Evaluating relative compaction of fills using CPT

G. Agrawal
Willdan Geotechnical, Anaheim, California, USA

O. Pekin
CDM, Irvine, California, USA

D. Chandra
Leighton and Associates, Inc., Irvine, California, USA

ABSTRACT: Coastal land reclamation, hillside land development, and construction of earth structures and embankments involve placement of large quantities of fill. Such fills sometimes need to be evaluated post-placement for a number of reasons – the need to certify an old, undocumented fill, for forensic investigations, or to perform a more rigorous fill quality evaluation by continuous profiling. Fill certification is a time consuming and expensive task. This paper presents a simple methodology to use Cone Penetrometer Testing (CPT) as a fast, relatively inexpensive way to estimate compaction of large areal fills. An application example is presented using data from a coastal site in Southern California. The results show that log-normal functions adequately model the relationship between relative compaction and normalized cone tip resistance. The authors assert that with some limitations, this method can be used for fill control in many situations.

1 INTRODUCTION

Cone Penetration Testing (CPT) has proven capable of providing reliable correlations for various geotechnical engineering parameters. Some of the widely used CPT correlations include soil classification (Robertson & Campanella 1983, Kurup & Griffin 2006), estimating Standard Penetration Test blow counts (Robertson et al. 1983), and soil shear strength parameters (Chen & Juang 1996, Jamiolkowski et al. 2001). Such correlations of fundamental parameters have subsequently led to derived parameters and analyses of earth material behavior such as liquefaction (Robertson & Campanella 1985).

This paper presents the use of CPT for estimating relative compaction, perhaps the most common task in geotechnical engineering, but where the use of CPT is minimal. CPT can be a useful tool for monitoring fill compaction, especially when dealing with large areal fills where it is a time consuming task and can quickly become very expensive.

A fast and relatively inexpensive way to estimate the relative compaction of existing fills is needed when post-construction evaluation has to be done for large quantities of artificial fill placed during coastal land reclamation, hillside land development, or construction of earth structures and embankments. Although such fills are usually placed under engineering control, sometimes they still need to be evaluated after they have been placed. This may happen for a number of reasons. A fill may be old and undocumented, and needs to be certified for a different development. A fill needs to be independently evaluated as part of a forensic investigation. The original compaction monitoring and testing data is judged to be sparse or otherwise inadequate, and a more rigorous fill quality evaluation is desired. This paper demonstrates that CPT provides such a way.

A simplified method of estimating relative compaction of both cohesionless and cohesive soils using correlations with CPT data is presented. A comparison with relative compaction determined by conventional field density testing was made and found to be in good agreement.

2 CASE STUDY

A case study using data from a coastal site in Southern California is presented. The sample site ("Site") included 68.8 ha (≈ 170 acres) with fill thickness ranging from 3 to 18 m (10 to 60 feet). The fill material throughout the site consisted of a mixture of sandy clays (CL) and silty sands (SM) with some interspersed gravel content and local areas of lean clays (CL).

The fill certification process was on a fast track, and so to satisfy the time constraints, CPT was used in conjunction with test pits/trenches and boreholes to estimate the relative compaction of the fill within the top 4.5 to 6 m (15 to 20 feet), the primary zone of interest.

2.1 *Field data collection*

As the first step, bulk samples of representative fill materials were collected from thirty-three test pits/trenches and an approximately equal number of other surface locations across the site. These samples were tested in the laboratory to obtain the maximum dry densities and optimum moisture contents.

Next, data from the laboratory compaction curves was used to evaluate the compaction of the existing fill across the site. Relative compaction was estimated from field density data obtained by nuclear gauge testing or from in-situ density values from ring samples collected from borings. Field density tests using a nuclear gauge were performed at depths up to 1.8 m (6 feet) in test pits/trenches excavated in existing fill areas. Ring samples for density testing were collected from nineteen hollow-stem auger borings drilled at critical building locations.

Finally, CPT soundings were advanced at 91 locations, placed in a rough grid pattern with a center-to-center distance of approximately 100 m, predominantly at the locations of critical building sites.

2.2 *Relationship between CPT and relative compaction based on existing correlations*

As the data were collected, the first attempt to model the relationship between the relative compaction and cone tip resistance was based on existing correlations between CPT data and soil behavior parameters. All soil types were categorized into two broad groups, sandy and clayey, based on the classification of soil materials into soil behavior type (SBT) zones based on CPT data, as suggested by Douglas & Olsen (1981) and Robertson & Campanella (1983) and summarized in Table 1. Sandy soils comprise zones 7, 8, 9 and 10, with the other 8 zones comprising clayey soils.

Table 1. Numerical Designation of Soil Behavior Type (SBT) Zones

Soil Behavior Type (SBT)	Zone No.
Sensitive Fine Grained	1
Organic Material	2
Clay	3
Clay to Silty Clay	4
Clayey Silt to Silty Clay	5
Sandy Silt to Clayey Silt	6
Silty Sand to Sandy Silt	7
Sand to Silty Sand	8
Sand	9
Gravelly Sand to Sand	10
*Very Stiff Fine Grained	11
*Sand to Clayey Sand	12

2.2.1 *Sandy soils*

For sandy soils, the percentage relative compaction is estimated by following the steps outlined below.

Step 1 – Estimate the relative density using the relationship suggested by Schmertmann (1976):

$$D_R = 0.415 \ Ln\left(\frac{Q_t}{157}\right) \quad (1)$$

where D_R = relative density expressed as a percentage; and Q_t = overburden normalized cone tip resistance (dimensionless).

Step 2 – Estimate the maximum and minimum void ratios using Equation 2 below.

$$e = \frac{SG \times \gamma_w}{1 + \gamma_d} \quad (2)$$

where γ_d = in-situ dry density; SG = specific gravity, 2.7; γ_w = density of water; and e = void ratio.

The maximum void ratio, e_{max}, is computed from Equation 2 with γ_d = 1,520 kg/m^3 (≈ 95 pcf), corresponding to a relative compaction of 80% (Holtz & Kovacs 1980). The minimum void ratio, e_{min}, is computed from Equation 2 with γ_d corresponding to the maximum dry density, γ_{max}, obtained as per ASTM D 1557. In cases where a representative bulk sample of the soil is not tested, γ_{max} = 2,000 kg/m^3 (≈ 125 pcf) is a good approximation for the fill material used at the site.

Step 3 – The in-situ void ratio, e, is iteratively computed as:

$$e = e_{max} - \left((e_{max} - e_{min}) \times \left(\frac{e^{\frac{D_R}{100}} - 1}{e - 1} \right) \right) \quad (3)$$

where D_R = relative density, computed using Equation 1; e_{max} = maximum void ratio; and e_{min} = minimum void ratio, computed using Equation 2.

Step 4 – Estimate the in-situ dry density using the in-situ void ratio, computed from Equation 3, as follows:

$$\gamma_d = \frac{SG \times \gamma_w}{1 + e} \quad (4)$$

Step 5 – The relative compaction is now computed by definition as:

$$RC = \frac{\gamma_d}{\gamma_{max}} \quad (5)$$

where RC = relative compaction expressed as a percentage; γ_d = in-situ dry density from Equation 4; and γ_{max} is the maximum dry density as defined above.

2.2.2 *Clayey soils*

For clayey soils, the percentage relative compaction is estimated using the relationship suggested by Schmertmann et al. (1986):

$$RC = \left(\frac{Q_t - C_1}{C_2} \right) + C_3 \quad (6)$$

where C_1, C_2 and C_3 are empirical constants specific to the fine-grained fill material used at the site. Table 2 lists the different sets of empirical constants developed for a range of cone tip resistance for the clayey fill materials present at the site. The corresponding RC computed using Equation 6 is also presented in Table 2.

Table 2. Relative Compaction Estimation For Fine-Grained Fill Materials

Q_t Range	C_1	C_2	C_3	RC Range (%)
$Q_t < 15$	0	3.0	79	79 – 84
$15 \leq Q_t < 63$	15	8.0	84	84 – 90
$63 \leq Q_t < 135$	63	18.0	90	90 – 94
$135 \leq Q_t < 245$	135	27.5	94	94 – 98
$Q_t > 245$	–	–	–	> 98

2.2.3 *Findings based on existing correlations*

Although the relative compaction estimated from the cone tip resistance using the procedures outlined above matched well with the relative compaction obtained from conventional methods, the process was not considered suitable because it required individual assessment and manual tweaking for each CPT sounding to account for material changes – at a considerable cost in time. Additionally, the results varied appreciably if a different maximum density-moisture content curve was assigned. Therefore, a decision was made to look for a simpler, more direct measure.

2.3 *Proposed simple, direct approach to estimating relative compaction from CPT*

The data set were examined to see if groupings could be found by location within the site or by soil type. Although most of the measured density–CPT data pairs were not distinguishable, 24 distinguishable data groupings could be extracted. These data groupings were then separated into data from predominantly clayey soils (CL) and data from predominantly sandy soils (SM/SP/SC).

The data groupings are plotted as Figure 1. The best-fit trend lines represent the correlations between Q_t and RC for the two major soil classifications, and are as follows:

$$RC = 11.9 \, Ln(Q_t) + 33.7 \; (R^2 = 0.79) \qquad (7)$$

for sandy material, and

$$RC = 9.2 \, Ln\,(Q_t) + 47.9 \; (R^2 = 0.72) \qquad (8)$$

for clayey material, where RC and Q_t are as defined above; and R^2 is the Coefficient of Determination of the correlation.

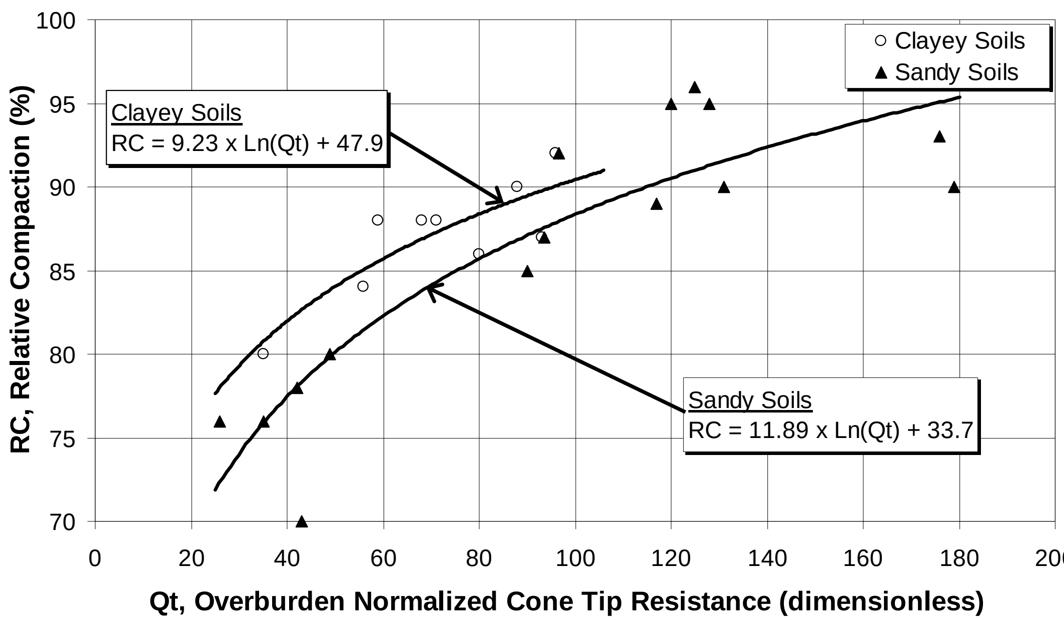

Figure 1. Correlation between Normalized Cone Tip Resistance and Relative Compaction estimated from in-situ density data

When the correlations from Equations 7 and 8 were used to estimate the relative compaction from CPT data, the results were consistent. Figure 2 graphically depicts a log of the relative compaction estimated using data from a CPT sounding, and the corresponding relative compaction computed from density data obtained from field and laboratory tests. The log of relative compaction estimated using existing correlations is also depicted in Figure 2. These results are typical. Similar plots for other CPT soundings, where field and laboratory density data was available for comparison, show that the relative compaction estimated from CPT data matches well with in-situ density data obtained from test pits and boreholes. The results show that a simple log-normal function adequately models the relationship between relative compaction and normalized cone tip resistance.

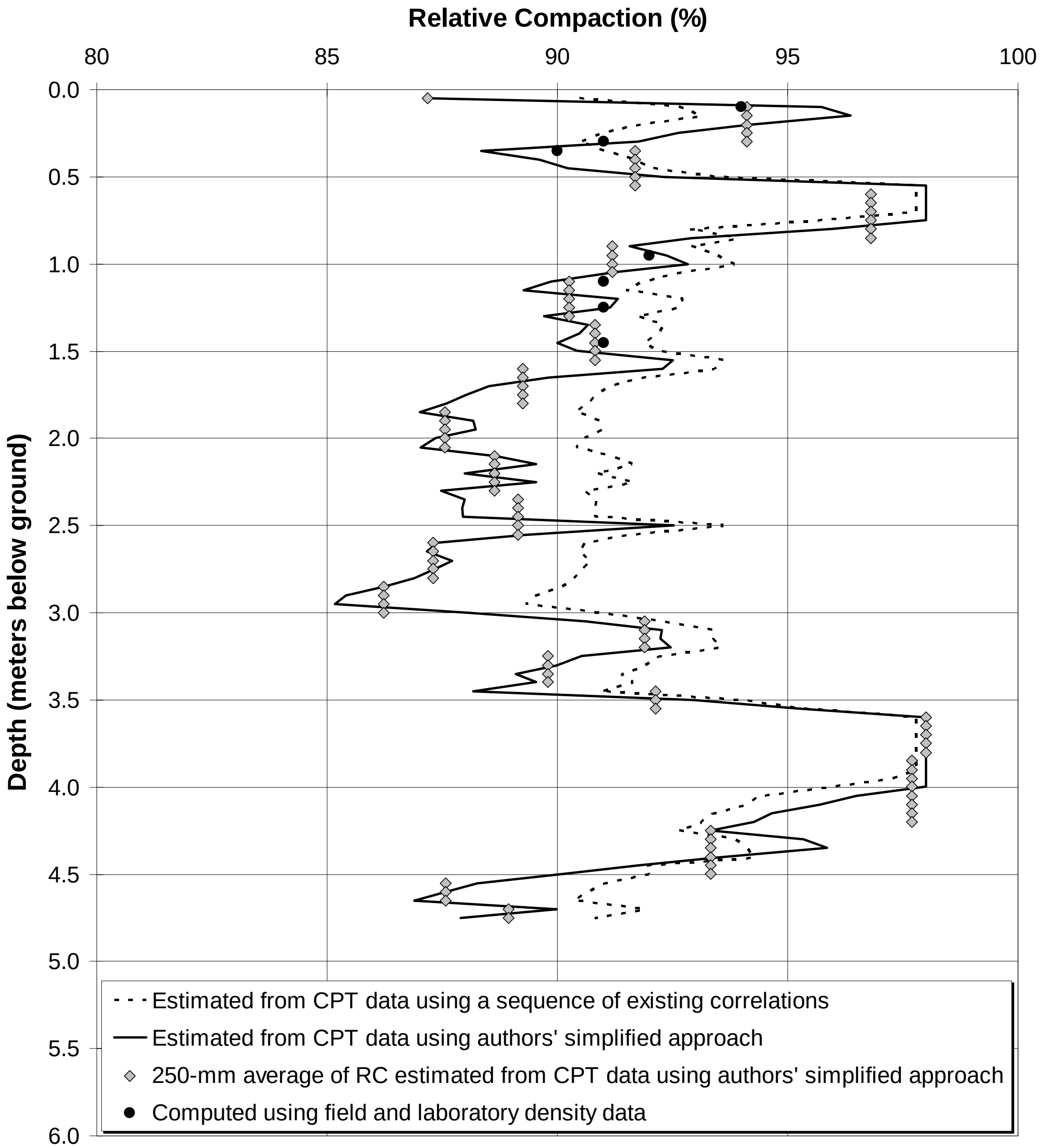

Figure 2. Typical log of relative compaction estimated from CPT Data and that obtained from conventional field testing

Use of the CPT may result in "too much" information, creating a challenge in certifying the fill. In the conventional fill certification process, one compaction test may be conducted for every 2,000 m^3 of fill and 30 cm of fill height. Less than the specified minimum compaction (commonly 90%) would not be allowed at any of the tested spots. The challenge of too much information in using CPT for estimating relative compaction comes because the number of 'compaction test data points' can be orders of magnitude higher, and inevitably, there will be a a small section in the soil column where the estimated compaction is less than the minimum specified value. This 'failing' data is not directly comparable to the data from conventional testing because each estimated compaction data point from a CPT sounding effectively represents the compaction status of a much smaller volume of soil than that represented by a conventional compaction test data point. The CPT-estimated RC data should therefore be averaged to match the test frequency that a conventional compaction specification for the same site would have called for.

In the present example, 91 CPT soundings were advanced to an average depth of 6 m below ground, penetrating between 0.3 to 5 m of fill, with a site-wide average of 3 m. Since the site area is 68.8 ha, a 3 m average thickness of fill means that the site has approximately 2,000,000 m^3 of fill. CPT data was recorded at 50 mm intervals, resulting in a total of approximately 5,500 estimated RC data points. Thus, each CPT-estimated RC value represents about 380 m^3 of fill compared to 2000 m^3 for each conventional RC test. Consequently, in order to obtain an approximate equivalency, CPT data would need to be averaged over a depth of 250 mm rather than 50 mm. CPT-estimated RC values can now be compared in a more realistic manner to conventional RC values by averaging the former CPT values over 250 mm depths and taking care to avoid averaging across material change boundaries. Such a 250-mm-averaging for the CPT-estimated RC is shown as the rhombuses on Figure 2. As can be seen, several thin zones that 'failed' a minimum-90%-RC criterion now 'pass.' This is particularly evident for the fill material present at depths between approximately 1 m and 1.5 m below ground.

3 CONCLUDING REMARKS

Recently, there has been an increasing interest in automating and improving the fill quality control process. Costs can be reduced if compaction can be evaluated more rapidly and quality can be improved if such rapid tests can reliably be applied to check fill conditions at more points. However, attempts to estimate RC from rapid indicators also come with obstacles. First and foremost is the issue of reliability of correlations. Then, there are the regulatory constraints until new techniques are standardized and adopted.

Intelligent Compaction (IC) or Continuous Compaction Control (CCC) systems approach this problem by utilizing soil stiffness or modulus as the indicator of RC (Van Hampton 2009). Modulus based systems have shortcomings in how materials below the contact surface are evaluated. For example, if a well-compacted layer overlies less compacted fill a few lifts below, the modulus criteria may be met, but long-term settlements may occur. Changes in soil type also pose challenges since different soil types are not identified in IC as directly as in CPT. Nevertheless, a modulus based interpretation is useful in that it is essentially a proof-rolling test.

Another related, though less sophisticated method is the Dynamic Cone Penetrometer (DCP), used for quality control of fill compaction (ASTM D 6951). This is a hand-driven or machine driven cone penetrometer of limited depth and limited correlative/interpretive capability. Its success in RC correlations for fill evaluation has been limited (Amini 2004).

A possible step forward in the endeavor of automating fill compaction evaluation is to use a combination of the concepts discussed in this paper. An IC system could benefit from a modified, short-stem CPT system mounted onto the roller that would not require a separate operator. CPT data can be gathered and evaluated in conjunction with other data to obtain more robust site-specific correlations to RC. An example of such correlations and their validation with conventional field density testing were presented in this paper.

The authors expect that any method that supplants conventional RC testing will be a tough sell to reviewing agencies, particularly in areas such as Southern California where many residential areas are situated on thick canyon fills and fill settlement problems can persist for decades and the fear of litigation haunts all parties, including the permit issuer. As such, there is little incentive for grading permit issuers to consider new approaches. Nonetheless, the hope is that in other arenas such as transportation, where the regulatory agency itself is often the financial stakeholder, innovative approaches may be more readily adopted.

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