PMT-009 and CPT-576 (in between impact points)
- After phase 3: PM-010 and CPT-595 (in impact point)

The cone resistances of the CPTs are shown in Figure 3. Likewise, the limit pressure and pressuremeter modulus of the PMT are respectively shown in Figure 4 and Figure 5.

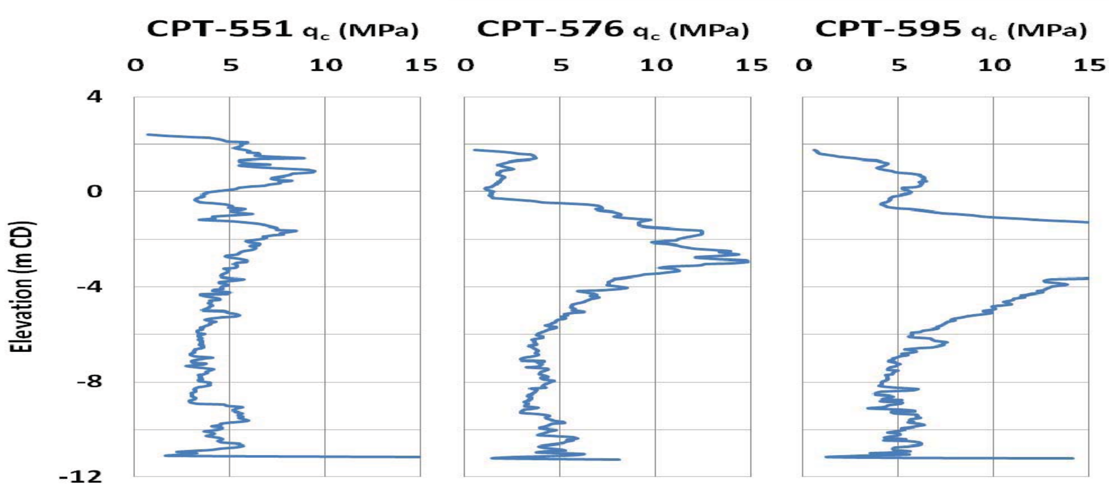


**Figure 3. Cone resistance values used in the correlation**

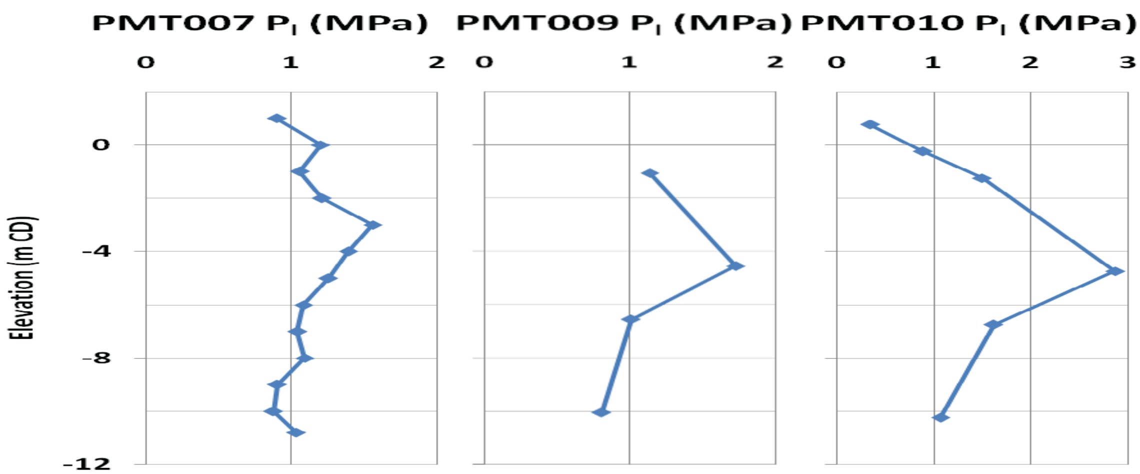


Figure 4. PMT limit pressure values used in the correlation

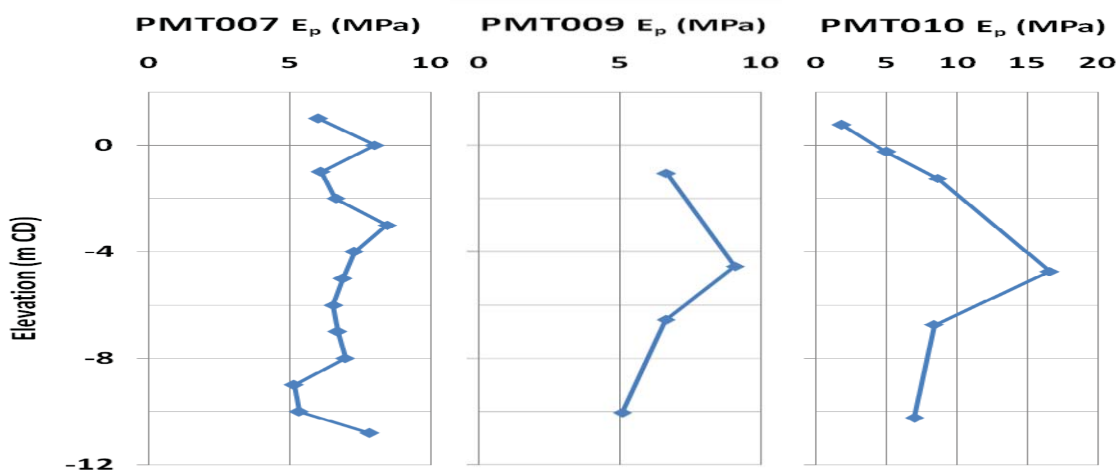


Figure 5. PMT modulus values used in the correlation

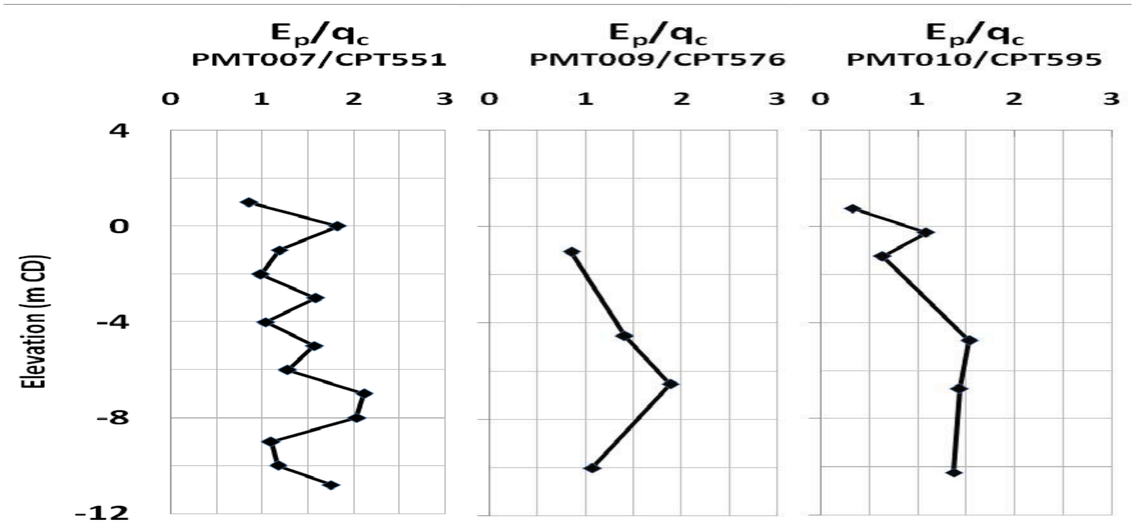


Figure 6. $E_p/q_c$ ratios for Ras Laffan carbonate sand

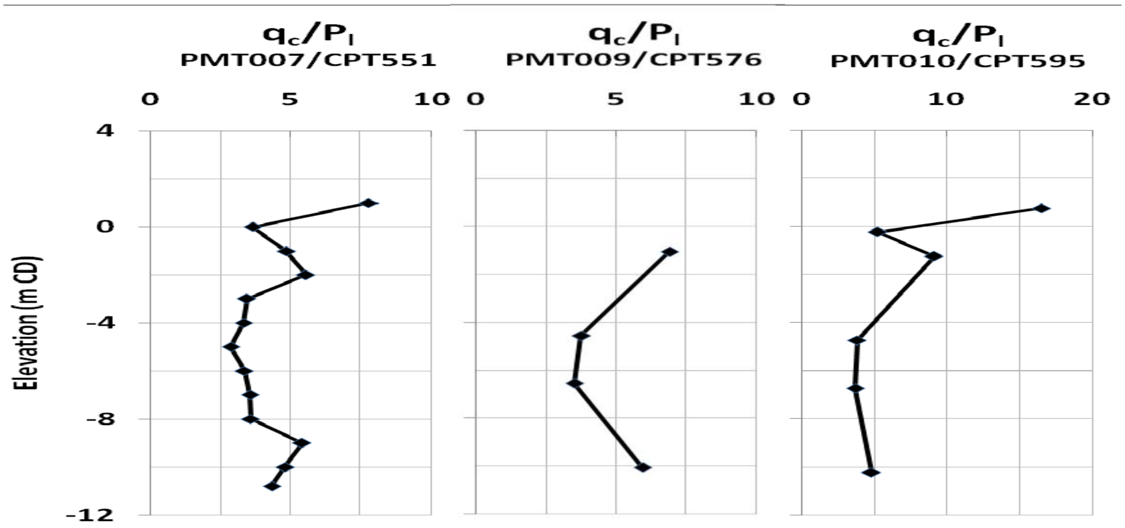


Figure 7. $q_c/P_l$ ratios for Ras Laffan carbonate sand

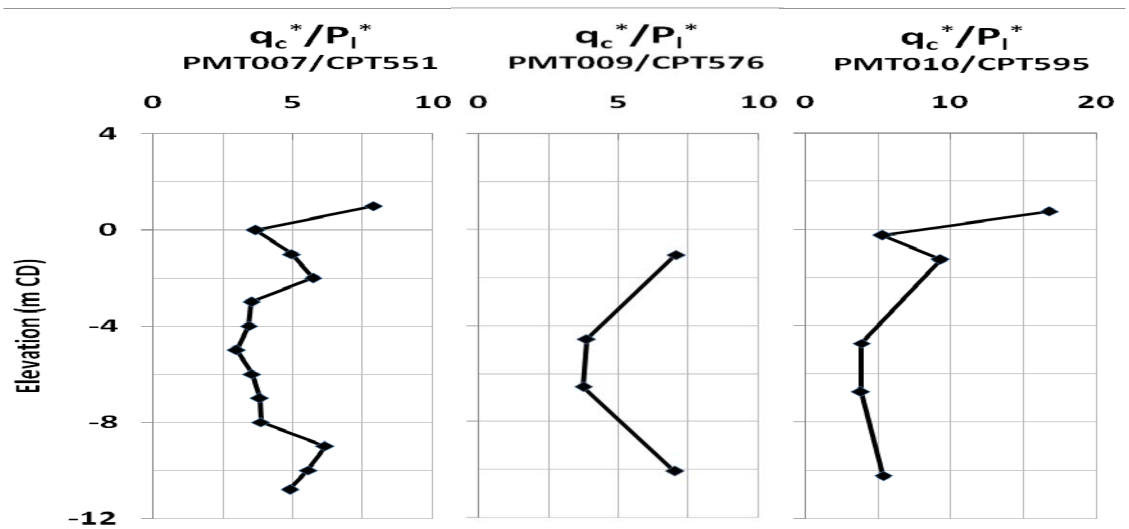


Figure 8. $q_c^*/P_l^*$ ratios for Ras Laffan carbonate sand

As shown in Figure 6, the $E_p/q_c$ ratios are substantially less than Briaud et al.'s (1985) correlation. Here, the uppermost shallow points do not seem to correlate differently due to the differences between the shallow and deep failure modes. The average $E_p/q_c$ value for the 23 test points is 1.35. The average $E_p/q_c$ ratios for the three comparisons on Ras Laffan carbonate sand are 1.5, 1.3 and 1.1. The maximum and minimum ratios for the points were respectively 0.3 and 1.91.

Briaud et al. have proposed an average value of 2.5 for $E_p/q_c$. This value is 1.85 times more than what has been measured for Ras Laffan carbonate sand, and is basically within the range (95%) of the correction factor of 1.94 that was applied to Baldi et al.'s equation (1986) to calculate relative density for carbonate sand.

The ratios of $q_c/P_l$ have been shown in Figure 7. It can be observed that the average $q_c/P_l$ ratios for 21 tests points are equal to 4.54. That value is 90% of what has been proposed by Briaud et al. (1985). The 21 test points do not include the uppermost test points of PMT007 and PMT010 due to the differences in between the shallow and deep failure modes. The average $q_c/P_l$ ratios for the three correlations on Ras Laffan carbonate sand are 4.1, 5 and 5.3 excluding the mentioned uppermost points. The minimum and maximum ratios were respectively 2.9 and 9.1 for the 21 points.

As shown in Figure 8, the $q_c^*/P_l^*$ ratios are identical in shape and very close in value to the $q_c/P_l$ ratios. The average $q_c^*/P_l^*$ ratios for the 21 tests points are equal to 4.82 which is just below the range of 5 to 12 that has been proposed by Baguelin et al. (1978). The average $q_c^*/P_l^*$ ratios for the three correlations are 4.3, 5.4 and 5.2 excluding the mentioned uppermost points. The minimum and maximum ratios for the 21 points were respectively 3 and 9.3.

## 4 CONCLUSION

The correlation results of CPT and PMT for densified Ras Laffan carbonate sand did not demonstrate any advantages of $q_c^*/P_l^*$ over $q_c/P_l$. Both ratios were slightly less than what Bageulin et al. and Briaud et al. have proposed, but for preliminary purposes the ratios may be assumed to be 5. $E_p/q_c$ ratios appear to be less than what Briaud et al. have proposed, and the same correction factor that is been used for calculating relative density from Baldi's formula may relate the relation between carbonate and non-carbonate $E_p/q_c$ ratios as well.

## 5 ACKNOWLEDGEMENT

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