Open Journal of Civil Engineering, 2020, 10, 239-249
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Unified Approach to Assess Engineering Performance of Fill Improved by Shallow to Deep Compaction Based Techniques Using Relative Density

Ahmed Alaaeldin[1], Emmanouil Spyropoulos[2], Anas Orabi[3]

[1]Keller Grundbau GmbH, Dammam, KSA
[2]Saudi Aramco, Dhahran, KSA
[3]Keller Grundbau GmbH, Dubai, United Arab Emirates
Email: ahmed.alaaeldin@keller.com, emmanouil.spyropoulos@aramco.com, anas.ourabi@keller.com

How to cite this paper: Alaaeldin, A., Spyropoulos, E. and Orabi, A. (2020) Unified Approach to Assess Engineering Performance of Fill Improved by Shallow to Deep Compaction Based Techniques Using Relative Density. *Open Journal of Civil Engineering*, **10**, 239-249.
https://doi.org/10.4236/ojce.2020.103020

Received: August 6, 2020
Accepted: August 24, 2020
Published: August 27, 2020

Abstract

The setting of pre assessment criteria for soil compaction is hardly determined, especially, in case of undecided structure locations. Different design guidelines recommend achieving a specific value of relative density for the compaction of fill placement works. Alternatives were discussed through the literature to predict the value of relative density based on soil field tests (e.g. cone and standard penetration tests). This paper presents the weakness of using the Over Consolidation Ratio (OCR) as guidance to assess the value of cone tip resistance using the soil relative density. The variation of OCR (from 1 to 10) has a significant effect on the q_c value up to 110% when compared to the normally consolidated state. Then normally consolidated state can logically cover the compaction process with variation of 20%, 33%, and 4% for relative density values 85%, 70%, and 60%, respectively. A unified approach is recommended to predict the compaction q_c-performance line using normally consolidated condition and sand relative density.

Keywords

Compaction, Relative Density, Performance Specifications

1. Introduction

In recent years, the field of construction has witnessed a great leap in building technologies with targeting a maximum cost saving. Nonetheless, the nature of the ground may obstacle this aim. Traditionally, for these cases, deep foundations (e.g. piles) are used to cope with the super-structure loads. Unfortunately, the using of piles leads to increase the cost of the project. Soil Improvement techniques are the most common solution utilized to achieve, for example, a proper soil bearing capacity with a target allowable settlement (*i.e.* the design criteria or the performance specifications) where the traditional over-excavation and replacement are not practicable for environmental, technical or economic reasons.

The design criteria for soil-treatment/fill-compaction may be unknown, especially, at the tender or site preparation stages in addition to undecided structures locations. However, the underneath soil/fill performance needs to be assessed prior to start the treatment process to determine the type and the depth of ground modifications.

This paper presents the weakness of using the Over Consolidation Ratio (OCR) as guidance to assess the value of cone tip resistance using the soil relative density. The variation of OCR (from 1 to 10) has a significant effect on the q_c value up to 110% when compared to the normally consolidated state. A unified approach is recommended to predict the compaction q_c-performance line using normally consolidated condition and sand relative density.

2. Background and Problem Statement

Due to the difficulties in obtaining undisturbed samples of cohesionless soils, geotechnical engineers often rely on field tests to obtain in situ soil characteristics. A conventional analysis using Standard Penetration (SPT), Cone Penetration (CPT), or Pressure Meter (PMT) tests is suggested to check the minimum adequate criteria of a project [1]. The electronic CPT has emerged as one of the most popular tool for ground investigation due to its relatively lower cost, simplicity, continuous measurement with depth and excellent repeatability and accuracy. [2] and [3] suggested correlations between CPT results and soil characteristics such as unit weight (γ), friction angle (φ), relative density (D_r), and elastic modulus (E).

However, the soil parameters to be utilized within the basic correlations of cone resistance and relative density is the analysis objective of this paper and whether Normally Consolidated (NC) or Over Consolidated (OC) concepts are applicable for the cases of densifying shallow soil formations. Scope is to define those parameters that are not over-conservative leading to excessive costs but also allows achieved soil compaction degrees that are safe for the subsequent top facilities construction. Therefore, an attempt is herein provided to show that through an integrated methodology the compaction q_c-performance line using normally consolidated condition and sand relative density is adequate to obtain the necessary densification amounts of the related soil formations without compromising the safety of the proposed structures upon such formations.

This paper presents the weakness of using the Over Consolidation Ratio (OCR) as a guidance to assess the value of cone tip resistance using the soil relative density. The variation of OCR (from 1 to 10) has a significant effect on the q_c value up to 110% when compared to the normally consolidated state. A unified approach is recommended to predict the compaction q_c-performance line using normally consolidated condition and sand relative density.

3. Relationships of Relative Density and Cone Resistance

One of the most operational correlations is relating the measured cone tip resistance (q_c) to the soil relative density as a factor to measure the compaction effectiveness. [4] and [5] performed calibration chambers tests, that was developed in 1969 [6], to appraise the D_r-q_c relationship. In a calibration chamber test with well-defined boundaries, a large cylindrical sand sample is deposited at a known soil properties (e.g. relative density) and consolidated to a desired stress state followed by a CPT (along the axis of the sample). Each test after completion provides one value of q_c for a given value of D_r. The size and the boundaries conditions of the chamber are the most important parameters that affect the results as studied and listed by [7] and [8].

The value of the cone tip resistance (q_c) can also be predicted based on the soil relative density (D_r) as suggested by [9] in Equation (1) using 631 CPT tests that collected from different calibration chamber test sources (*i.e.* [3] [10] [11] [12]). The utilized soil types were Ticino, Hokksund, Toyoura, Monterey, and Leighton Buzzard sands.

$$q_c = C_0 p_a \left(\frac{\sigma'_h}{p_a}\right)^{C_1} D_r^{C_2} \tag{1}$$

where, C_0, C_1, and C_2 are empirical constants that vary with the calibration chamber boundary conditions (see **Table 1**). The values of C_0, C_1, and C_2 equal to 360, 0.50, and 1.50, respectively, had been recommended by the research authors to be generally utilized. p_a is a reference or the atmospheric pressure, and σ'_h is the initial

Table 1. The value of C_o, C_1, and C_2 according to chamber boundary conditions.

Constant	BC1	BC2	BC3	BC4
Lateral boundary conditions	Constant stress	No displacement	No displacement	Constant stress
Top and bottom boundary conditions	Constant stress	No displacement	Constant stress	No displacement
C_o	350	320	370	320
C_1	0.50	0.24	0.45	0.48
C_2	1.51	1.10	1.51	1.29

effective lateral stress ($\sigma'_h = k_0\sigma'_{v_0}$) where σ'_{v_0} is the effective overburden pressure and k_0 is the at rest coefficient of lateral earth pressure ($k_0 = (1-\sin\varphi)\mathrm{OCR}^{\sin\varphi}$). OCR is the over consolidation ratio and φ is the soil effective friction angle which can be calculated using soil relative density ($\varphi = 28 + 0.15D_r$, [13]).

[14] used the results of about 80 correlation calibration chamber tests on saturated Normally Consolidated (NC) sand, in addition to his work previously performed tests in 1976, to indicate the soil relative density from the cone tip resistance. The utilized samples were two artificial sands with opposite extreme crushabilities, two natural fine sands, and one natural and one artificial medium sands. **Figure 1** presents the results obtained from the research.

[15] predicted the soil relative density for cohesionless soils based on calibration chamber tests on five different NC sands (Ticino, Ottawa, Edgar, Hokksund, and Hilton mines). The results produced the following relationship:

$$D_r(\%) = 68\left[\log\left(\frac{q_c/K_q}{\sqrt{p_a\sigma'_{v_0}}}\right) - 1\right] \tag{2}$$

where, $K_q = 1 + (D_r - 30)/300$. It should be noted that an iteration process has to be applied to get the value of D_r .

[13] studied the normally consolidated and the over consolidated sand performance by using calibration chamber tests on Ticino and Hukksund sands. The following relation was obtained considering the calibration chamber boundary effects.

$$D_r = \frac{1}{C_2}\ln\left(\frac{q_c}{C_0\sigma'^{C_1}}\right) \tag{3}$$

The value of $\sigma' = \sigma'_{v_0}$ for normally consolidated sand and equal to σ'_h for over consolidated sand. The values of C_0, C_1, and C_2 had been recommended by the research authors for normally and over consolidated sandy soil as presented in **Table 2**. Nonetheless, the two series of coefficients for each soil case give very close results.

[16] finally suggested another formula to obtain the relative density from the cone tip resistance as shown in the following equation:

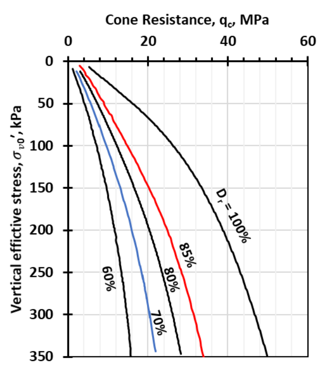


Figure 1. Cone tip resistance as a function of overburden pressure and soil relative density (after [14]).

Table 2. The value of C_o, C_1, and C_2 according to stress history.

Soil Case	Sand type	σ'	C_o	C_1	C_2
NC	Ticino	σ'_{v_0}	157	0.55	2.41
	Hukksand		86	0.53	3.29
OC	Ticino	σ'_h	220	0.53	2.64
	Hukksand		170	0.54	3.01

$$D_r(\%) = \frac{1}{3.1}\ln\left[\frac{q_c/p_a}{17.68\left(\sigma'_{v_0}/p_a\right)^{0.5}}\right] \tag{4}$$

Based on the above-mentioned existing literature, the current assessment presents the weakness of using the Over Consolidation Ratio (OCR) as a guidance to assess the value of cone tip resistance using the soil relative density.

4. Stress-Strain History Effect

The over-consolidated (OC) soils, by means of dense state, can sustain larger loads when compared to the normally consolidated case. As such sands are generally identified as loose (behavior similar to NC clay) or dense (behavior similar to OC clay).The prediction of the soil relative density of the engineering performance of the soil is relatively unreliable. Although, the availability of correlations for estimating various parameters for soil (e.g. Elastic Modulus) depending on the NC and OC conditions.

By observing the behavior of NC and OC Sands, it is evident that the over-consolidated soil attains a higher shear strength comparing to the normally consolidated soil. However, both samples approach the same failure shear stress irrespective of the initial relative density, even though the OC soil exhibits more shear strength (dense soils dilate when sheared). This value is difficult to quantify in terms of relative density, so an effort to select a criteria that is more standardized and overall stronger is attempted.

As presented above, the value of σ' and the coefficients C_0, C_1, and C_2 shown in Equation (3) have been changed to be used in the same equation to account for over consolidation ratio [3]. [17] suggested the following ratio (Equation (5)) between the NC and OC q_c values. Nevertheless, some other researchers proved that the q_c value is slightly affected by the strain history of the sandy soil, on the other hand, the strain history considerably influences the sand stiffness ([3] [16] [18]).

$$q_c^{OC} = q_c^{NC}\left[1 + x\left(\text{OCR}^{\beta} - 1\right)\right]$$

$x = 0.75$, ([17])

$x = 0.50$ (OCR = 2) to 0.25 (OCR = 15), ([15])

$\beta = 0.42$, ([17])

Table 3. The value of Q_f.

Soil Case	Sand State	Q_f
NC	Low, medium, high	305
	OCR < 3	390
OC	OCR (3:8)	403
	OCR > 8	443

$$\beta = 0.25 + 0.25 D_r, \ ([15]) \tag{5}$$

[19] carried out twelve Standard Penetration Tests (SPT) on normally (NC) and over consolidated (OC) sands with OCR = 3. The results indicated that there is no effect of the soil stress history on SPT values which means that influence of the OCR value on the soil characteristics is negligible.

[20] provided a more coherent, straight-forward and simplistic approach (Equation (6)) to the estimation of Relative Density correlated from CPT q_c values which accounted for the chamber boundary effects. The NC and OC tested sands were predominantly fine and medium sands in low, medium, and high compressibility states.

$$D_r^2 = \frac{1}{Q_f Q_c \mathrm{OCR}^{0.18}} \frac{q_c / p_a}{\left(\sigma'_{v0} / p_a\right)^{0.5}} \tag{6}$$

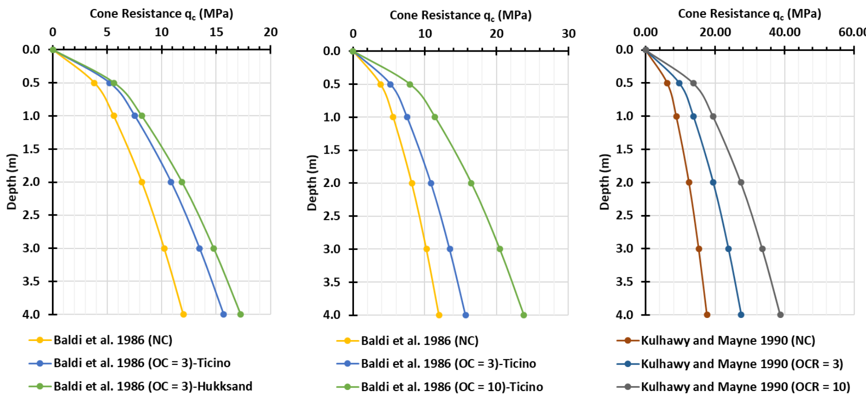
where, Q_f is a constant value which vary according to the soil state (**Table 3**). Q_c is the compressibility factor which equals to 0.91, 1.0, and 1.09 for high, medium, and low compressibility, respectively.

5. Over Consolidated Analysis

The over consolidation ratio might be determined from the results of field tests (e.g. Cone Penetration Tests) However, it is very difficult to estimate the value of OCR from the energy produced by the top-bottom compaction (Dynamic and Rapid Impact Compactions).

Figure 2(a) shows the influence of the type of the sand, utilized by [3], on the values of cone resistance. As glanced from the graph, a negligible difference can be observed between the results of Ticino and Hukksand sands for OCR = 3.0.A significant effect is witnessed by changing the OCR value from 1.0 to 3.0 for [3] and [20], see **Figure 4(b)** and **Figure 4(c)**. **Table 4** presents the sand properties used for this study.

Figure 3 presents the q_c-profile predicted based on 85% sand relative density and OCR = 3.0 up to 4.0 m depth using the different approaches presented above. The value of q_c obtained from [20] increases by 24%, 44%, 59%, and 73% when compared to that attained using [3] [9] [14] [15] equations, respectively. While, a maximum variation of 10% to 20% is observed between the correlations of [3] [9] [14]. However, a unified approach cannot be prepared using OCR = 3 as this value depends on the stress-strain history state which cannot easily estimated as a project criteria from compaction process.



(a) (b) (c)

Figure 2. Effect of over consolidation ratio on the cone tip resistance performance line. (a) Effect of sand type on the value of q_c; (b) Variation of OCR from [3]; (c) Variation of OCR from [20].

Table 4. Sand properties used in the analysis.

Unit weight, γ (kN/m^3)	Relative Density, D_r (%)	OCR	Friction angle, φ, (Degree)
16.00	85.0	1, 3, and 10	41

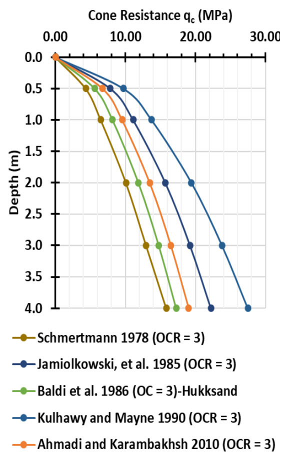


Figure 3. q_c profile based on over consolidation ratio (OCR = 3).

6. Normally Consolidated Analysis

For normally consolidated analysis, where the preconsolidation pressure equals to the existing overburden pressure, the approaches presented above are utilized and the results are presented in **Figure 4**. As indicated from **Figure 4(a)** (D_r = 85%), [15] and [20] almost have the same predicted q_c-value which soar by 40% from the nearest results. Whereas, the other three correlations have a maximum difference of 20%. On the other hand, for D_r = 70% (see **Figure 4(b)**), the results of [14] have the lowest values by 33% less than the nearest approach (*i.e.* [3]). Nonetheless, in this case a unified approach may be followed as the value of

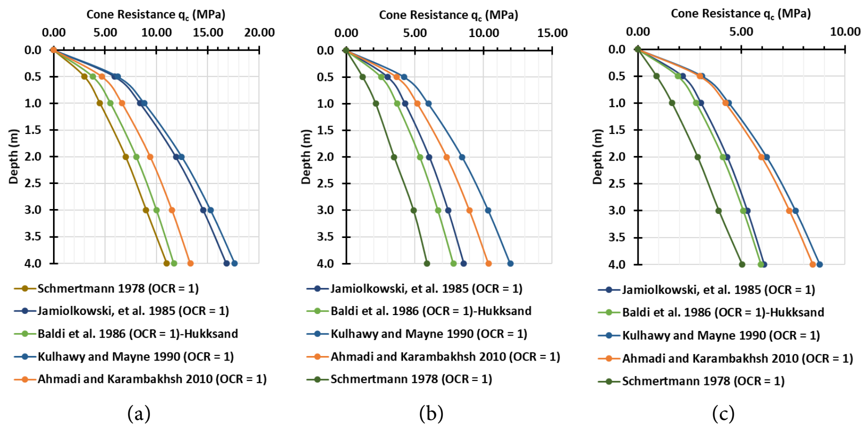


Figure 4. q_c profile for Normally consolidated sands. (a) D_r = 85%; (b) D_r = 70%; (c) D_r = 60%.

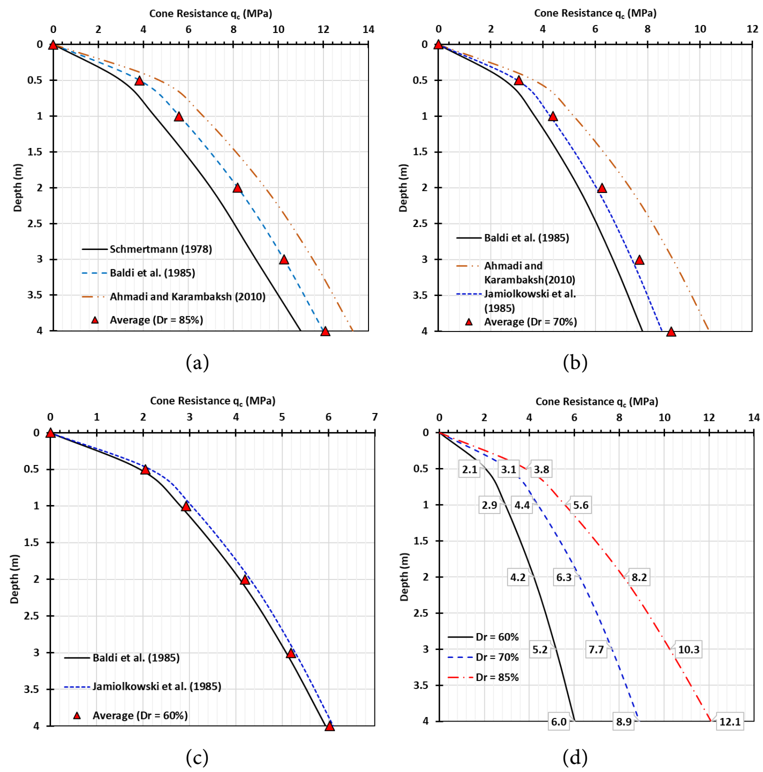


Figure 5. Recommended q_c performance line based on sand relative density. (a) q_c-profile for D_r = 85%; (b) q_c-profile for D_r = 70%; (c) q_c-profile for D_r = 60%; (d) Average q_c-profiles.

OCR = 1 for normally consolidated sandy soil.

As a result, the formulas suggested by [3] [9] [14] can be merged or used separately to assess the q_c values along the entire depth for D_r = 85%. While, all of the correlations except [14] and [20] may be applied for D_r = 70%. Moreover, only [3] and [15] could be utilized as these two formulas represent the average between other suggestions.

7. Performance Criteria

Based on the above mentioned points and by assuming that the value of OCR will not be affected rapidly after the treatment process because of hammering which breaks the bonding between soil particles and, also, the stress-history effect need some time until the soil be remolded and recemented. Therefore, for non-preloaded areas, the normally consolidated criteria may be applied to assess a CPT cone resistance performance line, especially, if there is no decided other criteria such as the bearing capacity and settlement.

By determining the anticipated value of relative density, **Figure 5** can be used to predict the performance line of the cone tip resistance for sandy soils up to 4.0 m depth which is the usual soil thickness that the Rapid Impact Compaction soil improvement method can mitigate on a single run from the top surface.

8. Conclusions

Due to the lack of information provided before finalizing the foundation design of a project, a criteria for performance achievement needs to be placed. By spotting the recommendation of different specifications to achieve sufficient relative compaction/density, this paper studied the different alternatives presented on the literature to unify the criteria of using relative density to assess a compaction performance line.

However, the soil parameters to be utilized within the basic correlations of cone resistance and relative density and whether Normally Consolidated (NC) or Over Consolidated (OC) concepts are applicable for the cases of densifying shallow soil formations was examined.

Having completed the analysis of the existing literature, it was concluded that the Over Consolidation Ratio (OCR) cannot be utilized to suggest a guidance to assess the value of cone tip resistance using the soil relative density. The variation of OCR (from 1 to 10) has a significant effect on the q_c value up to 110% when compared to the normally consolidated state. Therefore, an attempt was provided to show that through an integrated methodology the compaction q_c-performance line using normally consolidated condition and sand relative density is adequate to obtain the necessary densification amounts of the related soil formations without compromising the safety of the proposed structures upon such formations. It was concluded that the normally consolidated state can logically cover the compaction process with variation of 20%, 33%, and 4% for relative density values 85%, 70%, and 60%, respectively.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] FHWA (2017) Ground Modification Methods. Federal Highway Administration (FHWA), Washington DC.

[2] Robertson, P.K. and Campanella, R.G. (1983) Interpretation of Cone Penetration Tests: Sands and Clays. *Canadian Geotechnical Journal*, **20**, 719-745. https://doi.org/10.1139/t83-079

[3] Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M. and Pasqualini, E. (1986) Interpretations of CPT's and CPTU's, 2nd Part: Drained Penetration of Sands. 4*th International Conference on Field Instrumentation and in-Situ Measurements*, Singapore, November 1986, 143-156.

[4] Olsen, R.S. (1994) Normalization and Prediction of Geotechnical Properties Using the Cone Penetrometer Test (CPT). US Army Engineer Waterways Experiment Station.

[5] Gupta, R., Rodrigo, S., Mitchell, J. and Jamiolkowski, M. (2001) Calibration Chamber Size Effects on Penetration Resistance in Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, **127**, 628.

[6] Holden, J.C. (1971) Research on Performance of Soil Penetrometers. Internal Report, Country Roads Board of Victoria, Victoria.

[7] Ghionna, V.N. and Jamliolkowski, H. (1991) A Critical Appraisal of Calibration Chamber Testing of Sands. *Proceedings of the* 1*st International Symposium on Calibration Chamber Testing*, Potsdam, 28-29 June 1991, 13-39.

[8] Salgado, R., Mitchel, J.K. and Jamiolkowski, M. (1998) Calibration Chamber Size Effects on Penetration Resistance in Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, **124**, 878-888. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:9(878)

[9] Ahmadi, M.M. and Karambakhsh, P. (2010) K_0 Determination of Sand Using CPT Calibration Chamber. 2*nd International Symposium on Cone Penetration Testing*, Huntington Beach, May 2010, 1-8.

[10] Salgado, R. (1993) Analysis of Penetration Resistance in Sand. PhD Thesis, University of California, Berkeley.

[11] Lunne, T., Robertson, P.K. and Powell, J.M. (1997) Cone Penetration Testing in Geotechnical Practice. Blackie Academic & Professional, London.

[12] Houlsby, G.T. and Hitchman, R.C. (1988) Calibration Tests of Cone Penetrometers in Sand. *Géotechnique*, **38**, 39-44. https://doi.org/10.1680/geot.1988.38.1.39

[13] Meyerhof, G.G. (1959) Compaction of Sands and Bearing Capacity of Piles. *Transactions of the American Society of Civil Engineers*, **126**, 1292-1322.

[14] Schmertmann, J.H. (1978) Guidelines for Cone Penetration Test, Performance and Design. Report FHWA-TS-78-209, Federal Highway Administration, Washington DC.

[15] Jamiolkowski, M., Baldi, G., Belloti, R., Ghionna, V. and Pasqualini, E. (1985) Penetration Resistance and Liquefaction of Sands. *Proceedings of the* 11*th International Conference on Soil Mechanics and Foundation Engineering*, 57-153.

[16] Jamiolkowski, M., Lo Presti, D.C.F. and Manassero, M. (2001) Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT. *Soil Behavior and Soft Ground Construction*: *Geotechnical Special Publication*, **11**, 201-238.

[17] Schmertmann, J.H. (1975) Measurement of *In-Situ* Shear Strength. *Proceedings of ASCE Spec. Conference on In-Situ Measurement of Soil Properties*, Raleigh, NC, Vol. 2, 57-138.

[18] Marchetti, S. (1982) Detection of Liquefiable Sand Layers by Means of Quasi-Static

Penetration Sand Layers by Means of Quasi-Static Penetration. ESPOT II, Amsterdam.

[19] Bieganousky, W.A. and Marcuson, W.F. (1976) Liquefaction Potential of Dams and Foundations, Report No. 1, Laboratory Standard Penetration Tests on Reid Bedford Model and Ottawa Sands. Research Reports-76-2, W.E.S Vicksburg, Miss.

[20] Kulhawy, F.H. and Mayne, P.H. (1990) Manual on Estimating Soil Properties for Foundation Design. Report EL-6800, Electric Power Research Institute, Washington DC.