# Computerized Cone Penetration Test for Soil Classification: Development of MS-Windows Software

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# Computerized Cone Penetration Test for Soil Classification

## Development of MS-Windows Software

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**Computerized MS-Windows Visual Basic software of a cone penetration test (CPT) for soil classification was developed as part of an extensive effort to facilitate the implementation of CPT technology in many geotechnical engineering applications. Five CPT soil engineering classification systems were implemented as a handy, user-friendly, software tool for geotechnical engineers. In the probabilistic region estimation and fuzzy classification methods, a conformal transformation is first applied to determine the profile of soil classification index (*U*) with depth from cone tip resistance ($q_c$) and friction ratio ($R_f$). A statistical correlation was established in the probabilistic region estimation method between the *U* index and the compositional soil type given by the Unified Soil Classification System. Conversely, the CPT fuzzy classification emphasizes the certainty of soil behavior. The Schmertmann and Douglas and Olsen methods provide soil classification charts based on cone tip resistance and friction ratio. However, Robertson et al. proposed a three-dimensional classification system that is presented in two charts: one chart uses corrected tip resistance ($q_t$) and friction ratio ($R_f$); the other chart uses $q_t$ and pore pressure parameter ($B_q$) as input data. Five sites in Louisiana were selected for this study. For each site, CPT tests and the corresponding soil boring results were correlated. The soil classification results obtained using the five different CPT soil classification methods were compared.**

There has been an increased concern recently toward the use of in situ testing for subsurface investigation, and evaluating the different engineering soil properties have been evaluated, as an alternative to the conventional laboratory testing. The cone penetration test (CPT) has gained more acknowledgement and popularity as a preferred in situ tool for subsurface investigation and soil exploration. The CPT is a robust, simple, fast, reliable, and economical in situ test that can provide continuous soundings of subsurface soil with depth. The CPT test is essentially conducted by advancing a cylindrical rod with a cone tip down into the soil. During penetration, the cone penetrometer is capable of measuring the cone tip resistance ($q_c$) and sleeve friction ($f_s$) simultaneously. When the piezocone penetration test (PCPT or CPTu) is used, the pore pressures generated during penetration also can be measured, depending on the location of the pressure transducer (at the cone face, $u_1$, behind the base, $u_2$, or behind the sleeve, $u_3$). The CPT/PCPT measurements can be effectively used for soil stratification, identification, and classification and to evaluate different soil properties such as the strength and deformation characteristics of the geomedia.

During the past two decades, the CPT/PCPT technology has been incorporated into many geotechnical engineering applications. One of the earliest applications of the CPT is its use for soil type identification and classification profiling. Several charts were proposed in the literature to classify the subsurface soil from the CPT data (using cone tip resistance, $q_c$, and friction ratio, $R_f$) or from the PCPT data (using corrected cone tip resistance, $q_t$, $R_f$, and pore water pressure; e.g., *1–5*). These charts were developed from comparison and correlation between CPT/PCPT data profiles and soil type data bases collected and evaluated from extensive soil borings. Thus the CPT soil classification depends on the physical response of the soil during cone penetration, which is directly related to the mechanical properties of the tested soils. According to Douglas and Olsen (*2*), the CPT classification charts can not provide accurate prediction of soil type on the basis of soil composition but rather serve as a guide to the soil behavior type. The correlation between soil composition and mechanical properties is not simple, especially in transition zones of soil types, which leads to the probability of misclassifying the soil type using the current CPT classification charts. To account for such probability of misclassifying the soil, Zhang and Tumay (*6*) developed statistical-based probabilistic region estimation and fuzzy classification methods to classify the soil from CPT data that involves uncertainty in the correlation between soil composition and soil mechanical behavior. The probabilistic region estimation method provides a profile of the probability or the chance of having each soil type (clayey, silty, and sandy) with depth. However, the fuzzy classification method defines three soil types based on the certainty of soil behavior: highly probable clayey soil (HPC), highly probable mixed soil (HPM), and highly probable sandy soil (HPS).

Because of the soft nature of soil deposits in Louisiana, the CPT/PCPT is considered to be a perfect tool for subsurface investigation and site characterization. To optimize the benefits from the CPT/PCPT technology, the Louisiana Department of Transportation and Development (LaDOTD) incorporated three CPT systems for use in research and in situ productive testing: Louisiana Electric Cone Penetration System (LECOPS; *7*), Research Vehicle for Geotechnical in Situ Testing and Support (REVEGITS; *8*), and Continuous Intrusion

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**FIGURE 1 Louisiana CPT systems: CIMCPT on the right and REGEVITS on the left.**

Miniature Cone Penetration Test System (CIMCPT; *9*). Currently, the REVEGITS and CIMCPT are managed by the Louisiana Transportation Research Center (LTRC). Figure 1 depicts a photograph of the CIMCPT system and REVEGITS. To facilitate the use of CPT technology for soil classification, a Visual Basic MS-Windows program was developed in which five CPT/PCPT classification charts or methods were implemented. These methods are the probabilistic region estimation and fuzzy classification methods developed by Zhang and Tumay (*6*), Schmertmann (*1*), Douglas and Olsen (*2*), and Robertson et al. (*3*) methods. The program (www.ltrc.lsu.edu/downloads.html) performs the analyses on the CPT data profiles using the selected CPT classification method and provides the geotechnical engineers with a handy soil classification profile with depth for use in their daily design activities.

The main objective of this paper was to present the computerized MS-Windows Visual Basic CPT soil classification software that was developed to facilitate the implementation of CPT/PCPT technology for geotechnical engineering in Louisiana. Five sites in Louisiana were selected for this study. For each site, CPT tests and the corresponding soil boring results were correlated. The soil classification results obtained using the five different CPT soil classification methods were compared.

## PCPT MEASUREMENTS AND CORRECTIONS

During the CPT/PCPT tests, the cone tip resistance ($q_c$) sleeve friction ($f_s$), and pore water pressures measured at different locations depending on the location of the pressure transducer (at the cone face, $u_1$, behind the base, $u_2$, or behind the sleeve, $u_3$) are continuously recorded with depth. These measurements can be effectively used for soil identification, classification, and the evaluation of different geotechnical soil properties. Because of the geometric design of the piezocone, the pore water pressures generated on the shoulder behind the cone base ($u_2$) and at the both ends of friction sleeve ($u_2$ and $u_3$) might influence the total stress measured from the cone tip and the friction sleeve. Therefore, the measured cone tip resistance ($q_c$) and sleeve friction ($f_s$) may have to be corrected for certain cone configurations and soil types to account for the effect of this pore water pressure developing behind the cone tip.

Theoretically, the corrected cone resistance, $q_t$, is given by Equation 1:

$$q_t = q_c + (1 - a)u_2 \tag{1}$$

where

$a = \dfrac{A_n}{A_c}$, the effective area ratio of the cone (for the piezocones used in this study, $a = 0.59$);
$A_n$ = cross-sectional area of the load cell; and
$A_c$ = projected area of the cone.

The corrected sleeve friction, $f_t$, can be given as shown Equation 2:

$$f_t = f_s - \frac{(A_{sb}u_2 - A_{st}u_3)}{A_s} \tag{2}$$

where

$A_{sb}$ = bottom cross-sectional area of the friction sleeve,
$A_{st}$ = top cross-sectional area of the friction sleeve, and
$A_s$ = surface area of friction sleeve.

However, the authors' experience in primarily Louisiana soils and similar others showed that using either $q_c$ and $f_s$ or $q_t$ and $f_t$ does not appreciably change the CPT-based soil classification results by using methodologies depending on tip resistance and friction ratio.

## SOIL CLASSIFICATION BY CPT

Soil identification and classification of soil stratigraphy can be achieved by analyzing the CPT data. The general trend in CPT soil classification is that sandy soils usually have a high cone tip resistance and low friction ratio, soft clay soils show low cone tip resistance and high friction ratio, organic soils such as peat have very low cone tip resistance and very high friction ratio, whereas overconsolidated soils tend to produce higher cone tip resistance and higher friction ratio.

Traditional CPT classification methods provide two-dimensional charts for soil classification based either on cone tip resistance ($q_c$ or $q_t$), friction ratio ($R_f$), and pore pressure ($u$), or their normalization with respect to vertical overburden stress ($\sigma_{vo}$). These charts were developed through direct correlation between the CPT data ($q_c$, $q_t$, $R_f$, $u$) and the corresponding soil type determined from soil borings of the collected database. Several CPT charts have been proposed by investigators to classify the soil using the CPT data (e.g., *1–5*). Although almost all the CPT methods (basically charts) give a specific classification to each soil layer along the penetrated depth, the statistical based probabilistic region estimation and fuzzy classification methods proposed by Zhang and Tumay (*6*) are unique in addressing the uncertainty in misclassifying the soil. These methods are similar to the classic soil classification methods based on soil composition. The probabilistic region estimation method provides a profile of the probability or the chance of having each soil type (clayey, silty, and sandy) with depth, whereas the fuzzy classification method defines three soil types on the basis of the certainty of soil behavior: HPC, HPM, and HPS. The following sections summarize the CPT methods implemented and upgraded in the new Visual Basic software.

### Probabilistic Region Estimation Method

The probability of incorrectly identifying soil type using the tradition CPT classification charts, especially in transition zones, motivated the development of the probabilistic region estimation method. This CPT classification method addresses the uncertainty of correlation between the soil composition and soil mechanical behavior.

In this method, a conformal mapping was performed on the Douglas and Olsen (*2*) chart to transfer the chart axis from the CPT data ($q_c$, $R_f$) to the soil classification index ($U$). The soil classification index, $U$, provides a soil profile over depth with the probability of belonging to different soil types, which more realistically and continuously reflects the in situ soil characterization, which includes the spatial variation of soil types. The conformal transformation is accomplished using the following equations:

$$x = 0.1539\, R_f + 0.8870 \log q_c - 3.35 \tag{3}$$

$$y = -0.2957\, R_f + 0.4617 \log q_c - 0.37 \tag{4}$$

The soil classification index ($U$) is given as follows:

$$U = \frac{(a_1x - a_2y + b_1)(c_1x - c_2y + d_1)}{(c_1x - c_2y + d_1)^2 + (c_2x + c_1y + d_2)^2} - \frac{(a_2x + a_1y + b_2)(c_2x + c_1y + d_2)}{(c_1x - c_2y + d_1)^2 + (c_2x + c_1y + d_2)^2} \tag{5}$$

The coefficients in Equation 3 are as follows:

$a_1 = -11.345$,
$a_2 = -3.795$,
$b_1 = 15.202$,
$b_2 = 5.085$,
$c_1 = -0.296$,
$c_2 = -0.759$,
$d_1 = 2.960$, and
$d_2 = 2.477$.

A statistical correlation was then established between the $U$ index and the compositional soil type given by the Unified Soil Classification System (USCS). A normal distribution of $U$ was established for each reference USCS soil type (GP, SP, SM, SC, ML, CL, and CH). Each $U$ value corresponds to several soil types with different probabilities. Boundary values were used to divide the $U$ axis into seven regions, as shown in Figure 2*a.* Soil types were further rearranged into three groups: sandy and gravelly soils (GP, SP, and SM), silty soils (SC and ML), and clayey soils (CL and CH). Figure 2*a* also gives the probability of having each soil group within each region. The original method gives constant probability of each soil type (represented by the step lines) regardless of the $U$ value within the same region ($R_1$ to $R_7$ in Figure 2*a*). This will allow for a sudden drop in the probabilities of $U$ value across the border from one region to another. This method was further modified from origin to allow a smooth transition of probability (curved lines) with $U$ values and hence to provide a continuous profile of the probability of soil constituents with depth. An example of $U$ profile compared with $q_c$ and $R_f$ profiles and the corresponding probability soil profiles from region estimation method obtained for Manwell Bridge, Evangeline, Louisiana, is presented in Figure 3.

## Fuzzy Classification

Most of the existing CPT classification methods are based on a statistical correlation between the CPT profile data and the USCS soil classification, hence leading to soil identification according to mechanical behavior. By contrast to other methods, the CPT fuzzy soil classification approach is fundamentally different in releasing the constraint of soil composition and is instead based on the certainty of soil behavior (i.e., cone tip resistance and local friction).

In CPT fuzzy soil classification, three soil types are defined: HPC, HPM, and HPS. The corresponding fuzzy membership functions of HPC, HPM, and HPS are given as Equations 6, 7, and 8:

$$\mu_c(U) = \begin{cases} \exp\left(-\dfrac{1}{2}\left(\dfrac{U + 0.1775}{0.86332}\right)^2\right) & U^3 \geq -0.1775 \\ 1.0 & U < -0.1775 \end{cases} \tag{6}$$

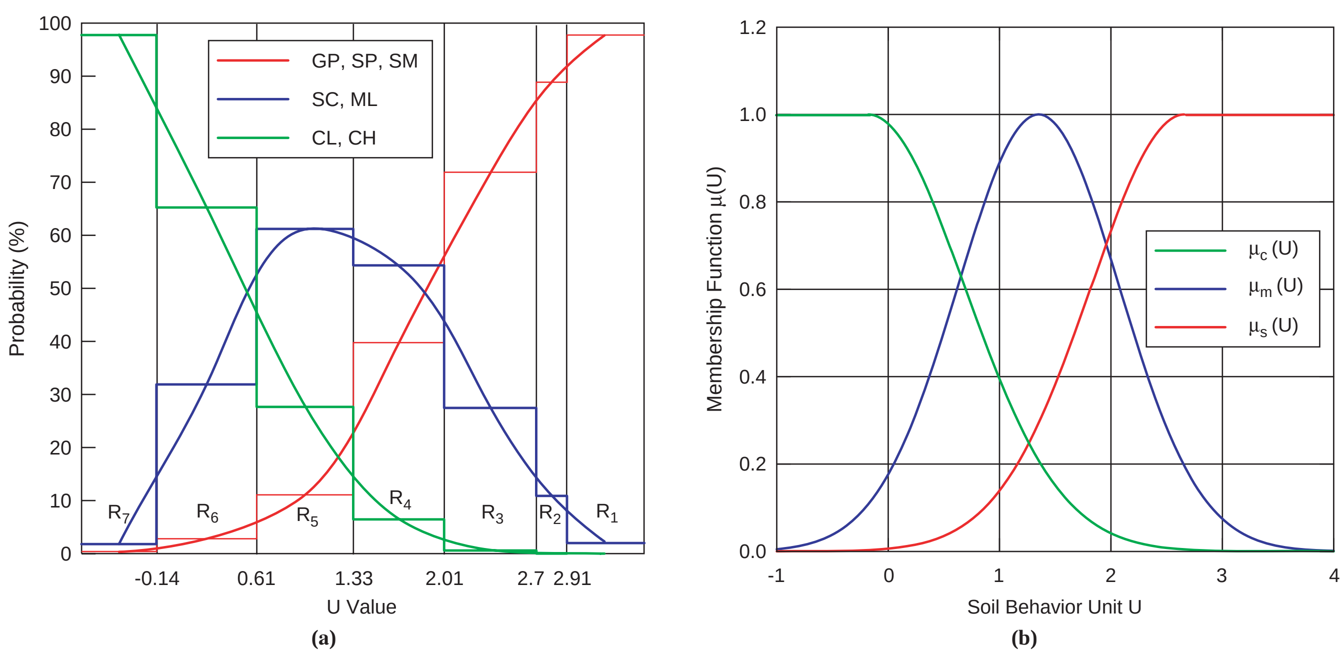



FIGURE 2 (*a*) Regions' boundaries along the U-axis corresponding probabilities of each soil group and (*b*) CPT fuzzy soil classification chart.

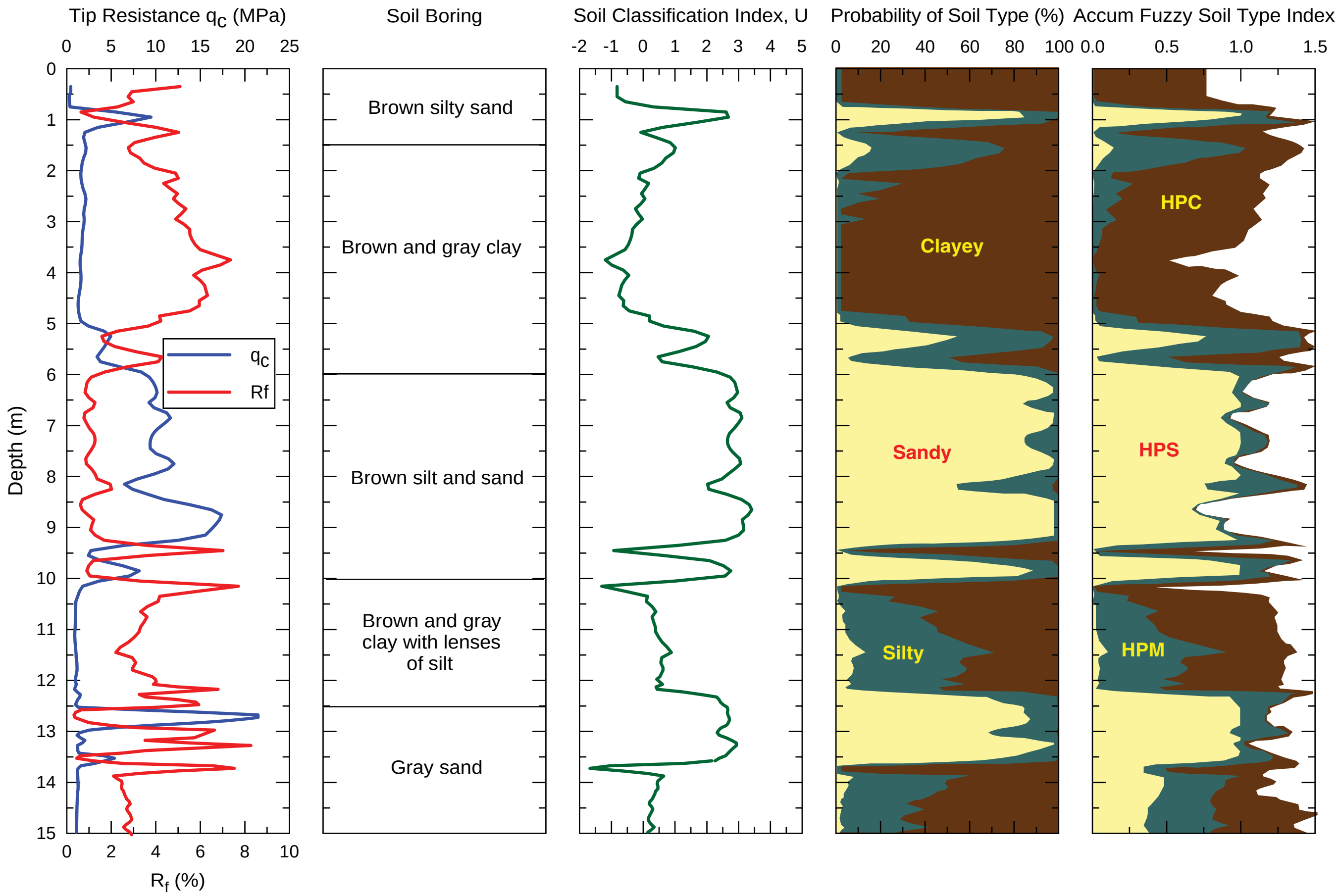



FIGURE 3 Probability profiles and fuzzy soil type index profiles for Manwell Bridge, Evangeline.

$$\mu_m(U) = \exp\left(-\frac{1}{2}\left(\frac{U-1.35}{0.724307}\right)^2\right) \qquad -\infty < U < \infty \tag{7}$$

$$\mu_s(U) = \begin{cases} 1.0 & U > 2.6575 \\ \exp\left(-\frac{1}{2}\left(\frac{U-2.6575}{0.834586}\right)^2\right) & U \le 2.6575 \end{cases} \tag{8}$$

These empirical functions represent either an "S" curve or a "bell" curve with a maximum membership value of 1.0 for each soil type, as depicted in Figure 4. However, as seen in the figure, it is unlikely for all three membership values to have maximum values simultaneously, and the accumulated sum depends on the *U* value. These empirical functions approximately relate the quantity change to quality change in soil composition and properties, reflecting an overall perspective of soil properties. The change is gradual from one soil type to another. The profile of fuzzy functions as compared with *U* profile and $q_c$ and $R_f$ profiles for Manwell Bridge, Evangeline, Louisiana, are also shown in Figure 2*b*.

## Schmertmann Classification Method

The original CPT soil classification chart proposed by Schmertmann (*1*) is shown in Figure 5*a*. Based on CPT data taken from different sites in Louisiana, as well as the CPT data taken from California,

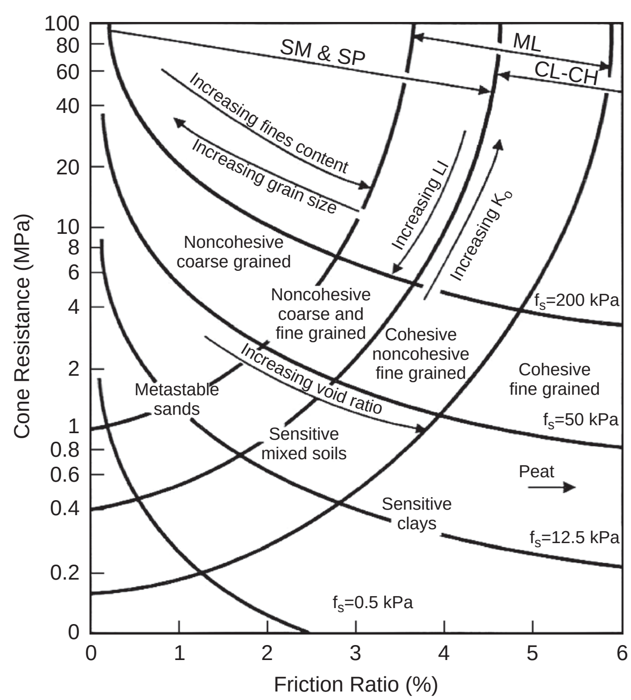



FIGURE 4 Douglas and Olsen (*2*) soil classification chart [from Lunne et al. (*10*)].

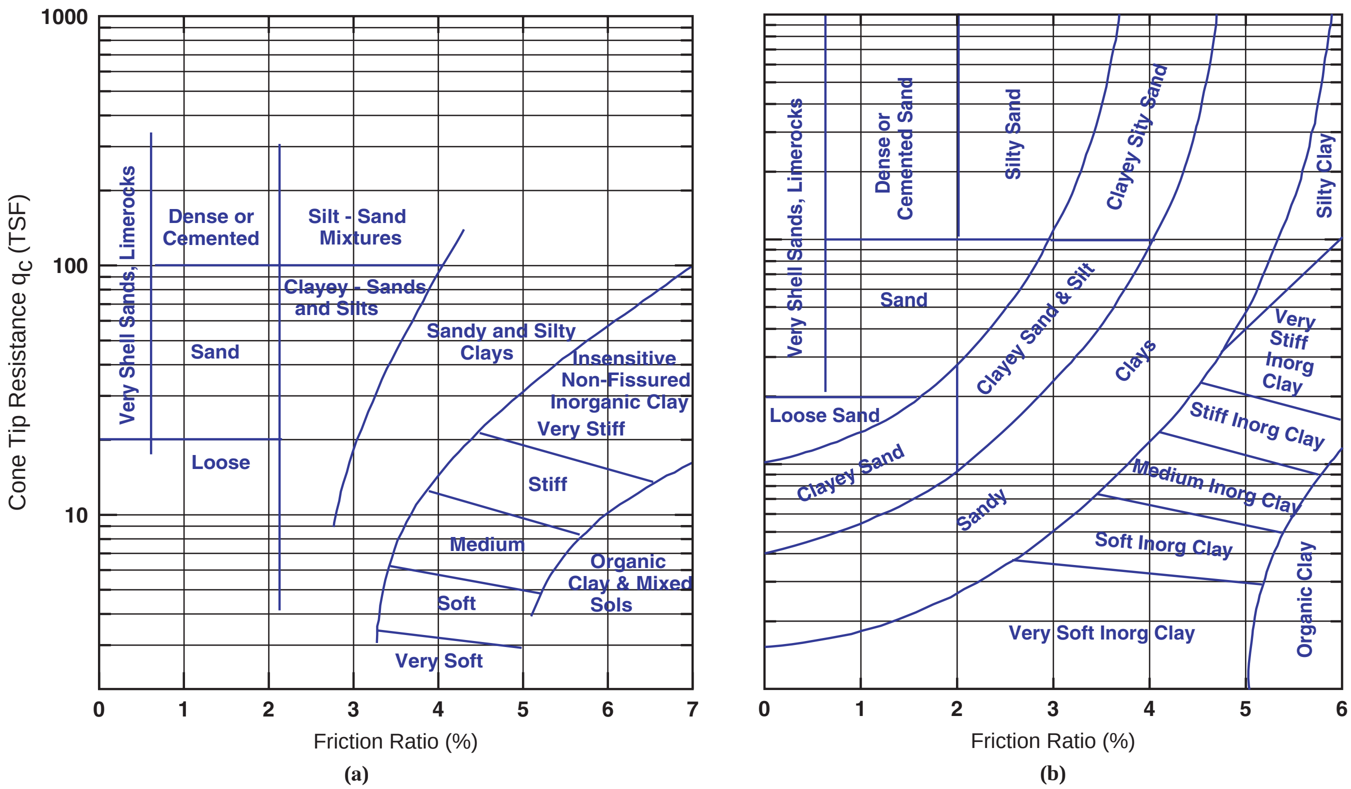



FIGURE 5 Schmertmann classification charts: (*a*) original and (*b*) modified.

Oklahoma, Utah, Arizona, and Nevada, as reported by Douglas and Olsen (*2*), and comparison with soil borings, the original Schmertmann chart was modified by Tumay (*11*) as shown Figure 5*b.* The chart depicts four distinct regions as identified by Douglas and Olsen (*2*). These are clays, sandy and silty clays, clayey sands, and silts and sand. Each region is further divided into subregions sorted out using the Schmertmann classification modified slightly to reflect Louisiana research experience. The chart shows the soil classification change (diagonally) from sand to clayey sand and silt to sandy and silty clay to clay as the cone tip resistance decreases and friction ratio increases.

### Douglas and Olsen Classification Method

Douglas and Olsen (*2*) conducted comprehensive work correlating between the USCS soil classification and CPT data to develop a CPT-soil behavior type classification method. The development of this method was based on extensive data collected from sites in the western United States. The classification chart for the Douglas and Olsen method uses the cone tip resistance ($q_c$) and friction ratio ($R_f$) input parameters, as shown in Figure 4. The chart depicts four distinct regions: cohesive fine grained, cohesive and noncohesive fine grained, noncohesive coarse and fine grained, and noncohesive coarse grained. The chart shows the soil classification change (diagonally) from SP to SM to ML to CL to CH as the cone tip resistance decreases and friction ratio increases. The Douglas and Olsen (*2*) method demonstrates that the CPT classification charts can not provide an accurate prediction of soil type based on soil composition, but rather serve as a guide to soil behavior type (*10*).

### Robertson et al. Classification Method

Because measurements of sleeve friction are less accurate than cone tip resistance and pore pressure measurements, it is believed that soil classification can be improved by including all three PCPT input parameters ($q_t$, $f_s$, $u$). Robertson et al. (*3*) were the first to introduce a soil behavior type classification method derived from PCPT that incorporates all three input parameters. They proposed a three-dimensional classification system that is presented in two charts; one chart uses corrected tip resistance ($q_t$) and friction ratio ($R_f$) as input data and the other chart uses $q_t$ and pore pressure parameter ($B_q$) as input data. The $B_q$ parameter is defined as follows:

$$B_q = \frac{(u_2 - u_0)}{(q_t - \sigma_{vo})} \tag{9}$$

where $u_o$ is the equilibrium pore pressure and $\sigma_{vo}$ is the total overburden stress.

They identified 12 different soil behavior types ranging from sensitive fine grained (Zone 1) to sand to clayey sand (Zone 12), as shown in Figure 6. In case a soil falls within two different zones in respective charts, engineering judgment is required to classify the soil behavior correctly. Only the second chart was implemented in the Visual Basic soil classification software developed in this study.

## DEVELOPMENT OF SOIL CLASSIFICATION SOFTWARE

An MS-Windows Visual Basic CPT soil engineering classification program, Louisiana Soil Classification by Cone Penetration Test (LSC-CPT) program, was developed to provide geotechnical

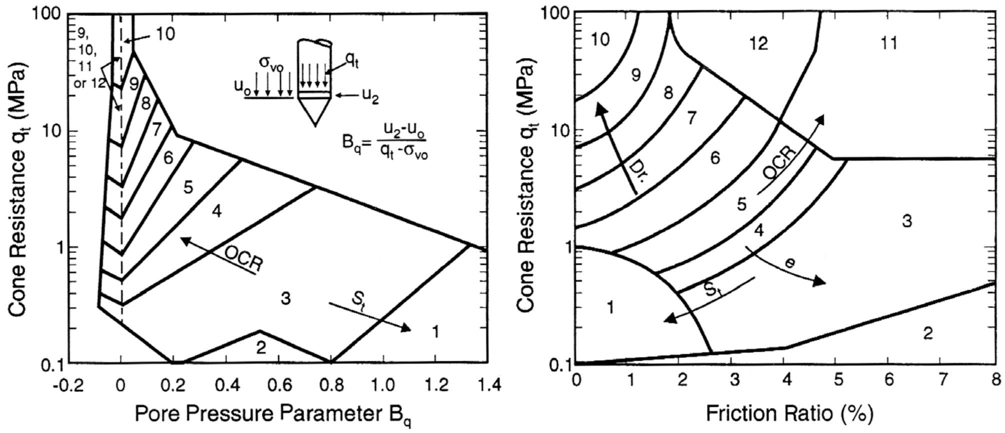



FIGURE 6 Robertson et al. (*3*) soil classification charts [from Lunne et al. (*10*)] (OCR = overconsolidation ratio).

engineers with a user-friendly tool for subsurface soil identification. The program uses the CPT/PCPT data as input parameters for soil classification. Five CPT soil classification systems/charts were implemented in this program. These include the probabilistic region estimation and fuzzy classification methods developed by Zhang and Tumay (*6*), the Schmertmann chart (*1*), the Douglas and Olsen chart (*2*), and the Robertson et al. classification chart (*3*). These methods and charts were described earlier. Although four of these methods use the cone tip resistance ($q_c$) and friction ratio ($R_f$) as input parameters, the Robertson et al. implemented chart uses the corrected cone tip resistance ($q_t$) and friction ratio ($R_f$) as input parameters.

The CPT classification program reads CPT data files in ASCII format with extensions *.txt, *.dat, and *.prn. The program is capable of reading CPT input data of different units, including the International System of Units (SI), English units, and raw data in millivolts. Before running the program, the user can view the input data file. The first step for the user, after selecting the input data file, is to enter the project information such as project number and title, station number, and groundwater elevation. The program then plots the profiles of cone tip resistance, sleeve friction, and friction ratio with depth. The user has the option to select the CPT classification method and the corresponding display charts for output (e.g., graph or text). If the user selects a text chart for soil profile, he or she can always modify or merge the layers manually. The program also allows the user to switch from SI units to English units and vise versa, as well as allowing zooming in and zooming out of the graphs. The program is available for free download from LTRC web site (www.ltrc.lsu.edu/downloads.html). Figure 7 describes the general features of the soil classification program.

## DESCRIPTION OF INVESTIGATED SITES

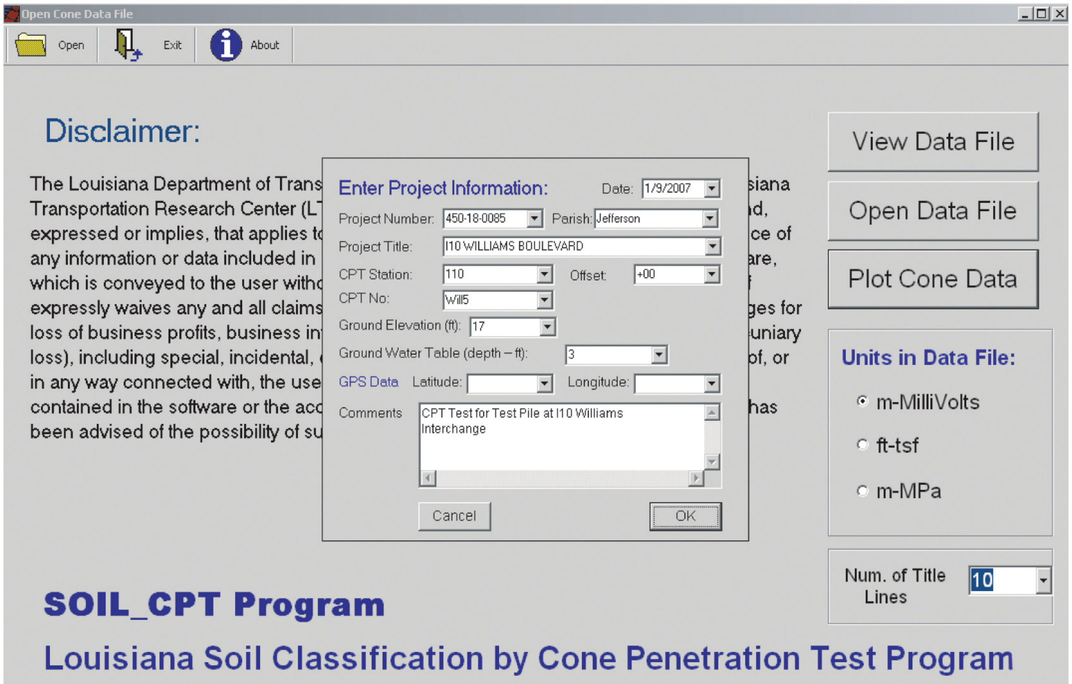
Five sites were selected in Louisiana to demonstrate the CPT soil classification program and to compare the different CPT soil classification methods with borings. These sites are Manwell Bridge, Evangeline; US-90–LA-88, New Iberia; La Peans Canal Bridge, Lafourche; Pavement Research Facility (PRF), Port Allen; and I10-Pearl River sites. At each site, boreholes were drilled, and Shelby tube samples were recovered at different depths for classification and laboratory testing. The laboratory testing program included basic soil characterization tests such as water content, unit weight, Atterberg limits, grain size distribution including hydrometer tests, and unconfined compression tests. Table 1 summarizes the geotechnical properties of the subsurface soils obtained at the five different sites.

In situ PCPT tests were also performed around the boreholes using the 20-ton REVEGITS cone truck. At least two PCPT tests were conducted at each site using the 10 and 15 cm$^2$, 600 Fugro type, piezocone penetrometers. The 10 cm$^2$ piezocone has a sleeve area of 150 cm$^2$ with a pore pressure transducer located 5 mm behind the base ($u_2$ configuration). The 15 cm$^2$ piezocone has a sleeve area of 200 cm$^2$ with two pore pressure transducers located on the cone face and behind the sleeve ($u_1$ and $u_3$ configurations). All PCPT tests were conducted at a penetration rate of 2 cm/s. The 10 cm$^2$ piezocone provided measurements of the cone tip resistance ($q_c$) sleeve friction ($f_s$), and pore water pressure behind the base ($u_2$), whereas the 15-cm$^2$ piezocone provided measurements of $q_c$, $f_s$, and pore water pressure at the cone tip ($u_1$). Figures 8*a* through 8*d* depict the PCPT data profiles side by side with soil type from borings and the corresponding probabilistic region estimation CPT soil classification for Evangeline, New Iberia, Lafourche, and PRF sites, respectively.

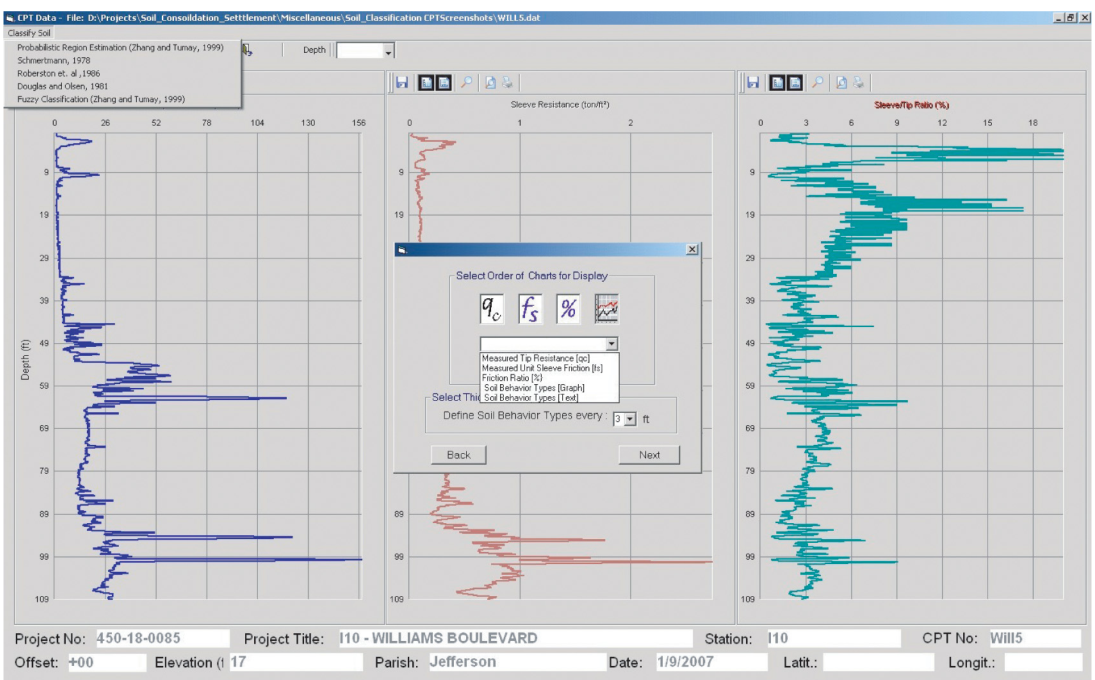
## COMPARISON OF CPT CLASSIFICATION METHODS

Five sites in Louisiana were selected to demonstrate the software and to compare the soil classification obtained using the different CPT soil classification methods/charts: probabilistic region estimation, fuzzy classification, Schmertmann (*1*), Douglas and Olsen (*2*), and Robertson et al. (*3*) classification methods. At each site, soil borings were drilled for conventional soil classification, and at least two PCPT (for $u_1$ and $u_2$) were performed around the boreholes for CPT soil classifications. The descriptions of soil types from borings for the different sites were presented earlier (Figures 8*a* through 8*d*). Figures 9 through 12 present the results of soil classification obtained from different CPT classification methods for Evangeline, New Iberia, Lafourche, and PRF sites, respectively.

The comparisons demonstrate that the CPT classification methods, in general, are capable of classifying the subsurface soil with accept-




**(a)**




**(b)**

FIGURE 7 Features of Louisiana Soil Classification by Cone Penetration Test Program (www.ltrc.lsu.edu/downloads.html): (*a*) data and information input screen, (*b*) CPT profiles and main menu screen.

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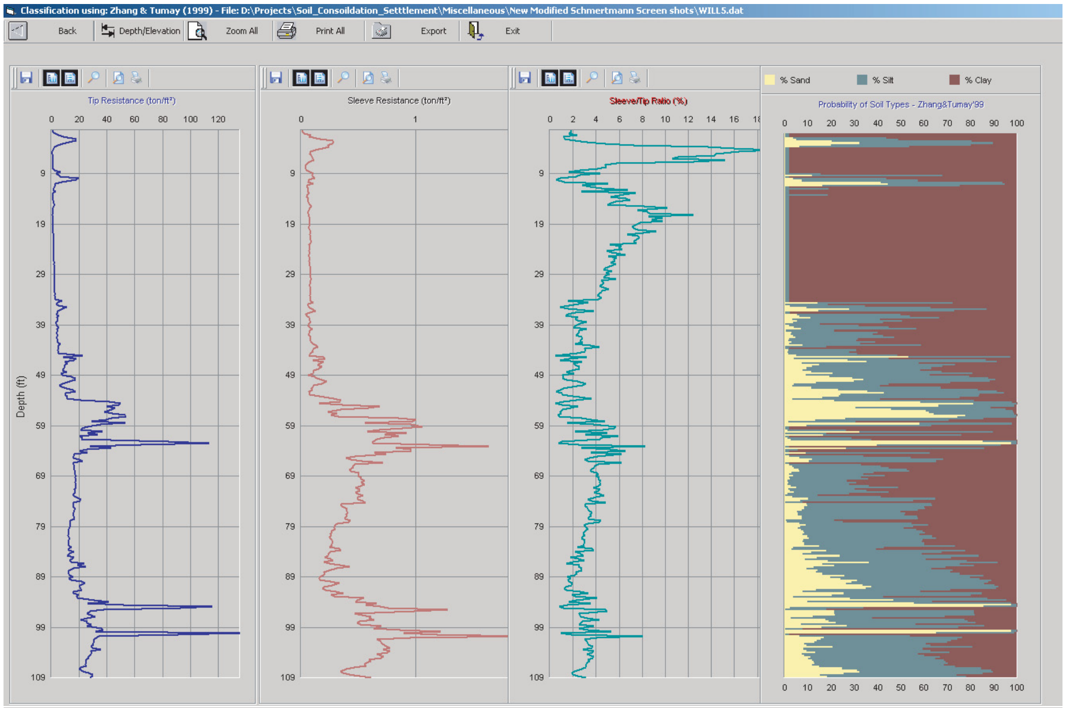
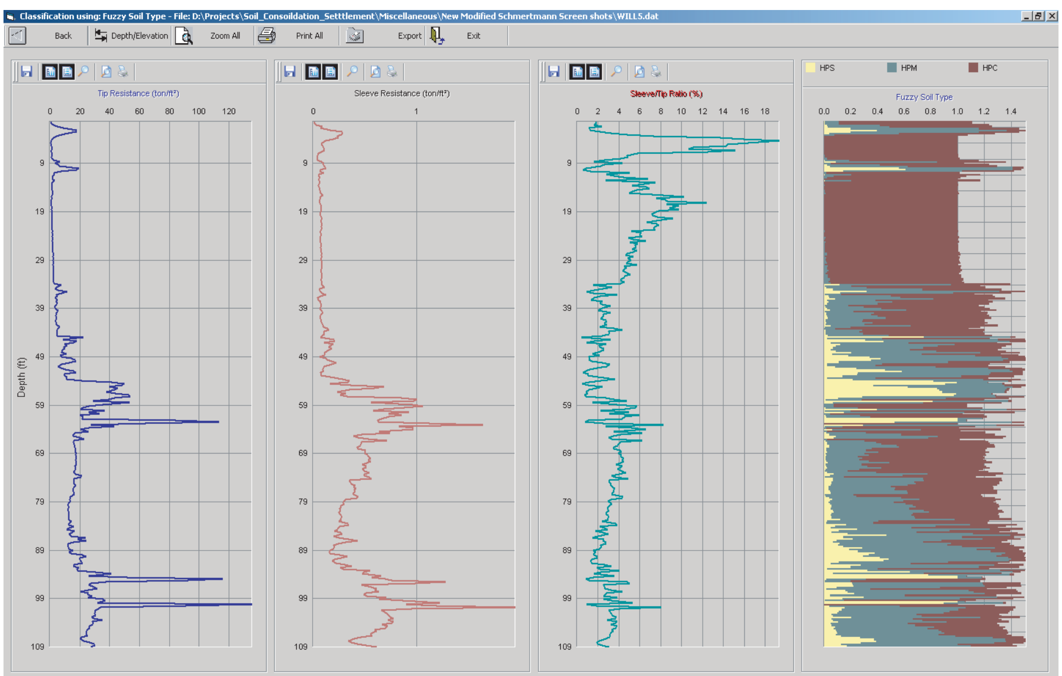


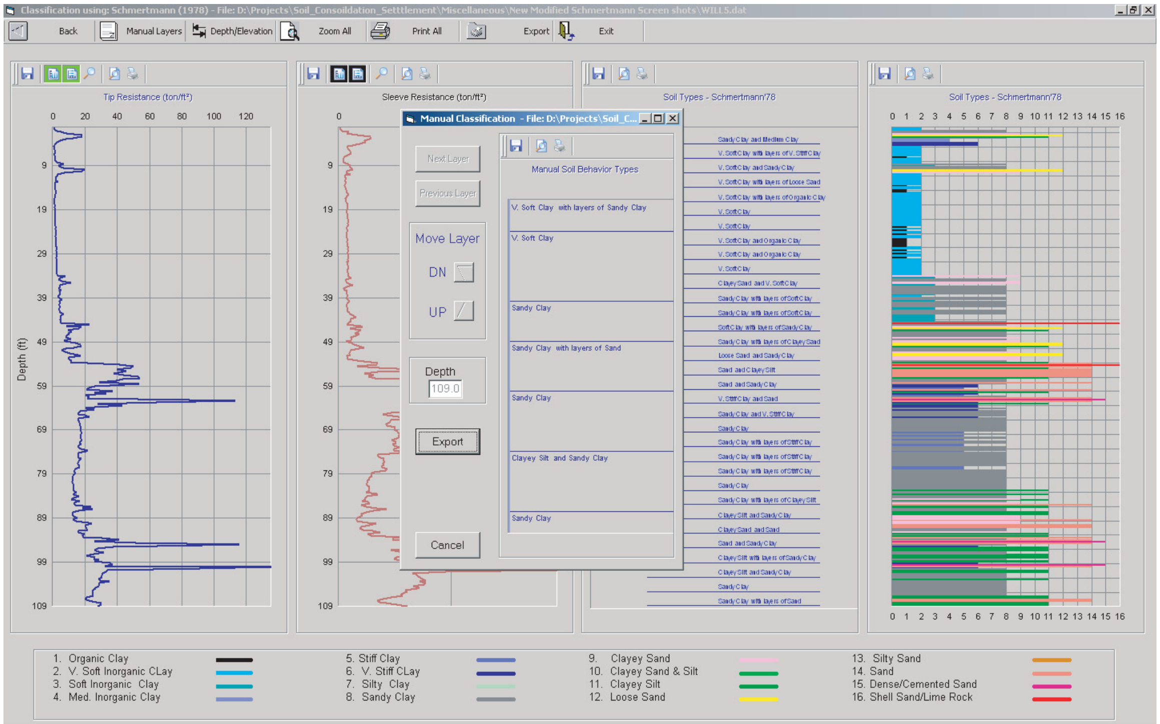

(c)



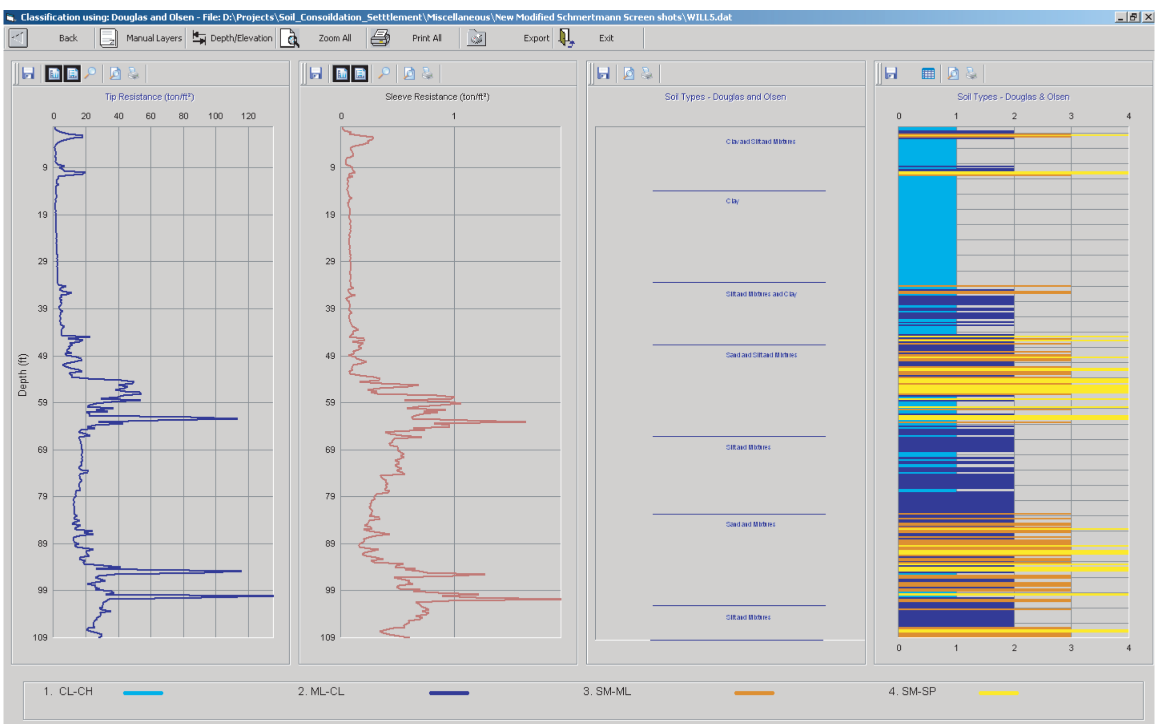

(d)

FIGURE 7 *(continued)* **Features of Louisiana Soil Classification by Cone Penetration Test Program (www.ltrc.lsu.edu/downloads.html): (*c*) probabilistic region estimation classification method, (*d*) fuzzy classification method.**

*(continued)*




**(e)**




**(f)**

FIGURE 7 *(continued)* **Features of Louisiana Soil Classification by Cone Penetration Test Program (www.ltrc.lsu.edu/downloads.html): (*e*) Schmertmann classification method (*1*), (*f*) Douglas and Olsen classification method (*2*).**

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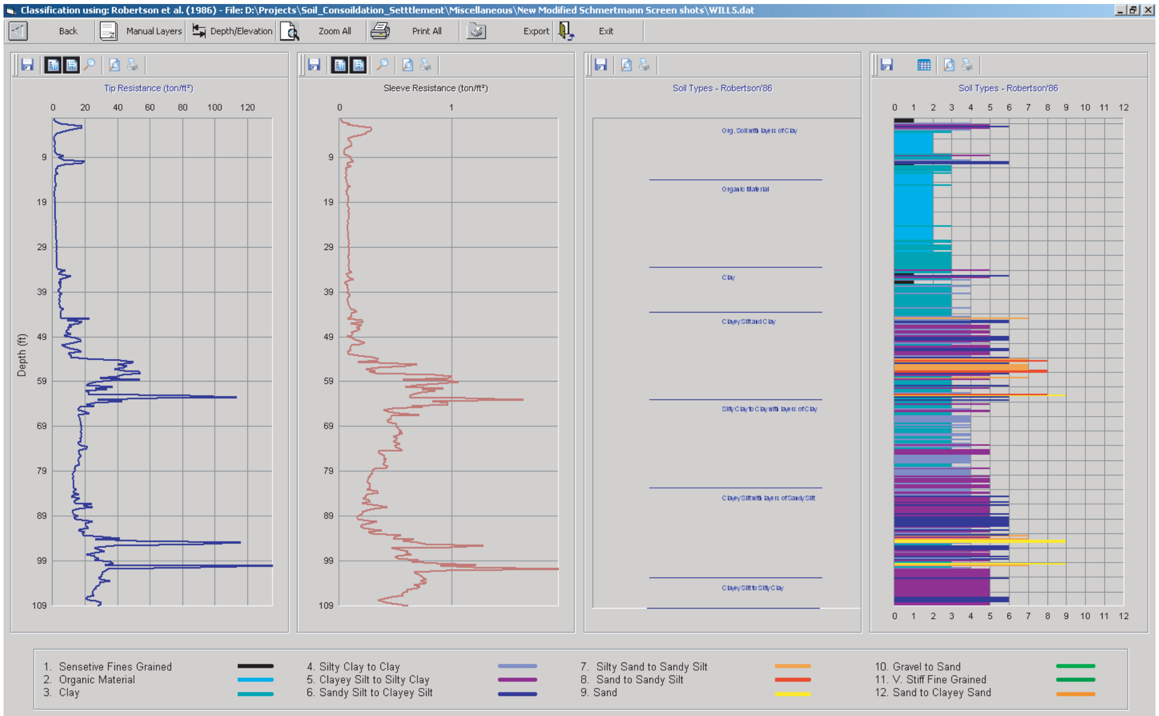


(g)

FIGURE 7 *(continued)* **Features of Louisiana Soil Classification by Cone Penetration Test Program (www.ltrc.lsu.edu/downloads.html): *(g)* Robertson et al. classification method *(3)*.**

able accuracy. The different CPT classification methods gave closer type behavior soil classification compared with the soil borings. Among the different methods, the probabilistic region estimation and the fuzzy CPT classification methods are considered superior in providing a continuous and accurate profile of soil type with depth, which makes them easy to implement in conjunction with other CPT application.

The effect of correcting the cone tip resistance against pore pressure generated behind the base ($u_2$) on CPT soil classification was demonstrated through comparison between soil classification using $q_c$ and $q_t$. Figures 13*a* and 13*b* depict the comparison in CPT soil classification for data obtained from the five investigated sites using Schmertmann (*1*) and Robertson et al. (*3*) charts, respectively. As can be seen, only soils located at the lower-right portion of the chart can be influenced by correction. For the purpose of soil classification, this is not considered significant and can affect only soils located close to the boarder between two classification regions.

## SUMMARY AND CONCLUSIONS

This paper presents the implementation of CPT soil engineering classification methods in a handy tool computerized MS-Windows Visual Basic program (Louisiana Soil Classification by Cone Penetration Test, LSC-CPT) for friendly use by geotechnical engineers in their daily activities for subsurface investigation and design. Five CPT soil classification systems were implemented into the software: the probabilistic region estimation and fuzzy CPT classification by Zhang and Tumay (*6*), Schmertmann (*1*), Robertson et al. (*3*), and Douglas and Olsen (*2*). In Zhang and Tumay's two

**TABLE 1 Summary of Soil Properties for Investigated Sites**

| Site | Unit Weight (kN/m$^3$) | Water Content (%) | Liquid Limit (%) | Plasticity Index (%) | Clay Content (%) | $S_u$(kN/m$^2$)[a] |
|---|---|---|---|---|---|---|
| Manwell Bridge, Evangeline | 16–20 (18.5) | 17–48 (32) | 23–77 (48.9) | 6–44 (25) | 17–66 (42.3) | 29–142 (71) |
| US-90–LA-88, New Iberia | 18.2–18.8 (18.3) | 23–33 (25.5) | 30–35 (33.2) | 9–17 (12) | 22–26 (24.3) | 38–118 (87) |
| La Peans Canal Bridge, Lafourche | 15–19 (16.8) | 29–61 (38.8) | 34–66 (46.8) | 13–39 (21.4) | 42–57 (52.2) | 12.5–48 (28.4) |
| Pavement Research Facility | 16–16.9 (16.6) | 31–63 (49.1) | 64–115 (91.7) | 25–41 (31.8) | 25–45 (41.4) | 18.3–43.9 (25.7) |
| Pearl River | 15–18.5 (16.2) | 21–45 (32.2) | 42–64 (53.6) | 22–39 (30.3) | 26–68 (43.6) | 14.5–43.9 (25.7) |

[a]Measured from unconfined compression tests.

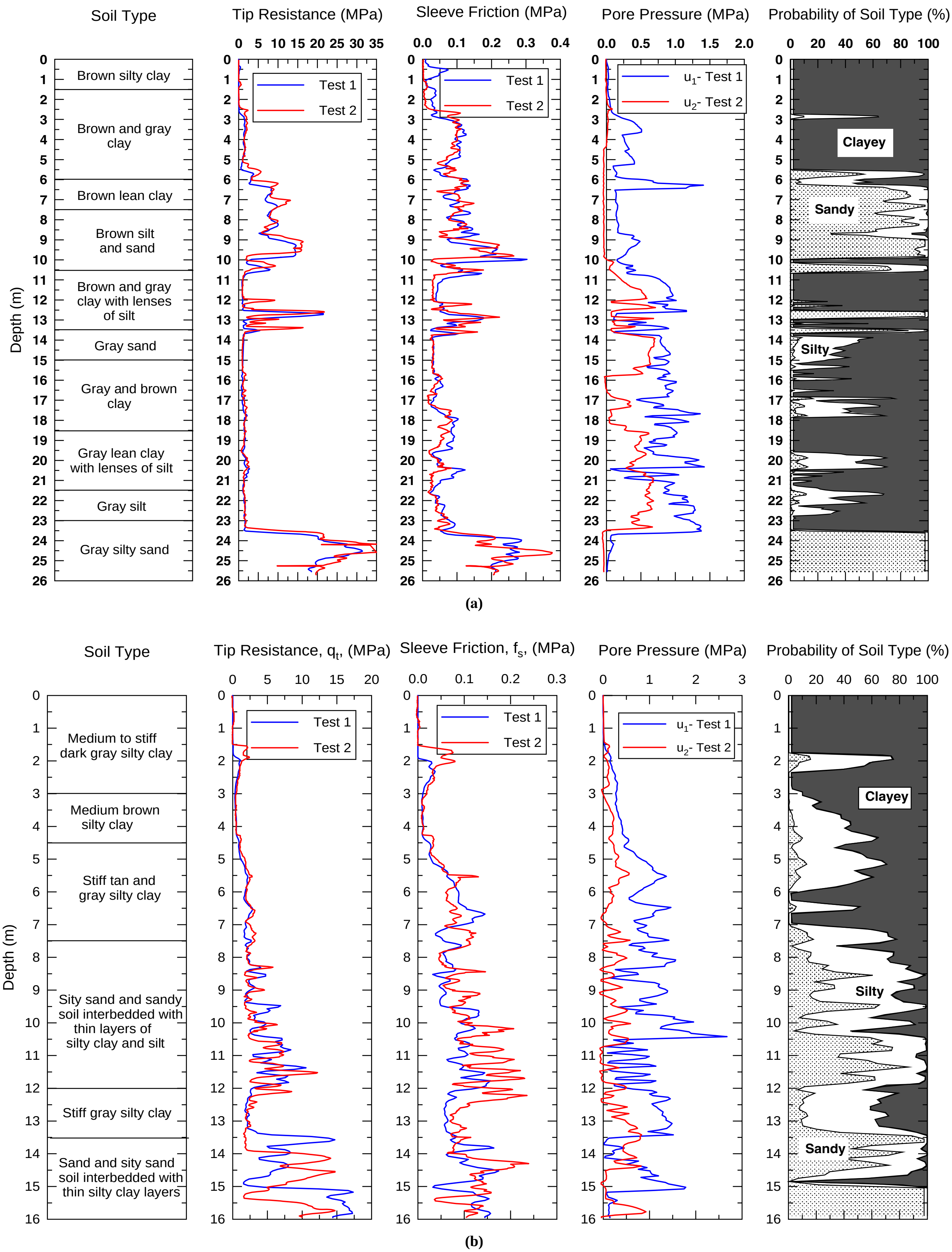
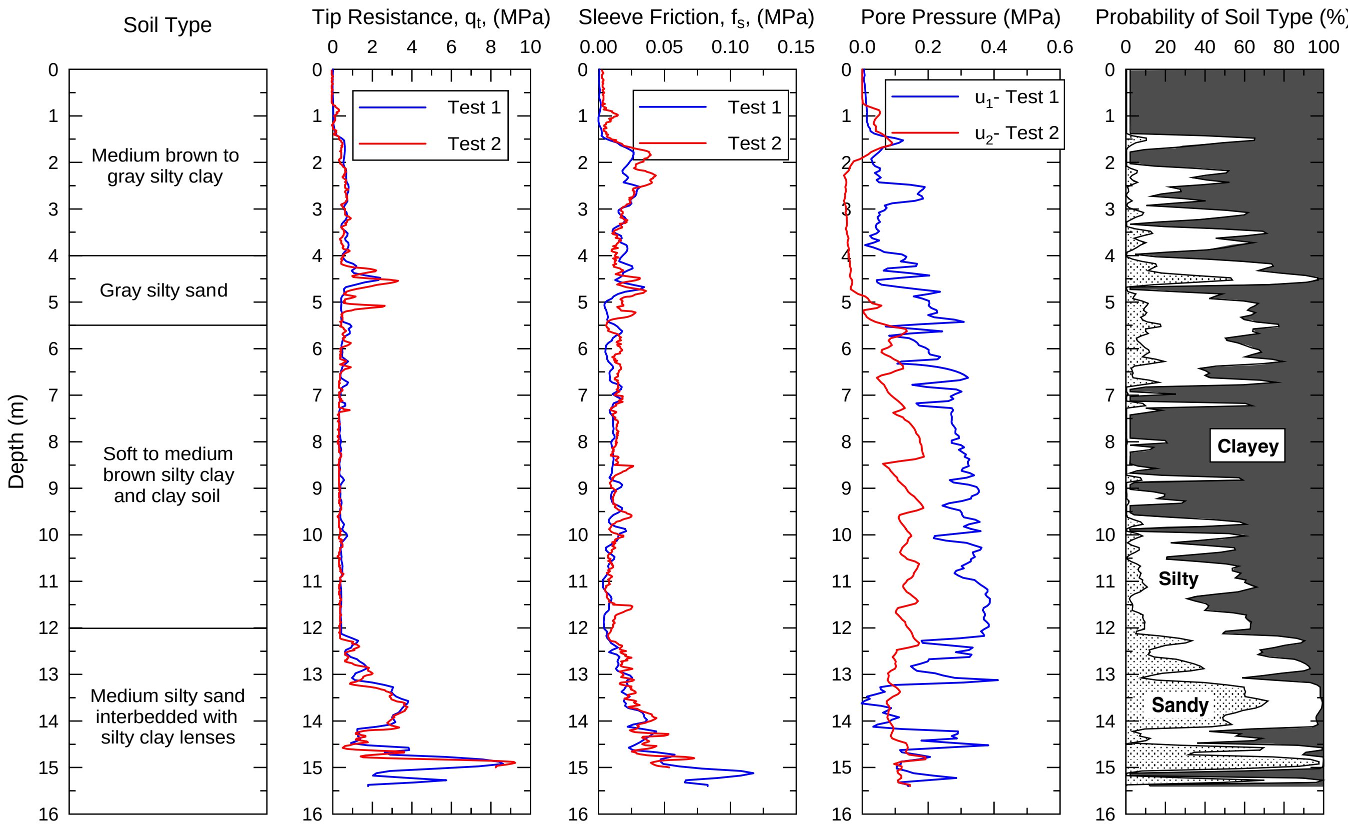
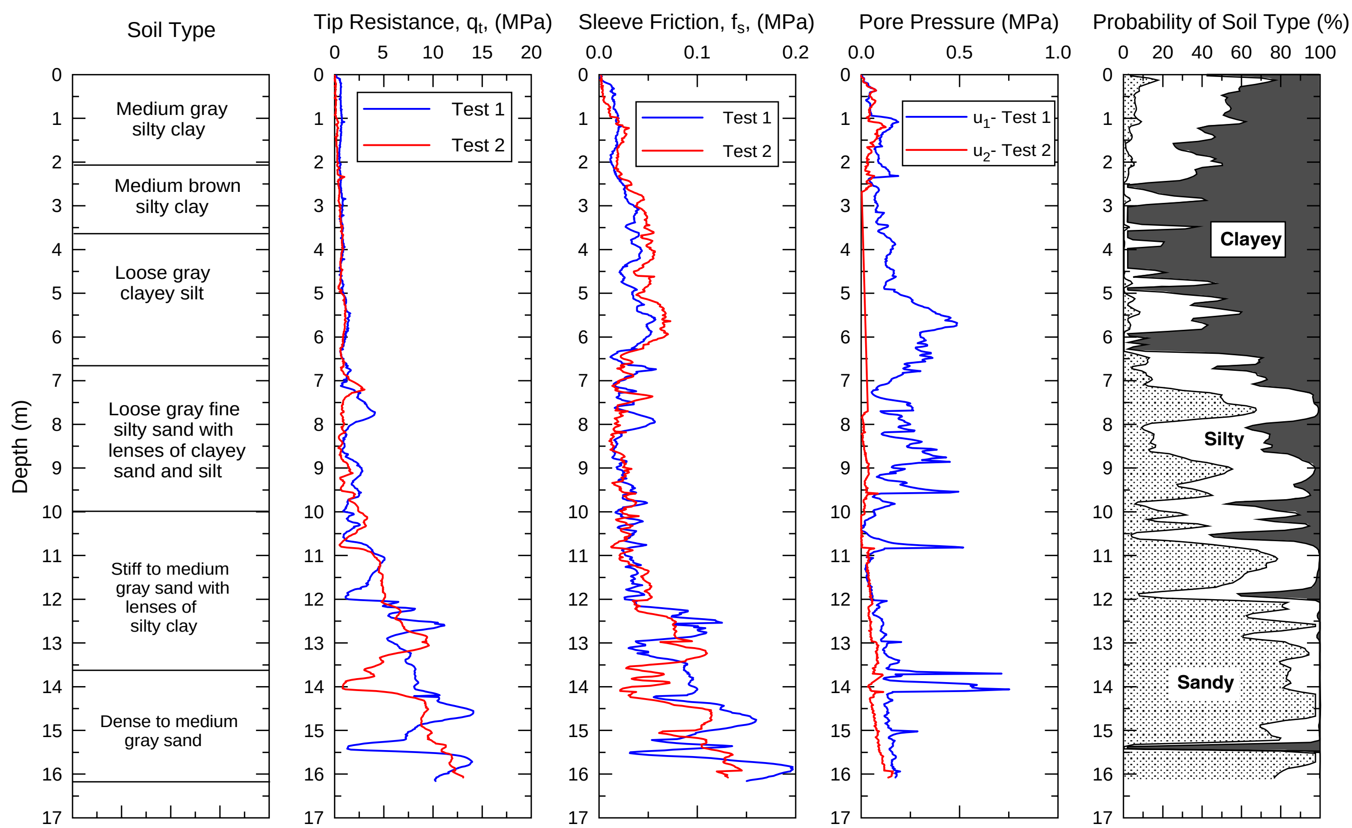



FIGURE 8 PCPT profiles and soil classification from boring and probabilistic region estimation method: (*a*) Evangeline site, (*b*) New Iberia site.

*(continued on next page)*




(c)




(d)

FIGURE 8 *(continued)* PCPT profiles and soil classification from boring and probabilistic region estimation method: (*c*) Lafourche site, and (*d*) PRF site.

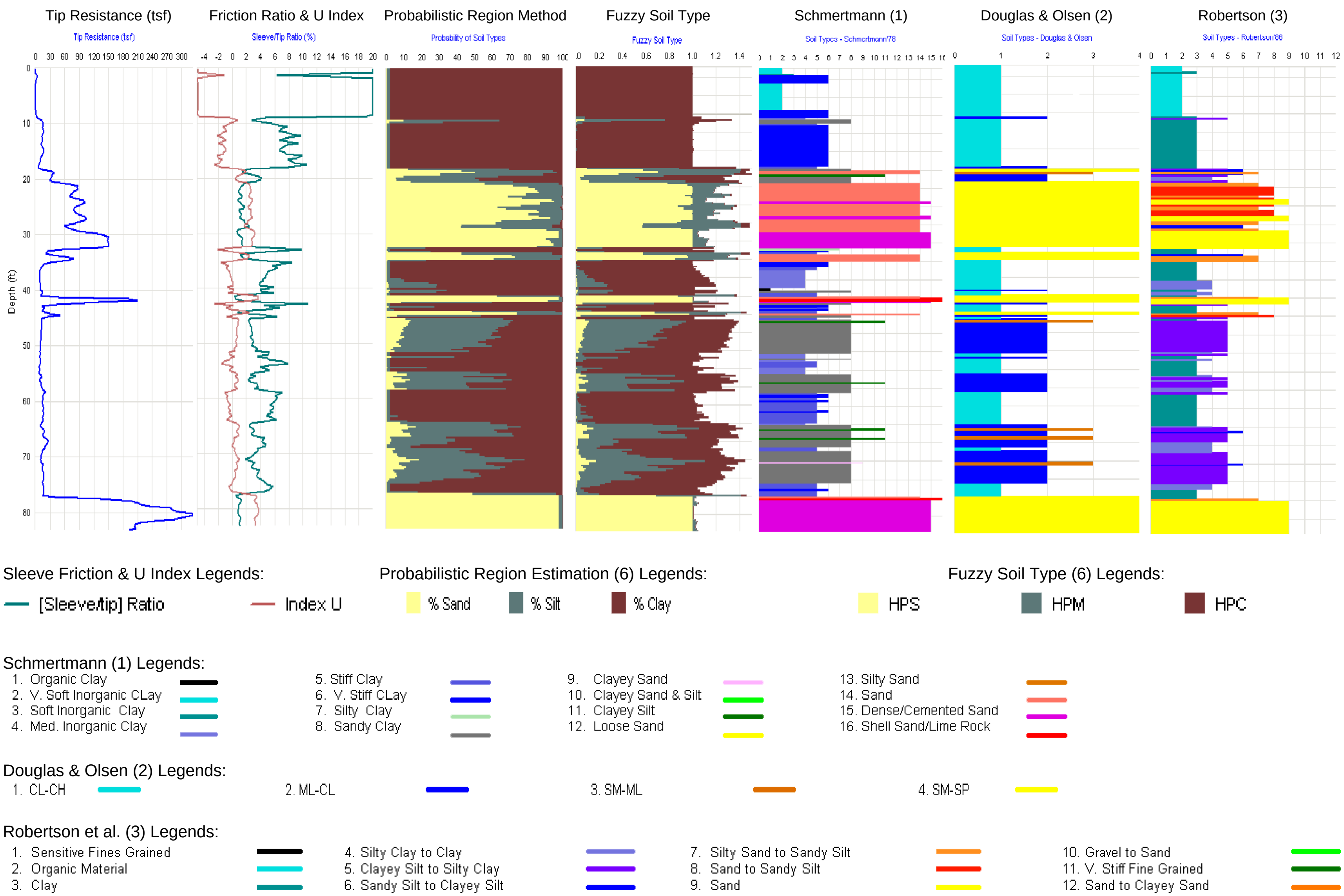
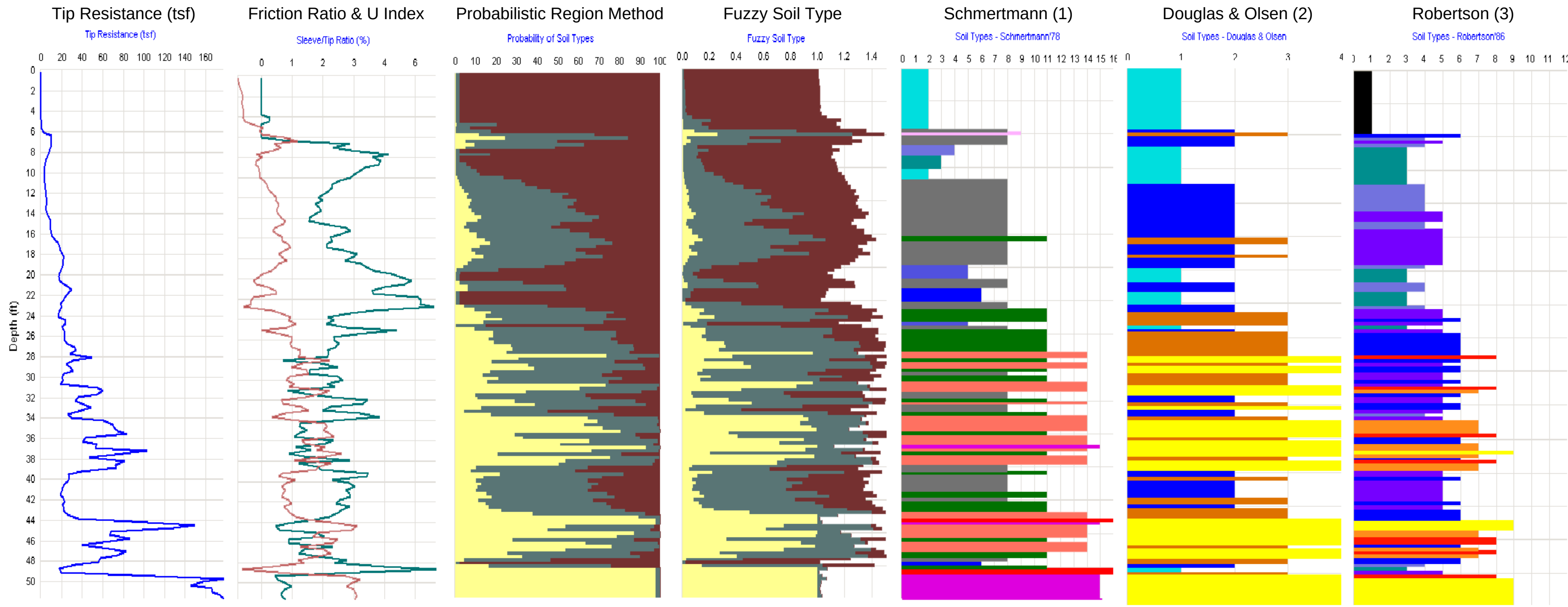



FIGURE 9 CPT data and corresponding CPT soil classification for Evangeline site.




Sleeve Friction & U Index Legends:

[Sleeve/tip] Ratio
Index U

Probabilistic Region Estimation (6) Legends:

% Sand
% Silt
% Clay

Fuzzy Soil Type (6) Legends:

HPS
HPM
HPC

Schmertmann (1) Legends:

1. Organic Clay
2. V. Soft Inorganic CLay
3. Soft Inorganic Clay
4. Med. Inorganic Clay
5. Stiff Clay
6. V. Stiff CLay
7. Silty Clay
8. Sandy Clay
9. Clayey Sand
10. Clayey Sand & Silt
11. Clayey Silt
12. Loose Sand
13. Silty Sand
14. Sand
15. Dense/Cemented Sand
16. Shell Sand/Lime Rock

Douglas & Olsen (2) Legends:

1. CL-CH
2. ML-CL
3. SM-ML
4. SM-SP

Robertson et al. (3) Legends:

1. Sensitive Fines Grained
2. Organic Material
3. Clay
4. Silty Clay to Clay
5. Clayey Silt to Silty Clay
6. Sandy Silt to Clayey Silt
7. Silty Sand to Sandy Silt
8. Sand to Sandy Silt
9. Sand
10. Gravel to Sand
11. V. Stiff Fine Grained
12. Sand to Clayey Sand

FIGURE 10 CPT data and corresponding CPT soil classification for New Iberia site.


Sleeve Friction & U Index Legends:

[Sleeve/tip] Ratio — Index U

Probabilistic Region Estimation (6) Legends:

% Sand — % Silt — % Clay

Fuzzy Soil Type (6) Legends:

HPS — HPM — HPC

Schmertmann (1) Legends:

1. Organic Clay
2. V. Soft Inorganic CLay
3. Soft Inorganic Clay
4. Med. Inorganic Clay
5. Stiff Clay
6. V. Stiff CLay
7. Silty Clay
8. Sandy Clay
9. Clayey Sand
10. Clayey Sand & Silt
11. Clayey Silt
12. Loose Sand
13. Silty Sand
14. Sand
15. Dense/Cemented Sand
16. Shell Sand/Lime Rock

Douglas & Olsen (2) Legends:

1. CL-CH
2. ML-CL
3. SM-ML
4. SM-SP

Robertson et al. (3) Legends:

1. Sensitive Fines Grained
2. Organic Material
3. Clay
4. Silty Clay to Clay
5. Clayey Silt to Silty Clay
6. Sandy Silt to Clayey Silt
7. Silty Sand to Sandy Silt
8. Sand to Sandy Silt
9. Sand
10. Gravel to Sand
11. V. Stiff Fine Grained
12. Sand to Clayey Sand

FIGURE 11 CPT data and corresponding CPT soil classification for Lafourche site.

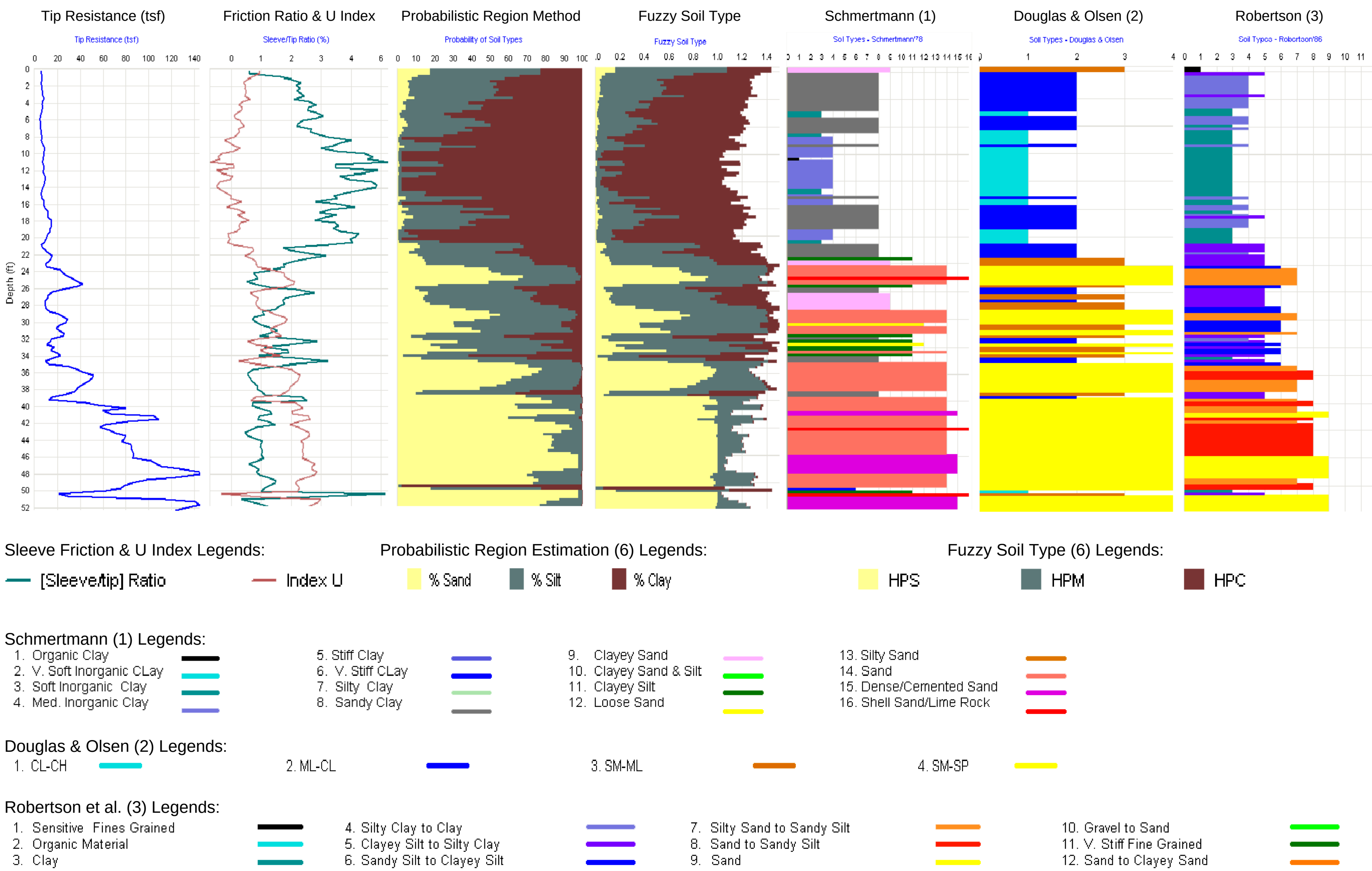
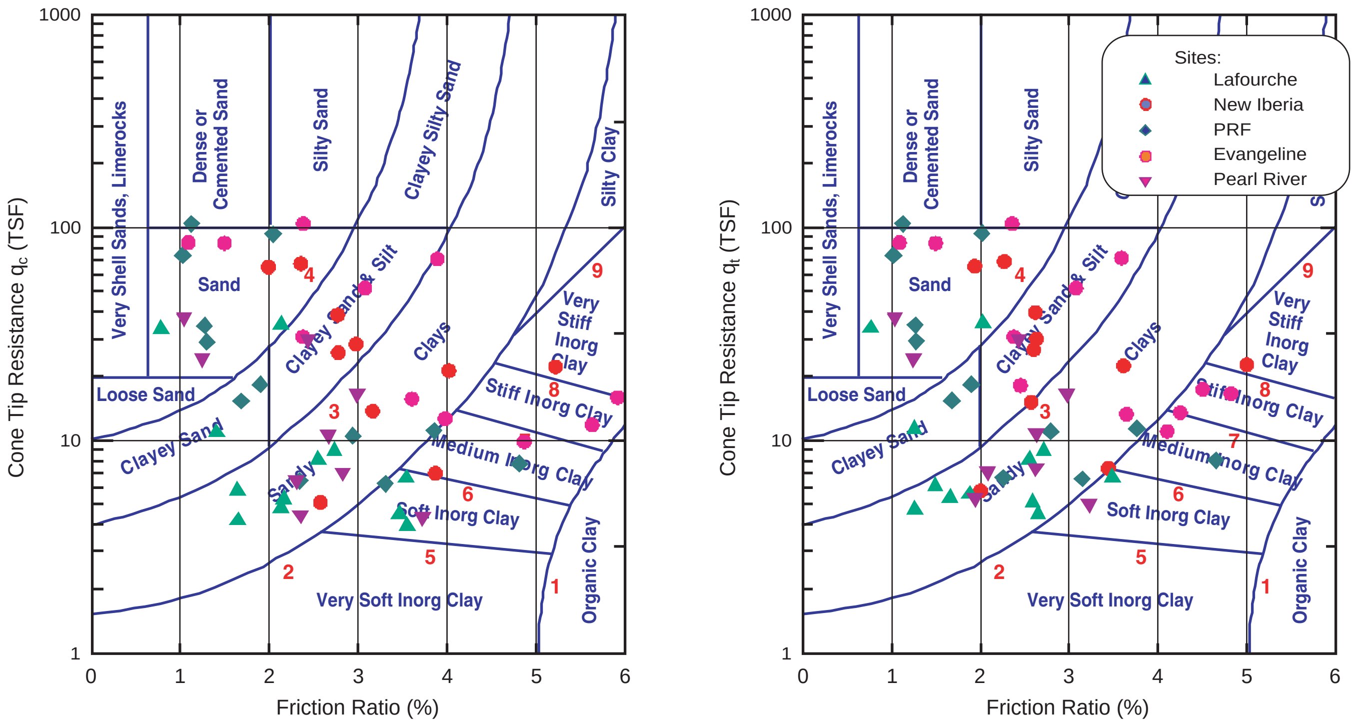
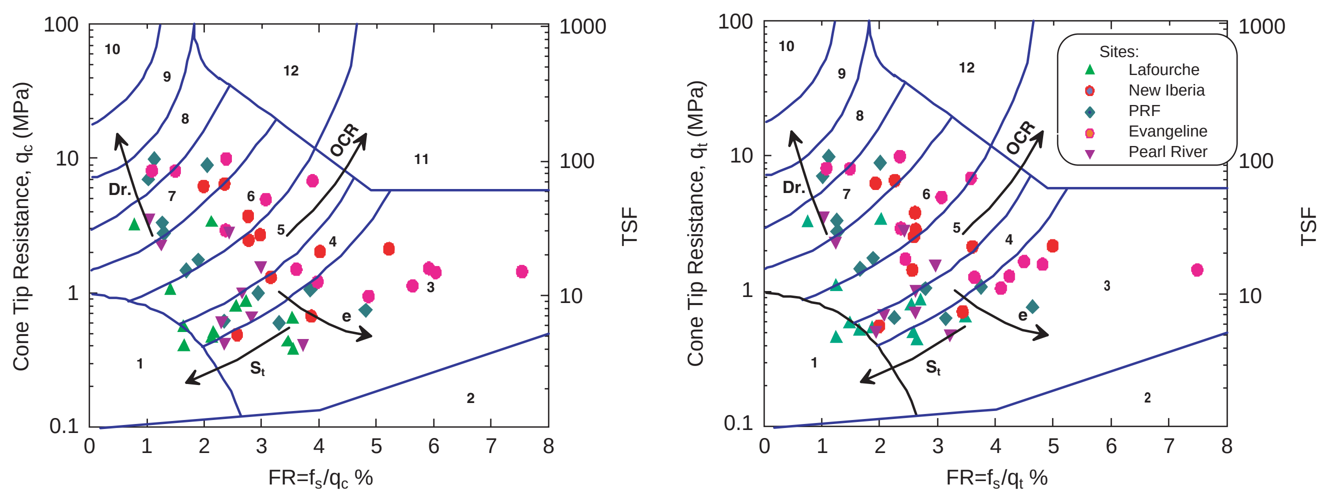



FIGURE 12 CPT data and corresponding CPT soil classification for PRF site.




(a)




(b)

**FIGURE 13** Comparison of CPT soil classification using $q_c$ versus $q_t$: (*a*) Schmertmann (*1*) method and (*b*) Robertson et al. (*3*) method.

methods, a soil classification index, *U,* is first determined and used to provide a continuous soil classification profile with gradual changes from one subsurface layer to another. However, Schmertmann (*1*), Robertson et al. (*3*), and Douglas and Olsen (*2*) methods provide soil classification charts based on cone tip resistance ($q_c$ or $q_t$) and friction ratio ($R_f$) input parameters. The general features of the program were demonstrated. The program also was used to compare the different CPT classification methods and charts in conjunction with the soil borings. Five sites in Louisiana were selected for this comparison, which showed that the CPT classification methods are capable of classifying the subsurface soil behavior with good accuracy compared with the soil borings. Contrary to CPT classification charts, the probabilistic region estimation and fuzzy CPT classification methods are capable of predicting, with good accuracy, the continuous soil classification profile with depth including information on the probability of soil constituents in the layers encountered.

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