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Research Paper

Algorithm for generation of stratigraphic profiles using cone penetration test data

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ABSTRACT

Cone Penetration Test (CPT) data are often used directly in the design of shallow and deep foundations and many other applications. To produce more cost-effective designs, it is advantageous to use CPT data to establish stratigraphic profiles as well. Algorithms to generate a stratigraphic profile using data from an individual CPT sounding and a Soil Behavior Type (SBT) chart as inputs are presented. Two SBT charts from the literature were selected and modified to eliminate ambiguity in soil classification. Novel algorithms were developed for handling the occurrence of thin layers within a stratigraphic profile to account for the fact that the standard CPT cone cannot accurately sense layers with thickness below a certain limit and a representative cone resistance cannot be obtained if the layer is too thin. Likewise, the algorithms prevent the creation of a soil profile with adjacent layers of essentially the same soil by consolidating layers appropriately. The algorithms presented generate a design soil profile, produced using a precise classification based on soil type and state and by elimination of artificial layering, that can be more effectively used in design.

1. Introduction

Over the years, the cone penetration test (CPT) has gained acceptance as a fast, reliable and economical tool for soil profile characterization [4,16,17,22,33,36,39,42,50,51,53,56], foundation design [5,7,13,14,15,19,18,20,21,25,26,30,29,28,31,35,59] and liquefaction susceptibility [8,11,38,40,44,46]. One of the primary applications of the cone penetration test is stratigraphic profiling [6,12,32,39,41,57,60]. Stratigraphic profiling can be most useful in design if soil layers or strata consist of a well-defined soil type with equally well-defined state (typically density, indirectly represented by the degree of overconsolidation in clayey soils). Once clarity exists about the soil in an individual layer, then it is reasonable to compute statistics (expected value/trends, coefficient of variation, scale of fluctuation) for such a layer. The quantification of soil profile variability can lead to better choice of resistance factors in the design of footings, piles, slopes and embankments when following the LRFD method [1,19,18,23,24,34,47,54].

Typically, soil samples are not collected at the exact location where a CPT sounding is performed, so soil profiles are obtained from SPT tests performed nearby or inferred from the CPT test data using soil behavior type (SBT) charts. An SBT chart serves as a simple signal transfer function that converts cone resistance-skin friction pairs to "soil behavior" types. In using the CPT for any type of interpretation, it is important to keep certain core ideas in mind. For example, it is important to distinguish between soil intrinsic and state variables [3,46,48]. Intrinsic variables do not depend on the state of the soil, as defined by density, stress state and structure. Intrinsic variables would most closely relate to soil composition (in terms of the usual particle size-based terms such as clay, silt or sand). The measurements made by a CPT reflect both state and intrinsic variables, and so reflect the soil constitutive response (or "behavior") in its totality. Hence, layering should be defined in terms of both composition (e.g., "sand") and state (e.g., "dense") with accompanying quantitative data as the core of what is obtained from the CPT. Additionally, independent sampling to define composition and even intrinsic and state variables would be superior to interpreted values from a CPT test if possible to perform reliably.

As a result of the nature of the results obtained from the cone penetration test, the generation of soil profiles from SBT charts is subject to a degree of uncertainty. Robertson [42] gave examples of how soil behavior types obtained from SBT charts need not be in agreement with the traditional soil classifications based on grain-size distribution and soil plasticity (e.g., USCS soil classification). According to Robertson [42], differences in soil classification are likely to result from compositional and behavioral points of

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view. This is particularly true for mixed soils, for which the nature of the soil fabric plays a major role [9,10,42,45].

This paper presents the framework of a comprehensive algorithm for analysis of CPT test data for obtaining soil behavior-based stratigraphic profiles. These profiles are developed with the aim of understanding the nature of the behavior of the soil tested and to group regions of similar soil behavior within a soil profile appropriately. The paper has been divided into three main sections. The first section details the two modified SBT charts developed in this research, the second section focuses on the algorithm developed for generation of soil profiles using CPT data, and the third section gives an example of a soil profile generated using the algorithm proposed in this paper. The applicability of the algorithm is general, and thus the algorithm can be implemented for any SBT chart available in literature.

2. Modified soil behavior type charts

Many soil behavior type (SBT) classification charts have been proposed over the years. Some of the early SBT charts are those of Begemann [4], Sanglerat et al. [50], Schmertmann [51], Douglas and Olsen [16], Tumay [56], Robertson et al. [43], Senneset et al. [55], Robertson [39], Larsson and Mulabdic [27], and Jefferies and Davis [22]. Some of the more recent SBT charts include those by Ramsey [36], Schneider et al. [52,53], and Robertson [37,42].

While the soil profile generation algorithm that will be described in the subsequent sections can be used for any SBT chart in the literature, modified versions of the SBT charts by Tumay [56] and Robertson [39] were used to generate the soil profiles in this paper. This choice was made partly because of familiarity of engineers with these two charts and partly because the charts had certain core features that are required for a logical, quantitative algorithm to be used in CPT interpretation. Modifications to the selected charts were made to minimize ambiguities associated with behavior types. These modifications were necessary to develop a logical stratigraphic profiling algorithm using CPT data.

2.1. Modified Tumay chart

Fig. 1(a) and (b) shows the original and modified Tumay charts. The following modifications were made to the original Tumay chart [56]:

(1) The regions of the original chart (“loose sand”, “sand”, “shell sand or limerock”, “dense or cemented sand” and “silty sand”) were removed and consolidated into a single region referred to as “clean sand or silty sand”. When a soil falls into this “clean sand or silty sand” region of the chart, it is further classified into five different subtypes depending on the estimated relative density (from very loose to very dense), as shown in Table 1. Primarily, these subtypes serve to describe the state of the soil in situ. The relative density of the sandy soil is calculated using CPT data, as suggested by Salgado and Prezzi [49].

(2) The “silty clay” region in the original chart was removed, as it was believed that the resolution of the CPT may not be enough to distinguish, with a sufficient degree of certainty, “silty clay” from “sandy clay”.

(3) The “sandy clay” region in the original chart was renamed “sandy clay or silty clay”.

(4) The “organic clay” region in the original chart was also removed because the resolution offered by q_c-f_s pairs may not be enough to distinguish “organic clay” from the neighbouring “inorganic clay”. The “inorganic clay” regions of different stiffnesses in the original chart were changed to “clay” of different stiffnesses in the modified chart.

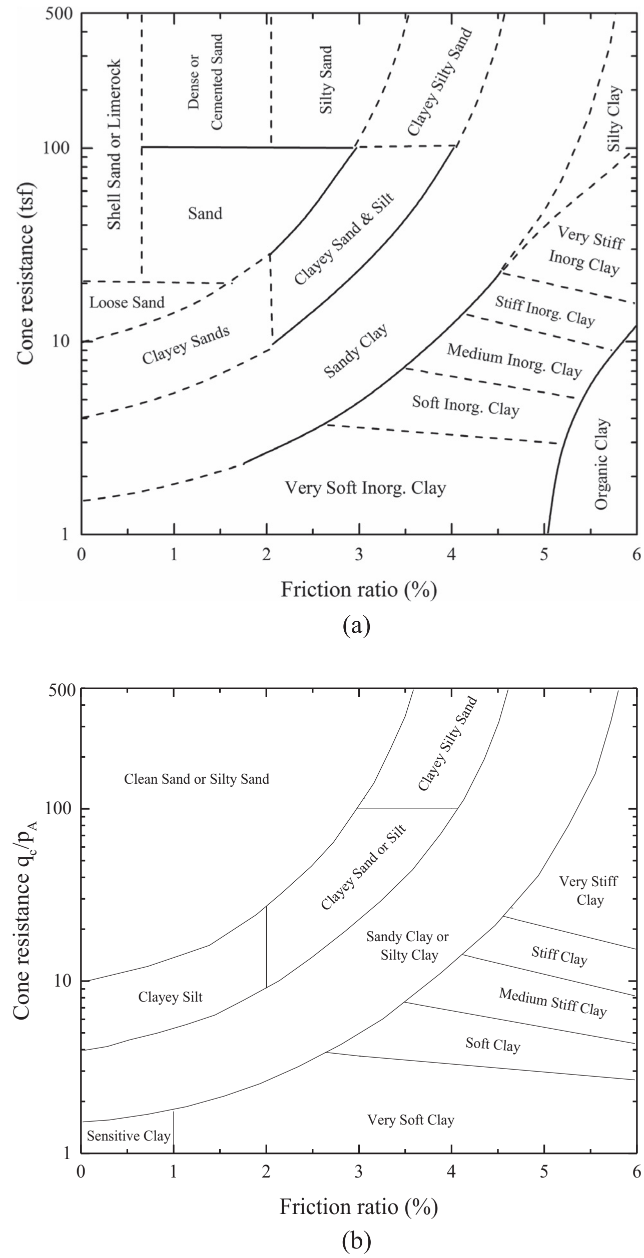

Fig. 1. SBT charts: (a) original Tumay chart [56] and (b) modified Tumay chart.

Table 1
Sand classification according to density.

Relative density (%)	Sand classification
0–15	Very loose sand
15–35	Loose sand
35–65	Medium dense sand
65–85	Dense sand
85–100	Very dense sand

(5) The “clayey sands” region in the original chart was changed to “clayey silt” in the modified chart. This was done to be consistent with the expected progressive increase in cone resistance with increasing sand content from “clayey silt” to “clayey sand or silt” and then to “clayey silty sand”.

(6) A new region, “sensitive clay”, was added. This region in the modified SBT corresponds to clays with *FR* less than unity, which is often found to suggest the presence of sensitive clays [17].