Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Data driven design- a vision for an automated approach

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ABSTRACT: Geotechnical calculation procedures require engineers to assign values to a number of input parameters. Usually there are a number of well-defined input parameters with clear guidance on how values should be assigned. However, there are also often a small number of less well defined parameters with little, if any, guidance given on how values should be selected; "engineering judgment" is required. It should, there-fore, not be surprising that there is strong evidence to demonstrate that geotechnical engineers given the same data and same design task will interpret the data in very different ways and ultimately produce vastly different design calculations. This is clearly unsatisfactory as a vital step in producing reliable and cost effective geo-infrastructure is to develop design procedures that can be applied with consistency. This paper will discuss a web based application that uses CPT or CPTu data directly as an input and performs a lateral analysis of pile foundation. The application interprets that CPT data and automatically assigns appropriate *p-y* curves for sands, silts or clays. In principle, the application requires no engineering judgment to analyse a pile founda-tion, other than to decide if the CPT data is appropriate for the task. This is likely to lead to more consistent and ultimately reliable designs.

1 INTRODUCTION

Many aspects of modern society have been automated, with machines processing data and making decisions. Commercial passenger planes all but fly themselves and self-driving vehicles are now a reality and are expected to be common place on public roads over the next 5-10 years. Yet, engineering design is still a labour intensive and highly subjective process. The subjective nature of engineering design has been demonstrated through a number of design or prediction competitions. For example, Lehane *et al.* (2009) conducted a foundation settlement prediction competition, involving vertical load tests on four square concrete footings. Prior to the load tests, engineers from around the world were invited to submit settlement predictions and were provided with high quality in-situ and laboratory data to use in their calculations. Figure 1 shows a comparison of predictions along with the actual measured settlement for a typical case.

What is arguably most alarming in the results from 26 group submissions is that the predictions varied by more than two orders of magnitude (from less than 1mm to up to100mm). Remarkably, many of the groups used the same calculation method, but came up with vastly different results. The differences clearly arise in the way engineers interpret the available data for use in their design calculations.

Codes of practice exist to try and standardise engineering design. However if engineers interpret data differently and end up with different design calculations, what genuine use is a code of practice?

If it is universally accepted that we should, as far as possible, remove subjectivity in design, then it logically follows that we should remove, as far as possible, engineering judgment from design tasks. This paper presents a "proof of concept" web based application that uses CPT or CPTu data directly as an input and performs analysis of pile foundation subjected to lateral loads. The application interprets the CPT/CPTu data and automatically assigns *p-y* curves for sands, silts or clays. In principal, the application requires no engineering judgment to analyse a pile foundation, other than to decide if the CPT data is appropriate for the task. Using the same data and the same design approach, engineers will almost certainly produce the same calculation result. This "data driven design" approach will lead to more consistent designs. Ultimately, as subjectivity is removed from the calculations, uncertainties related to specific formulations embodied within the automated procedure can be determined. Such a measure of method uncertainty can be incorporated in the procedures and lead to greater design reliability. Formulations with reduced method uncertainty will inevitably emerge.

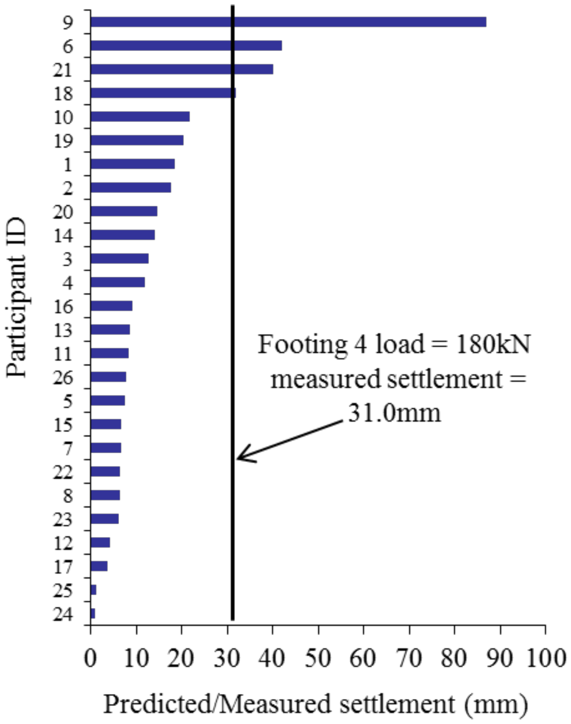

Figure 1: Lateral load test set up at Shenton Park

2 A PROOF OF CONCEPT APPLICATION FOR LATERALLY LOADED PILES

2.1 *The web app*

LAP: (Lateral Analysis of Piles) is a web-based application for calculating the behaviour of vertically orientated piles subjected to lateral loads. The pile is modelled with structural beam elements and can be assigned either linear elastic or elastic-perfectly plastic material properties. Up to five different pile sections can be included in a single analysis. The soil is modelled as a collection of independent (Winkler) springs. The load-displacement behaviour of the springs can be specified using parameters for common *p-y* load transfer functions. Load transfer functions can also be generated by directly pasting in Cone Penetration Test (CPT) data. Users can also specify their own *p-y* curves. Pile loads can be specified as a combination of horizontal forces, applied moments, prescribed horizontal displacements and prescribed rotations at any location on the pile. Horizontal and rotational reaction springs can also be included and a surcharge load adjacent to the pile can be included. The program solves for the pile response using non-linear finite element analysis. The calculations are performed on a cloud server. This means the programs run efficiently on all devices that can connect to the internet.

LAP was developed by James P. Doherty at the University of Western Australia. The program is made freely available for use as a research and teaching tool and can be accessed at www.geocalcs.com/lap

2.2 *The p-y method for laterally loaded piles*

The so called "*p-y* method" is the standard approach for the analysis and design of laterally loaded piles. It is popular due to its simplicity and long established record in Industry. The method uses non-linear independent (Winkler) springs to define a relationship between the net soil resistance at any depth per unit length of soil adjacent to a pile (*p*) and the lateral deflection of the pile at that depth (*y*).

There are a number of *p-y* formulations but all use some measure of soil strength to determine the relationship between *p* and *y*. For example, for soft clay, the American Petroleum Institute (API, 2011), recommends a formulation based on Matlock (1970), which requires an estimate of the unconsolidated undrained triaxial compression shear strength (s_u). The API method for piles in sand is also derived empirically from full-scale tests on free-headed piles and only requires specification of the soil's friction angle (ϕ') to determine the relationship between *p* and *y*.

Both API methods for clays and sands are highly sensitive to the choice of the material strength (s_u for clay and ϕ' for sand). This sensitivity is exacerbated by the need to employ empirical correlations with in-situ test results to estimate the strength parameters.

To address these limitations, researchers proposed using the cone penetration test (CPT) end resistance (q_c) as the measure of soil strength to determine the relationship between *p* and *y* for carbonate (Novello 1999, Dyson and Randolph 2001) and silica (Suryasentana and Lehane 2014) sand. Truong and Lehane (2014) present q_c-based *p-y* curves for clays. The primary advantage of these methods is that they utilise measurements directly and are therefore not susceptible to the subjectivity associated with estimating strength parameters.

These methods provide an opportunity to develop a "data driven design" pile application, where test data are used directly as an input into the calculation procedure.

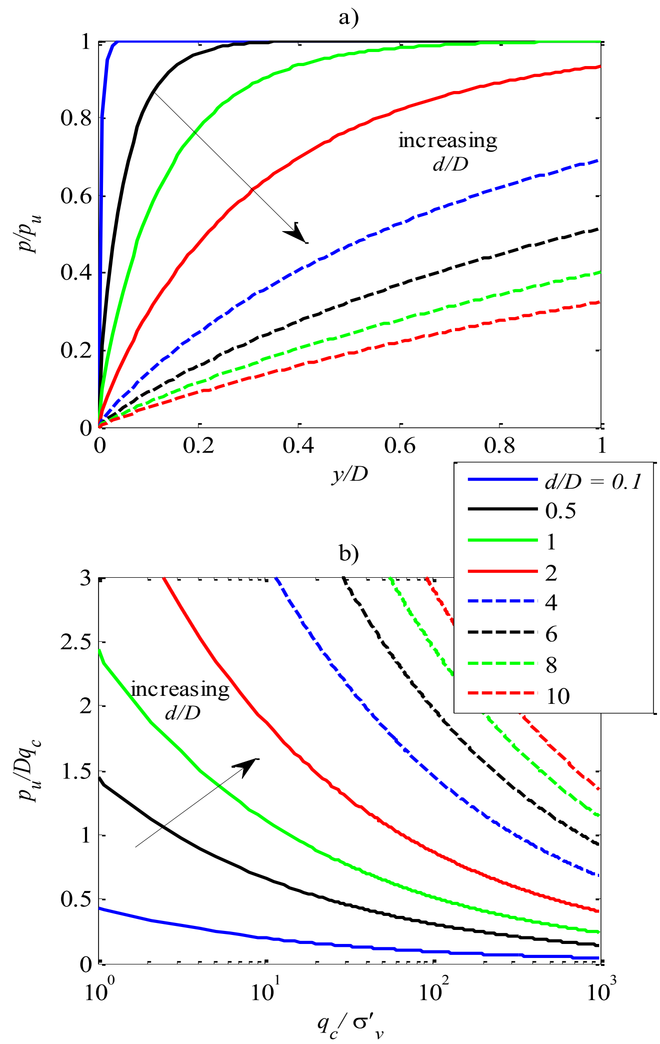

Figure 2: CPT sand *p-y* models a) normalised p-y response; b) normalised pu with normalised qc

2.3 *CPT based p-y curves in LAP*

LAP has a number of popular *p-y* models built in. It also has the option to select "CPT Auto" as a *p-y* type. The user must then specify if (u_2) pore pressure measurements are included (i.e. piezocone). A method for classifying the soil is then selected. The following four methods are considered in LAP:

1. Robertson F_r; Robertson (1990)
2. Robertson B_q; Robertson (1990)
3. The I_c method; Robertson (2009)
4. u_2 method; Schneider et al. (2008)

The cone area ratio is specified (if CPTu is selected) and then CPT data is pasted into a table.

When the analysis is executed, the program first classifies the soil using the CPT data according to one of the methods selected from the four options listed above.

At a particular depth, if the material is classified as sand (or a coarser grained material) then the q_c value at that depth is used as an input into the Suryasentana and Lehane (2014), which assumes:

$$p = p_u\left(1 - \exp\left(-6.2\left(\frac{d}{D}\right)^{-1.2}\left(\frac{y}{D}\right)^{0.89}\right)\right) \tag{1}$$

where d is the depth, D is the pile diameter and p_u is the ultimate lateral resistance (p_u) given as:

$$p_u = 2.4\sigma'_v D\left(\frac{q_c}{\sigma'_v}\right)^{0.67}\left(\frac{d}{D}\right)^{0.75} \tag{2}$$

The normalised shape of the *p-y* curves for a range of *d/D* values is plotted in Fig. 2a. It can be seen for low *d/D* ratios, the ultimate lateral resistance is mobilised after very small normalised displacements.

Equation 2 can be rearranged to explore the relationship between q_c and the ultimate lateral resistance pressure p_u/D,

$$\frac{p_u}{q_c D} = \left(\frac{q_c}{\sigma'_v}\right)^{-0.33}\left(\frac{d}{D}\right)^{0.75} \tag{3}$$

q_c values normalised in this way are is plotted against normalised p_u in Fig. 2b for a range of *d/D* ratios.

If the material is classified as a silt (or a finer grained material), lateral loading is assumed to lead to an undrained response. The q_c value at that depth is used as an input into the Truong and Lehane (2014) method, which assumes:

$$\frac{p}{p_u} = \begin{cases} \tanh\left((0.26I_r + 3.98)\left(\frac{y}{D}\right)^{0.85}\left(\frac{d}{D}\right)^{-0.5}\right) & \text{for } \frac{d}{D} < 3 \\ \tanh\left((0.15I_r + 2.3)\left(\frac{y}{D}\right)^{0.85}\right) & \text{for } \frac{d}{D} \geq 3 \end{cases} \tag{4}$$

where I_r is rigidity index and the ultimate lateral resistance is given by

$$\frac{p_u}{D} = q_{net}\left(\left(\frac{3}{4.7 + 1.6\ln I_r}\right) + (1.5 - 0.14\ln I_r)\tanh\left(\frac{0.65d}{D}\right)\right) \tag{5}$$

The general nature of this *p-y* formulation is illustrated in Fig. 3 which shows the ultimate pressure normalised by q_{net} ($=q_t-\sigma_{v0}$) plotted against rigidity index in Fig 3a and the normalised *p-y* response plotted in Fig 3b.

3 EXAMPLE APPLICATION

To demonstrate the application of *LAP* using CPT data as an input, a case history by Robertson *et al.* (1985) was examined. This case history provided the CPT traced presented in Fig. 4 which was digitized and entered into LAP. The pile was 0.915m in diameter with an 18mm wall thickness and a length of 90m. A lateral load was applied in increments of approximately 100kN until a lateral displacement of 150mm was measured.

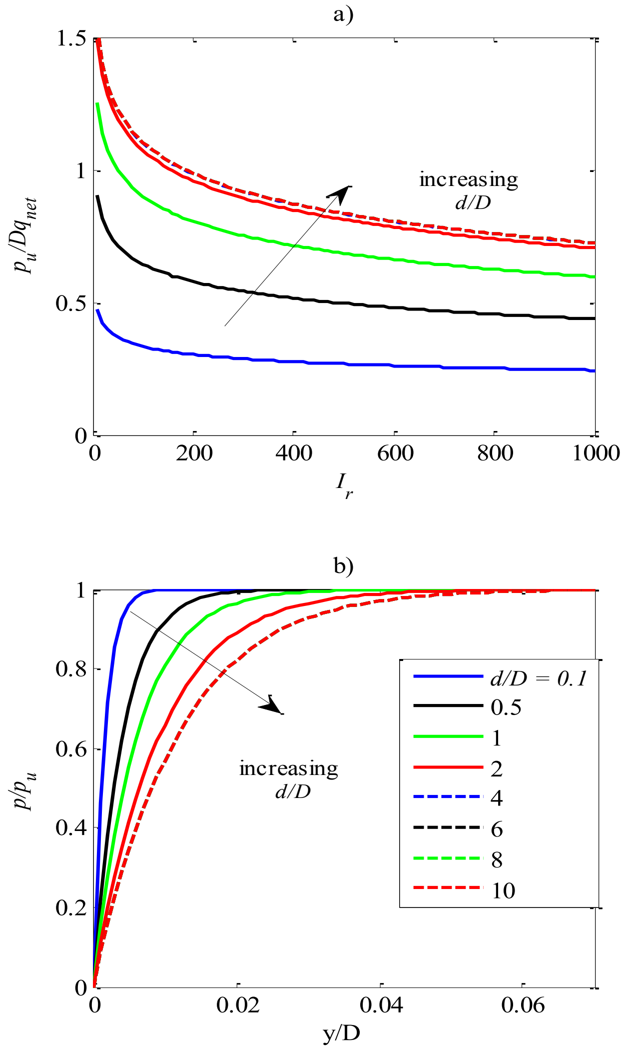

Figure 3: CPT clay *p-y* models (a) normalised p_u variation with rigidity index; (b) normalised *p-y* response

Prior to the pile testing, the upper 4m of rubble was removed and replaced with loose sand fill. No test data are presented for this upper layer and therefore a q_c profile had to be adopted in order to use this case history. The following relationship between q_c, relative density (D_r) and vertical effective stress was used, based on Lunne and Christoffersen (1983)

$$D_r = 1/2.91 \ln\left(\frac{q_c}{\sigma'^{0.71}_v}\right) \qquad (6)$$

where σ'_v is the vertical effective stress and both q_c and σ'_v are expressed in kPa.

The relative density was assumed to be 40% and the vertical effective stress variation with depth was estimated assuming a total unit weight of 17kN/m^3. Fig 5 shows the classification chart produced by LAP after running the analysis (and selecting Robertson F_r method of classification).

The computed load displacement response from *LAP* is compared with the measured load-displacement response presented by Robertson *et al.* (1985) in Fig. 6. While there is a reasonable agreement between the measured and computed response, it is difficult to draw any firm conclusions about the performance of the model *p-y* curves used as the response of the pile is largely dominated by the material in the upper 4m, where there was an absence of actual data. However, this example does demonstrate the possibility of analysing pile foundations using CPT data directly as an input. This approach paves the way for potential automation in engineering analysis and design.

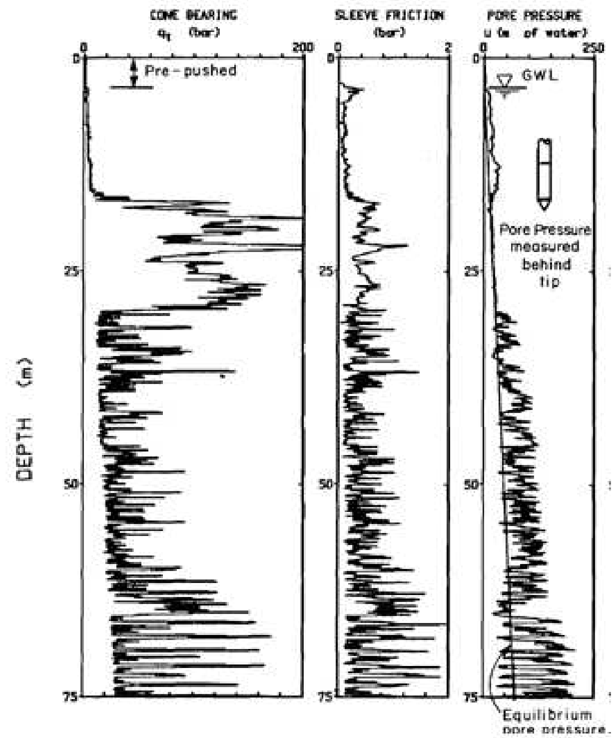

Figure 4: In-situ data (after Robertson et al (1985)

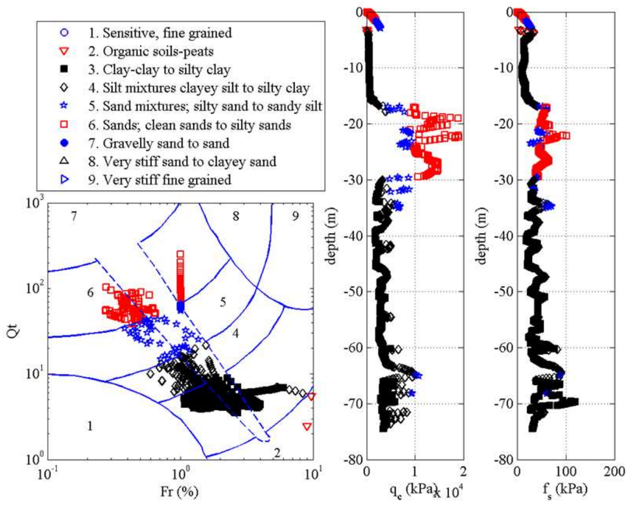

Figure 5: Robertson Q_t vs F_r classification chart from LAP

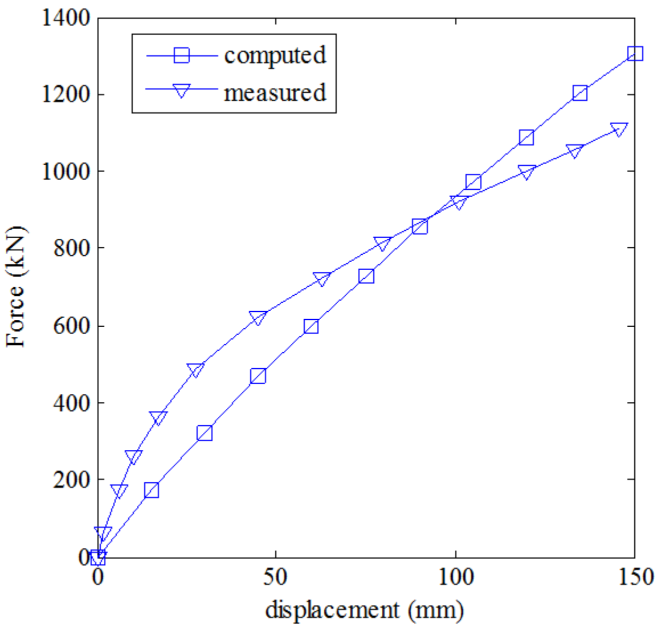

Figure 6: Comparison between measure caste history results and computed results from LAP

4 CONCLUSIONS

Engineering calculation procedures that require judgement to assign material parameter values introduce a significant issue with regard to reliability, as it has been shown that engineers with the same data and calculation tasks judge the data in different ways and ultimately produce vastly different calculation results. A proof of concept web based application was presented that uses CPT or CPTu data directly as an input and performs a lateral analysis of pile foundation. The application interprets that CPT data and automatically assigns appropriate *p-y* curves for sands, silts or clays. In principle, the application requires no engineering judgment to analyse a pile foundation, other than to decide if the CPT data is appropriate for the task. This is likely to lead to more consistent and ultimately more reliable designs. The case history presented was not ideal given some key data was missing. However, the basic principle of using in-situ data directly to conducted geotechnical analysis was demonstrated. This approach is one illustration of the automation of engineering analysis and removal of subjectivity in design.

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