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Validation of Correlation Factor between E_s and Q_c Using Load Tests

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***Abstract* –** Cone Penetration test (CPT) has been increasingly used in the past years as part of soil investigation regime or as in-situ quality control test for soil improvement works. CPT testing regime has many advantages since it provides quick and continuous soil profiling with repeatable and reliable data. It is economical and productive testing with strong theoretical basis for results interpretation. Although no samples can be obtained during normal CPT test, it allows for accurate measurements of critical geotechnical design parameters such as Elastic modulus Es which has been empirically related to the cone tip bearing resistance (Qc) by a correlation factor called alpha (α) . A widely used field test namely Plate load test (steel plate with 25mm thickness and diameter up to 762mm) sometimes called Zone load test when bigger plate size is used (up to 3m width), is performed to determine the ultimate bearing capacity of soil and the anticipated settlement under a given design load for shallow foundations. The elastic modulus Es can be found from the slope of settlement versus plate pressure graph. The correlation factor varies in a wide range of values according to the literature depending on the soil type, the cone bearing resistance value and the consolidation status. Series of CPT tests and PLT/ZLT tests performed on variable type of soils mainly granular soils has been used to conclude the correlation factor between Es and Qc.

***Keywords*:** ZLT, PLT, CPT, Young Modulus, Tip Cone Resistance, Correlation Factor

1. Introduction

Prior to start any construction works, it is mandatory to properly understand and evaluate the actual soil conditions by performing a detailed soil investigation campaign including field tests accompanied with the necessary sampling for laboratory tests. Civil and Geotechnical engineers will rely on the accuracy of such tests results to determine the physical and mechanical properties of soil layers, then, the soil's bearing capacity, its settlement rate under a given surcharge, its susceptibility for any liquefaction hazards and the best foundation system to support the upper structure.

2. Objective

A wide range of correlation factors between the Cone Penetration Test (CPT) cone resistance (Qc) and Plate Load Test (PLT) Elastic modulus (Es) are presented in several books and publications. This paper aims to benefit from several field load testing performed using variable plate sizes in three different projects where the soil consists mainly of granular material with variable fine contents of less than 12%. The subject plate load tests and zone load tests results will be used to calculate the elastic modulus (Es) of Sand / Sand with Silt over the influence depth below the plates. Average cone resistance (Qc) over the same influence depth will be calculated from several Cone Penetration tests (CPTu) performed in the vicinity of those load tests. The resultant correlation factor will be then calculated by simply dividing the Elastic modulus (Es) over the cone resistance (Qc).

3. Listing of Available Correlations

Table-1 below provides a brief listing of several correlations available in different references. The factor alpha relating the stress-strain modulus (Es) and Cone Resistance (Qc) varies based on the type of soil, and its over consolidation status.

Table 1: Stress-strain Modulus (E_s) vs Cone Resistance (Q_c) Correlations

Foundation Analysis and Design , Joseph E. Bowles, 5th Edition [1]		
Soil	**Correlation**	**Other Conditions**
Sand (normally consolidated)	$E_s = (2 \text{ to } 4)q_u$ $= 8000\sqrt{qc}$	
Sand (saturated)	$E_s = F\, q_c$	e =1.0, F = 3.5 e =0.6, F =7.0
Sand (overconsolidated)	$E_s = (6 \text{ to } 30)q_c$	
Clayey Sand	$E_s = (3 \text{ to } 6)q_c$	
Silts, sandy silt, or clayey silt	$E_s = (1 \text{ to } 2)q_c$	▪ If $q_c < 2500$ kPa, use $E'_s = 2.5q_c$ ▪ $2500 < q_c < 5000$ use $E'_s = 4q_c + 5000$ where: E's = constrained modulus $= \frac{Es(1-\mu)}{(1+\mu)(1-2\mu)}$
Soft clay or clayey silt	$E_s = (3 \text{ to } 8)q_c$	
Foundation Design Principals and Practice - Coduto [2]		
Sand/Gravels (Over consolidated)	$E_s = (6 \text{ to } 10)q_c$	
Sands (normally consolidated)	$E_s = (2.5 \text{ to } 6)q_c$	
Silty/Clayey Sands (normally consolidated)	$E_s = 1.5q_c$	
Silty/Clayey Sands (over consolidated)	$E_s = 3.0q_c$	
Schmertmann 1978 [3]		
Sand (Normally consolidated)	$E_s = 2.5q_c$	For Axisymmetric loading (circular & square footing)
Sand (Normally consolidated)	$E_s = 3.5q_c$	For plane strain (strip) foundations
Thomas 1968 [4]		
Sands	$E_s = \alpha q_c$	(α = 3 to 12)
Guide to Cone Penetration Testing 6th Edition - Robertson [5]		
Sands	$E' = \alpha_E q_c$ Where: $\alpha_E = 0.015\,[10^{(0.55Ic+1.68)}]$	α_E : function of degree of loading, soil density, stress history, cementation, age, grain shape & mineralogy. = 2 to 4 for very young, normally consolidated sands; = 4 to 10 for aged (> 1,000 years), NC sands; = 6 to 20 for overconsolidated Sands

4. Field Tests Procedure

4.1. Plate Load Test (PLT)

According to ASTM D 1194-94 [6], PLT method is used to estimate the bearing capacity of a soil under field loading conditions for a specific loading plate and depth of embedment. It consists mainly of the following elements:

Loading platform, hydraulic jack, bearing plates and settlement-recording devices such as dial gages. Figure-1 below reflects the typical PLT test arrangement as presented in the Foundation Analysis and Design [1].

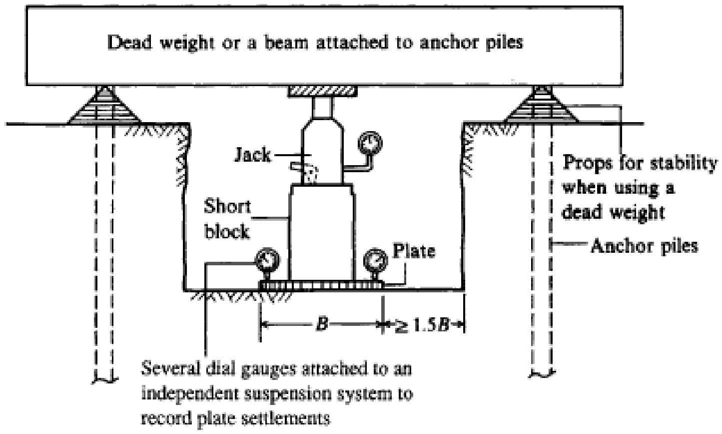


Fig. 1: Typical PLT test arrangement

Two plates sizes were used in three different projects considered in this study, to evaluate the actual settlement under given loads. For project-1 located in Jubail area Kingdom of Saudi Arabia, a plate with diameter of 750mm has been used for PLT tests while a rectangular plate of 2mx2m was used for ZLT tests. For project-2 and 3 located in Jubail and Jizan – Kingdom of Saudi Arabia – respectively, a plate having 600mm diameter has been used for PLT tests while ZLT tests were performed only in project-2 using two different plates sizes: 2.25mx2.25m and 2.50mx2.50m.

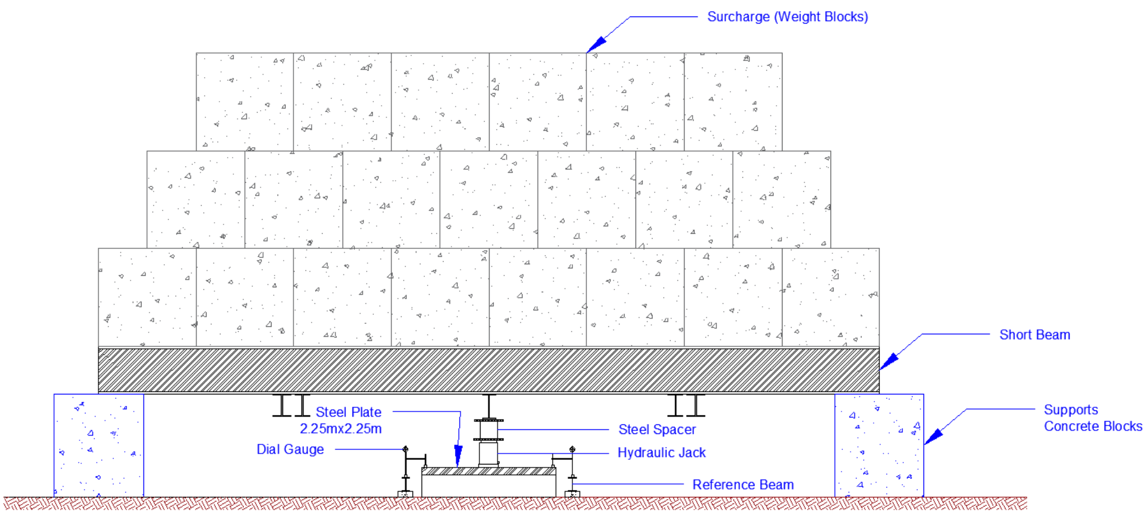


Fig. 2: Typical ZLT test arrangement

4.2. Cone Penetration Test (CPT)

The Cone Penetration Test (CPT), is performed by advancing a penetrometer tip with conical point having a 60° apex angle and a cone base area of 10 or 15cm^2. It is advanced through the soil at constant rate of 20mm/s. The force on the conical point (cone) required to penetrate the soil is measured by electrical methods at a minimum of 10-mm or 20-mm interval readings. Stress is calculated by dividing the measured force (total cone force) by the cone base area to obtain cone resistance, Q_c. Other parameters are also measured during CPT test such as sleeve resistance f_s calculated by dividing the measured axial force by the surface area of the friction sleeve present on the penetrometer immediately behind the cone tip. Modern piezocones are capable of registering pore water pressure induced during advancement of the penetrometer tip using an electronic pressure transducer.

CPT has extensive applications in a wide range of soils. Especially with the modern large pushing equipment and robust cones, CPT test can be performed in stiff to very stiff soils, and in some cases soft rock. CPT tests are very useful evaluation of site stratigraphy, homogeneity and depth to firm layers, voids or cavities and other discontinuities. It can provide an estimate of soil classifications, and correlations with engineering properties of soils.

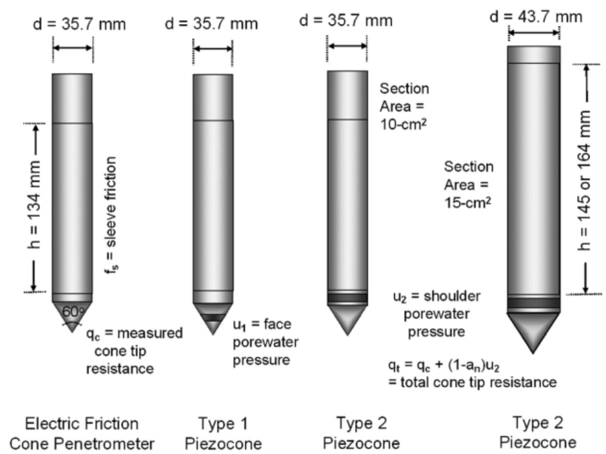


Fig. 3: Penetrometer Design Configurations, ASTM D5778-12 [7] (a) Electronic friction-type, (b) Type 1 Piezocone, (c) Standard 10-cm^2 Type 2 Piezocone and (d) 15-cm^2 Type 2 Version

A fully ballasted geomil truck was used in the field CPT tests. It has a thrust capacity of up to 200 kN. It is also equipped with 4 levelling jacks, an integrated hydraulic catching clamp, depth encoder, data acquisition system GME 500 for A/S conversion and data synchronization, push/pull clamp 3655 in addition to a windows computer for automatic recording of the CPT data. An electrical cone with 15cm^2 cross-sectional area was used.

Fig. 4: CPT rig used in field tests

5. Projects Data Analysis

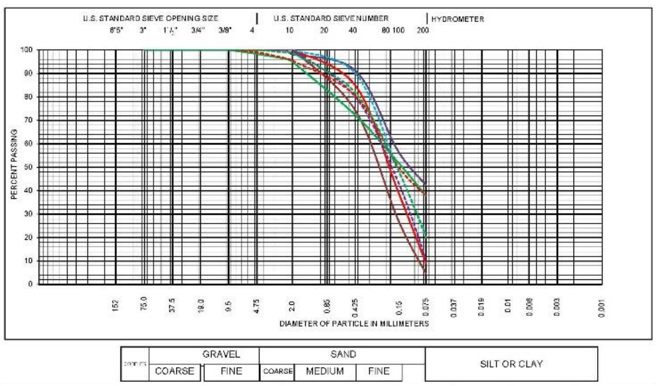
5.1. Soil Conditions

Field testing (CPT, PLT & ZLT) were performed in three different projects having the below briefed initial soil conditions:

- Project-1: Field tests were performed after completion of soil improvement works using the Rapid Impact Compaction (RIC) technique.

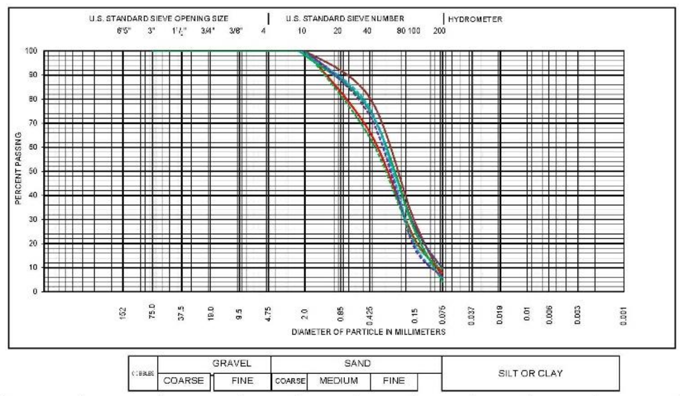
Area-1: 2m of backfilled poorly graded sand/ sand with silt overlaying Silty sandy material having maximum fine content of 42.4%.

Area-2: 5m of backfilled poorly graded sand/ sand with silt overlaying sandy material having maximum fine content of 9.5%.



SYMBOL	Borehole No.	DEPTH (m)	GRAVEL	SAND	SILT/CLAY	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	CLASSIFICATION
	SPT-101	0.0	0.0	95.4	4.6	-	-	N.P.	SP
	SPT-101	6.0	0.0	57.6	42.4	-	-	N.P.	SM
	SPT-102	1.5	0.0	91.1	8.9	-	-	N.P.	SM
	SPT-102	5.0	1.7	60.5	37.8	-	-	N.P.	SM
	SPT-103	3.0	0.0	78.8	21.2	-	-	N.P.	SM
	SPT-104	1.0	0.0	89.4	10.6	-	-	N.P.	SP-SM
	SPT-104	4.5	1.0	61.0	38.0	-	-	N.P.	SM
	SPT-105	2.5	0.0	80.0	20.0	-	-	N.P.	SM

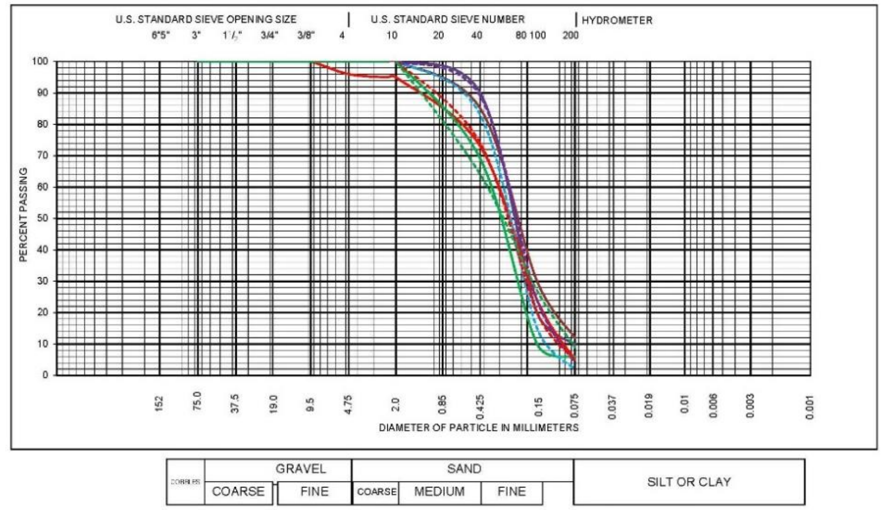
Fig. 5: Grain Size distribution for Project-1, Area-1



SYMBOL	Borehole No.	DEPTH (m)	GRAVEL	SAND	SILT/CLAY	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	CLASSIFICATION
	SPT-106	2.0	0.0	94.3	5.7	-	-	N.P.	SP-SM
	SPT-107	1.5	0.0	90.5	9.5	-	-	N.P.	SP-SM
	SPT-107	3.5	0.0	92.1	7.9	-	-	N.P.	SP-SM
	SPT-108	0.0	0.0	95.9	4.1	-	-	N.P.	SP
	SPT-108	4.5	0.0	94.0	6.0	-	-	N.P.	SP-SM
	SPT-109	5.0	0.0	93.7	6.3	-	-	N.P.	SP-SM
	SPT-110	5.0	0.0	91.1	8.9	-	-	N.P.	SP-SM

Fig. 6: Grain Size distribution for Project-1, Area-2

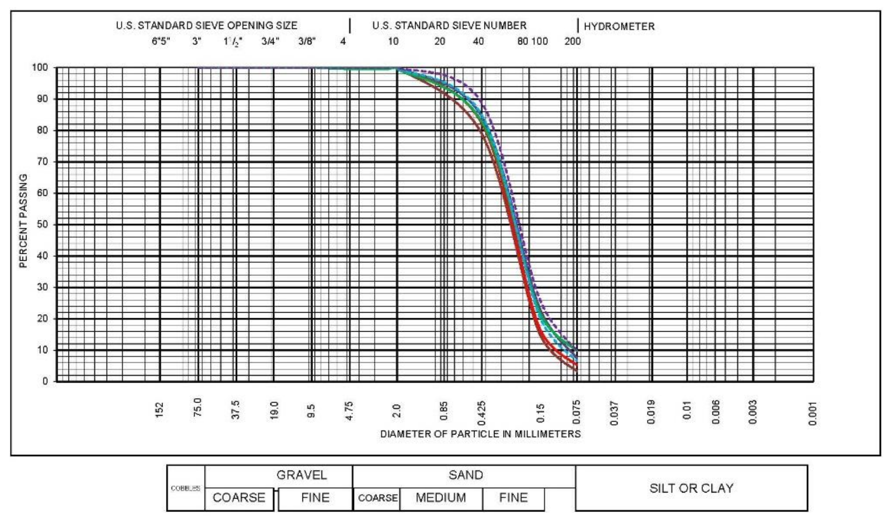
- Project-2: Field tests were performed after completion of soil improvement works using the Stone Columns (SC) technique. 7m of poorly graded sand/ sand with silt having maximum fine content of 12%.



SYMBOL	Borehole No.	DEPTH (m)	GRAVEL	SAND	SILT/CLAY	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	CLASSIFICATION
	BH-249	0.0	0.0	88.0	12.0	-	-	N.P.	SP-SM
	BH-249	6.0	0.0	90.0	10.0	-	-	N.P.	SP-SM
	BH-258	2.0	4.0	91.0	5.0	-	-	N.P.	SP-SM
	BH-258	6.0	0.0	94.0	6.0	-	-	N.P.	SP-SM
	BH-259	3.0	0.0	98.0	2.0	-	-	N.P.	SP-SM
	BH-259	7.0	0.0	96.0	4.0	-	-	N.P.	SP
	BH-261	2.0	0.0	95.0	5.0	-	-	N.P.	SP-SM
	BH-261	6.0	0.0	91.0	9.0	-	-	N.P.	SP-SM

Fig. 7: Grain Size distribution for Project-2

- Project-3: Field tests were performed after completion of soil improvement works using the Rapid Impact Compaction (RIC) technique. 3m of backfilled poorly graded sand / sand with silt having maximum fine content of 10%, overlaying silty sandy material.



SYMBOL	Borehole No.	DEPTH (m)	GRAVEL	SAND	SILT/CLAY	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	CLASSIFICATION
	S-1	0.0	0.0	96.7	3.3	-	-	N.P.	SP
	S-3	1.5	0.0	92.5	7.5	-	-	N.P.	SP-SM
	S4	2.5	0.0	94.7	5.3	-	-	N.P.	SP-SM
	S7	3.0	0.4	89.8	9.8	-	-	N.P.	SP-SM
	S9	2.5	0.0	93.4	6.6	-	-	N.P.	SP-SM
	S11	2.0	0.0	90.2	9.8	-	-	N.P.	SP-SM

Fig. 8: Grain Size distribution for Project-3

5.2. CPT Tests Graphs

CPT tests were performed in the intermediate locations between SC/RIC soil improvement points. The CPT cone tip tip resistance Qc graphs versus depth are presented herein below for all projects.

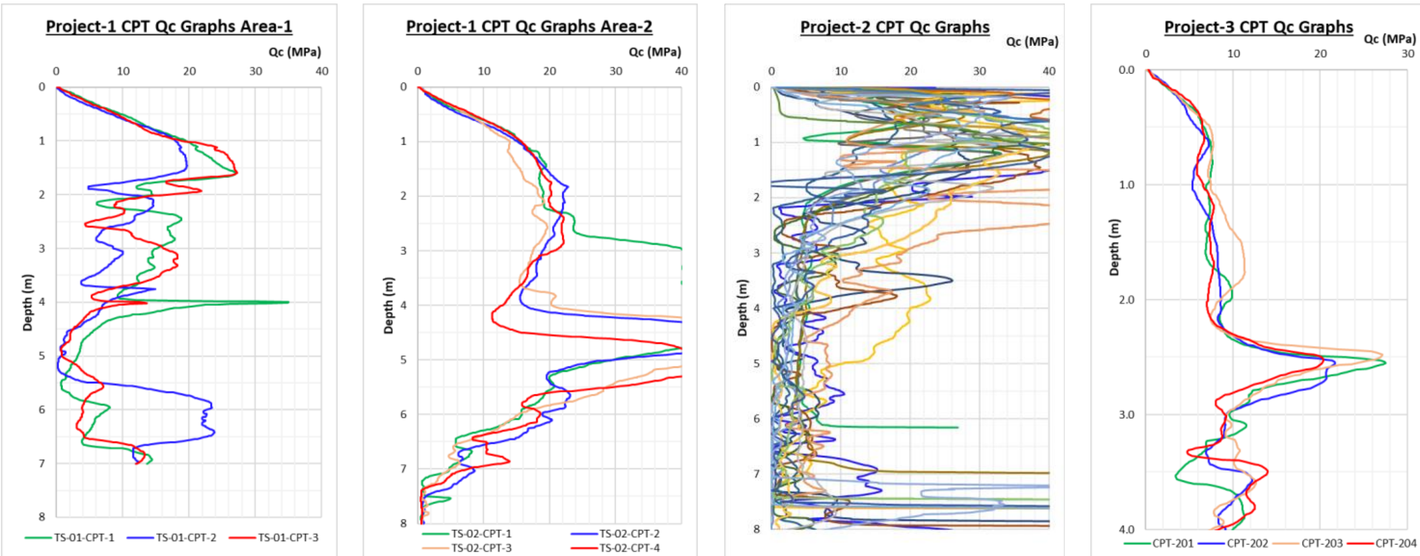


Fig. 9: CPT Q_c graphs

5.3. Field Load Tests PLT & ZLT

Modulus of Elasticity E_s values were verified by back calculation from the measured settlement during field loading tests, using the correlation proposed by the US Army Corps of Engineers Engineer Manual [8], presented below:

$$Es = \frac{\mathbf{1} - \mu^2}{\boldsymbol{\Delta\rho} / \boldsymbol{\Delta q}} * \boldsymbol{Bp} * \boldsymbol{Iw} \tag{2}$$

Where: Es = Modulus of Elasticity; μ = Poisson’s Ratio = 0.3; Δρ = applied pressure in psi; Δq = settlement from load tests in inches; B_p= width of load test footing/plate in inches; I_w = Shape factor 1 for square footing, π/4 for circular footing.

The measured settlement were plotted together with the calculated elasticity modulus on the graphs presented in Figure-10 and 11 below.

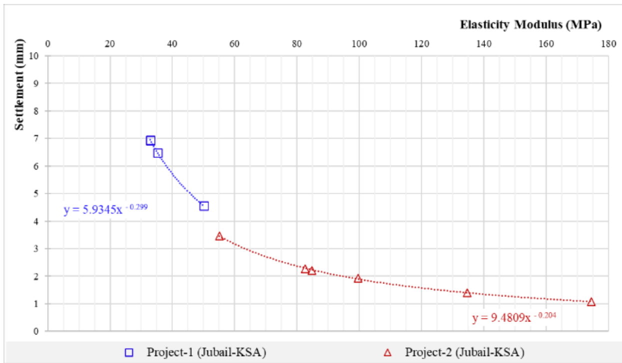


Fig. 10: Calculated elasticity Modulus vs Settlement from ZLT

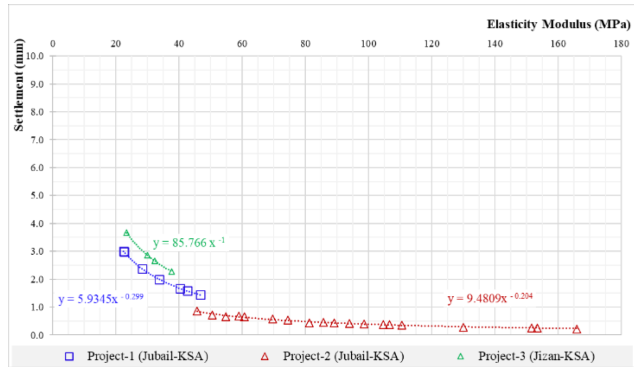


Fig. 11: Calculated elasticity Modulus vs Settlement from PLT

Table-2 below summarize the calculated elasticity modulus (E_s) and average Q_c readings over the influence depth. correlation factor alpha (α) was then derived as the ration between the elasticity modulus directly obtained from field loading results to the average cone resistance measured from CPT.

Table 2: Correlation Factor tabulated results

Project #	PLT/ZLT	E_s MPa	CPT	Q_c* MPa	Alpha E_s/Q_c
Proj-1	PLT-203	40.4	CPT-203	13.9	2.9
	PLT-204	22.4	CPT-204	12.0	1.9
	PLT-205	42.6	CPT-205	14.2	3.0
	PLT-206	46.8	CPT-206	11.3	4.2
	PLT-207	28.4	CPT-207	10.5	2.7
	PLT-208	22.6	CPT-208	9.6	2.4
	PLT-210	33.7	CPT-210	11.2	3.0
	ZLT-204	33.0	CPT-204	10.7	3.1
	ZLT-205	35.2	CPT-205	13.9	2.5
	ZLT-209	32.9	CPT-209	14.9	2.2
	ZLT-210	50.1	CPT-210	16.0	3.1
Proj-2	PLT-201	23.4	CPT-201	6.1	3.8
	PLT-202	37.6	CPT-202	5.5	6.8
	PLT-203	29.9	CPT-203	6.8	4.4
	PLT-204	32.2	CPT-204	5.9	5.5
Proj-3	ZLT-201	55.1	CPT-519	9.6	5.7
	ZLT-202	99.5	CPT-503	22.3	4.5
	ZLT-203	134.6	CPT-507	21.9	6.1
	ZLT-204	174.4	CPT-521	40.6	4.3
	ZLT-205	82.6	CPT-525	15.4	5.4
	ZLT-206	84.9	CPT-529	15.5	5.5
Proj-3	PLT-201	50.5	CPT-519	16.7	3.0
	PLT-202	130.0	CPT-519	16.7	7.8
	PLT-203	81.3	CPT-501	17.7	4.6
	PLT-204	166.0	CPT-502	22.0	7.6
	PLT-205	54.8	CPT-503	14.5	3.8
	PLT-206	58.9	CPT-504	24.4	2.4
	PLT-207	104.6	CPT-506	27.9	3.8
	PLT-208	98.6	CPT-507	22.0	4.5
	PLT-209	45.7	CPT-527	22.0	2.1
	PLT-212	60.7	CPT-521	30.9	2.0
	PLT-214	89.1	CPT-524	19.5	4.6
	PLT-215	69.6	CPT-525	28.1	2.5
	PLT-216	85.8	CPT-526	33.5	2.6
	PLT-217	110.5	CPT-529	26.6	4.2
	PLT-218	106.6	CPT-529	26.6	4.0
	PLT-219	153.5	CPT-530	29.2	5.2
	PLT-223	93.9	CPT-532	26.7	3.5
	PLT-224	74.4	CPT-534	15.6	4.8
	PLT-225	151.7	CPT-535	22.8	6.7

(*): Average Q_c over a depth equal 2*B for square plates and 2*Diameter for Circular plates.

Using the available field data, an average alpha (α) factor of 2.8, 4.4 and 5.2 was calculated for project-1, project-2 and project-3 respectively.

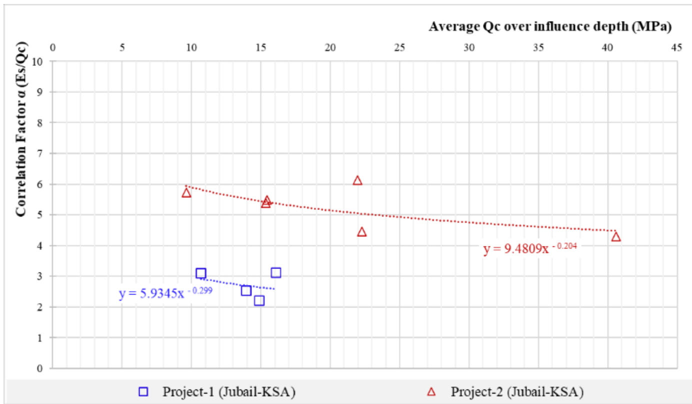


Fig. 12: Alpha “α” vs Cone Resistance Qc – Calculated from ZLT

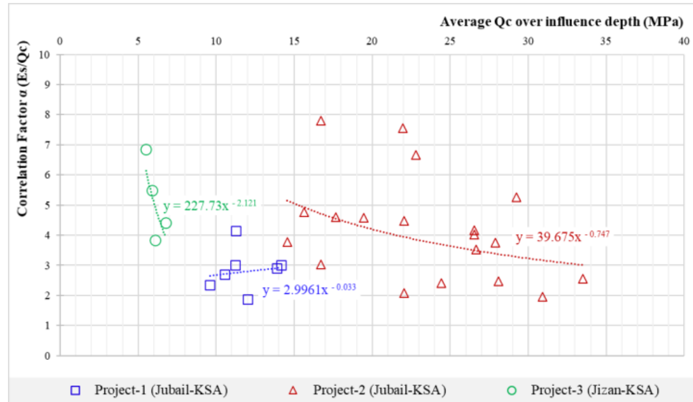


Fig. 13: Alpha “α” vs Cone Resistance Qc – Calculated from - PLT

6. Conclusion

In the present study, calculation of the correlation factor (α) was performed using variable field testing performed in three different projects including CPT, PLT and ZLT tests. Soils were subjected to soil improvement activities using Rapid impact compaction (RIC) / Stone Columns (SC) technique prior to perform the field tests. Elasticity modulus were obtained directly from field load tests (PLT and ZLT), while CPT tests were used to calculate the average Q_c values over the required depth of influence.

The calculated alpha factor (α) from the available data varies between a minimum of 1.9 and a maximum of 7.8 with an average of 4.1 over the three different projects.

Depending on the type of soil, its saturation conditions, degree of loading, soil density, stress history, cementation, age and grain shape, the correlation factor (α) relating the stress-strain modulus (E_s) and the cone resistance (Q_c) may varies.

As common practice in geotechnical engineering problems in the Kingdom of Saudi Arabia, an alpha factor (α) of around 2.5-3.5 is widely used. Higher factor can be safely used namely for coarse grained soils subjected to soil improvement activities. Specific site trials can be always done to estimate this factor following the same practice presented in this paper.

Acknowledgements

The authors would like to thank TREVI ASC for sharing all necessary information and data relevant to the three projects.

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