A site-specific fines content correlation using cone penetration test data

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ABSTRACT: The California Department of Water Resources (DWR) Urban Levee Geotechnical Evaluations Program was established to provide an assessment of the project levee systems estimated to protect urban areas with more than 10,000 people. For Reclamation District 17 (RD 17) located in San Joaquin County, California, 19 rotary borings and 86 cone penetration tests (CPT) were performed along the levee crest as part of the Phase 1 assessment of subsurface conditions and levee stability. Each boring was located adjacent to a CPT to assist in correlating stratigraphy and engineering soil parameters. Seepage is an important issue for the RD 17 levees. A key input parameter for seepage analyses is hydraulic conductivity of the levee and foundation soils. Site-specific correlations of fines content and soil type to hydraulic conductivity were developed as part of the analyses of the levee system. Using the data from the CPT-boring pairs, a site-specific correlation was constructed following the methodology by Robertson and Wride (1998) which uses the soil behavior type index (I_c) as an input. This paper presents the methodology and results of the site-specific fines content correlation and its use in seepage analyses.

1 INTRODUCTION

The DWR established the Urban Levee Geotechnical Evaluations Program (Program) to assess the approximately 350 miles of project levees within the Sacramento and San Joaquin River systems in the California Central Valley that protect urban areas with more than 10,000 people. One of the intended goals of the project is to access the seepage, beneath and through the levees. Hydraulic conductivity estimates are needed to perform seepage analyses, and fines content has a strong influence on hydraulic conductivity. For this reason, a method of utilizing CPT data to obtain a continuous profile of apparent fines content (AFC) versus depth appears valuable as a tool for aiding hydraulic conductivity assessments. A site-specific AFC to CPT correlation was developed and is presented in this paper following a similar form by Robertson and Wride (1998).

Reclamation District 17 (RD 17) is in San Joaquin County, California and encompasses the southwestern portion of the City of Stockton and western portion of Lathrop, with much of the district generally west of Interstate 5 and east of the San Joqauin River. RD 17 is protected by approximately 16 miles of levees along the south bank of the French Camp Slough, the east bank of the San Joaquin River, and the north bank of the Walthall Slough.

As part of the DWR Program, the team conducted a Phase 1 field exploration consisting of 19 borings and 86 CPTs along the levee crest of RD 17. Nineteen (19) of the CPTs were located within 5 feet of the borings for use as correlational soundings.

2 GEOLOGICAL AND GEOTECHNICAL CHARACTERISTICS

In the study area, the San Joaquin River lies at or very near the regional contact of young, near-tidal fluvial deposits within the Delta (on the west) and the gently west-sloping distal alluvial-fan surfaces formed by the Stanislaus and Calaveras Rivers (on the east).The deposits in the southern portion of RD 17 (the upstream portion of the San Joaquin River) are more coarse-grained (50% or more by dry unit weight of the test specimen is retained on the No. 200 sieve) than the relatively fine-grained (less than 50% by dry unit weight of the test specimen is retained on the No. 200 sieve) deposits to the north.

3 METHODS OF FIELD INVESTIGATION

The first phase of explorations consisted of CPTs performed at approximately 1,000-foot intervals along the levee crest, and exploratory borings generally drilled adjacent to every fifth CPT (one boring for every five CPTs, or approximately one boring every 5,000 feet). The exploratory borings adjacent to the CPTs are used to correlate the subsurface conditions encountered with results obtained from the CPTs.

3.1 *Exploratory Borings and laboratory data*

3.1.1 *Exploratory Borings and Sampling*

All borings were drilled to a minimum depth of 100 feet (at least three times the levee height into the foundation). In the borings, soil sampling was conducted continuously using soil coring (“punch core”) methodology, driven split-spoon samplers, modified California (MC) samplers, and thin-walled (Shelby) tubes. Drilling and sampling procedures were adjusted to soil conditions encountered to maximize sample recovery.

3.1.2 *Laboratory Data*

Soil classification was performed on selected samples to evaluate the engineering properties of subsurface materials. Laboratory tests include index property tests such as Atterberg limits, sieve analysis, moisture content, and dry density. In addition, the project team assigned hydrometer tests to select samples of silty sands and silts to assist with the hydraulic conductivity characterization of these materials.

3.1.3 *Cone Penetration Tests*

All CPTs were performed per ASTM D 5778-07, using a truck mounted, 25-ton thrust-reaction apparatus utilizing a pizeocone with the pore pressure transducer behind the shoulder (the u_2 position). CPTs were extended to a minimum depth of 100 feet below the levee crest. In these areas the CPTs were advanced to a minimum depth of 140 feet (in most instances).

4 HYDRAULIC CONDUCTIVITY ASSESSMENT

For fine-grained materials, hydraulic conductivities (k) were selected by the Project team per Terzaghi et al. (1996). For coarse-grained materials, values were estimated using site-specific data with the Kozeny-Carman (KC) equation from Carrier (2003) in conjunction with laboratory tests on collected samples that provided soil gradation data.

5 CONE PENETRATION TEST CORRELATIONS

Robertson and Wride (1998) proposed that the Soil Behavior Type Index (I_c) be used to calculate an Apparent Fines Content (AFC). The calculation of I_c requires correction for pore pressure behind the tip of the cone and for ambient effective and total overburden stress levels.

5.1 *Soil Behavior Type Index and Apparent Fines Content*

The Soil Behavior Type Index (I_c) is calculated using Equation (1) below:

$$I_c = \left[(3.47 - \log Q)^2 + (1.22 + \log F)^2\right]^{0.5} \quad (1)$$

where Q = normalized tip resistance and F = normalized friction ratio. The AFC can then be calculated as shown in Equations 2 through 4 below:

$$\text{If } I_c < 1.26, \quad AFC(\%) = 0, \quad (2)$$

$$\text{If } 1.26 \le I_c \le 3.5, \quad AFC(\%) = 1.75 I_c^{3.25} - 3.7 \quad (3)$$

$$\text{If } I_c \ge 3.5, \quad AFC(\%) = 100 \quad (4)$$

6 METHODOLOGY

The analytical methodology for developing the AFC-CPT correlation is based on the assumption that the 19 borings with adjacent CPTs encountered similar soils with similar properties. Cumulative frequencies for fines content data sets from the CPTs and borings should follow a similar trend. Further, the fines content for a particular cumulative frequency value and the I_c from the same cumulative frequency value should describe the same material. Once a relationship is established between fines content and the I_c for the same cumulative frequencies, a regression analyses provide relations from Ic to fines content.

The standard CPT penetration rate typically shears fine-grained materials in an undrained manner and coarse-grained materials in a drained manner. Non-plastic to low-plasticity soils may shear in a drained manner. Therefore, the AFC correlation may not be suitable for these non- to low-plasticity soils.

7 SAMPLE BIAS

Approximately 70% of the laboratory tests performed were conducted on coarse-grained samples while only 50% of the CPT data were considered coarse-grained materials. Therefore, while the borings and CPTs encountered similar materials, a greater number of laboratory fines content determinations were performed on coarse-grained materials than on fine-grained materials. Hydraulic conductivity estimates are sensitive to fines content when the fines content is low and become less sensitive as the fines content increases. For this reason, more laboratory tests were performed on coarse-grained materials than on fine-grained materials, therefore correlating the entire sample set of CPT data to the entire sample set of laboratory data would introduce sample bias.

To correct the model for sample bias, apparent coarse-grained CPT data (I_c<2.6) were regressed with coarse-grained laboratory data and apparent fine-grained CPT data (I_c>2.6) were regressed with fine-grained laboratory data. Cumulative frequency distributions for fine-grained and coarse-grained materials are presented for laboratory data and CPT data in Figures 1 and 2.

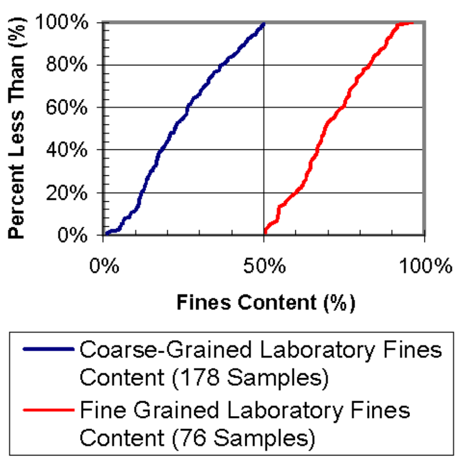

Figure 1. Cumulative distribution of fines contents.

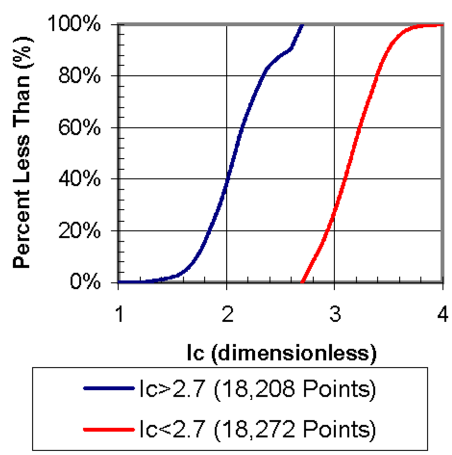

Figure 2. Cumulative distribution of I_c.

8 REGRESSION

Soil Behavior Type Indices (I_c) and laboratory fines content values for the same percentile are plotted in Figure 3 which suggests a linear relationship between I_c and fines content for the two data sets. A linear regression analysis was performed on both data sets showing a high correlation relationship between fines content and I_c for both coarse-grained and fine-grained soils.

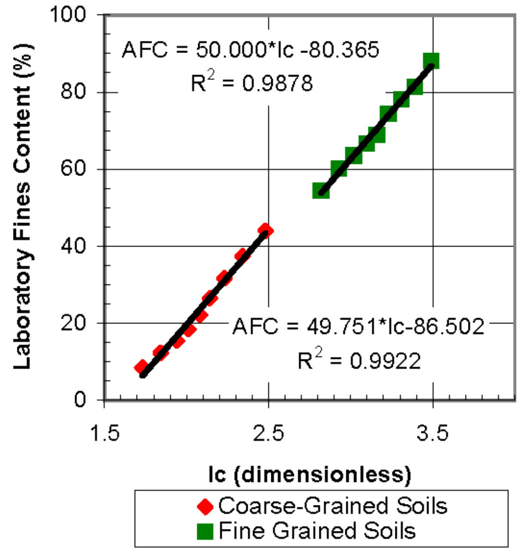

Figure 3. Regression analyses on San Joaquin River data.

Extrapolating the linear regression equations to fines contents of 0 and 100 percent and connecting the two regression equations using linear interpolation results in the correlation shown in Figure 4. Figure 4 also presents the correlation proposed by Robertson and Wride (1998).

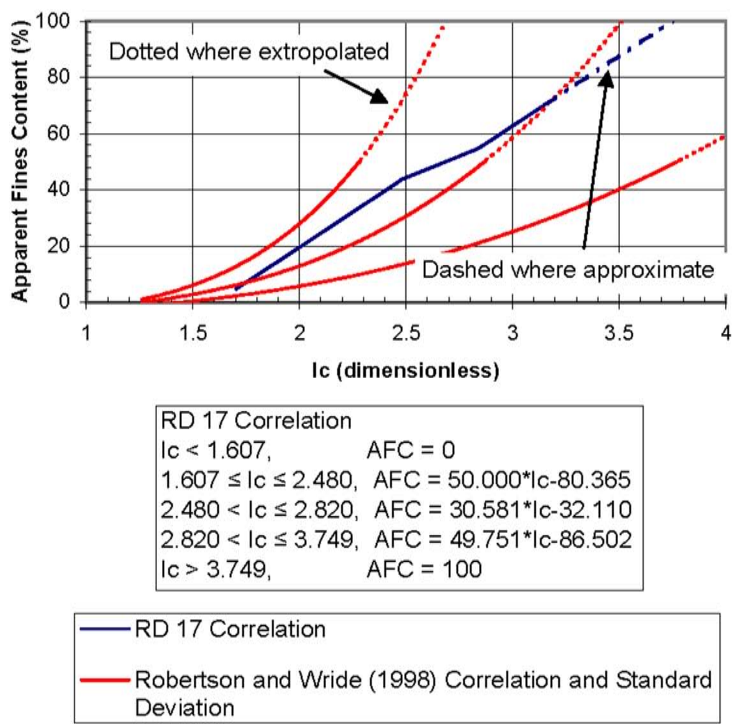

Figure 4. Apparent fines content results with Robertson and Wride (1998) correlation.

9 SEEPAGE ANALYSES

In order to assess the effectiveness of the AFC correlations, AFC profiles were used as inputs in seepage analyses. The apparent fines content (AFC) was used to develop hydraulic conductivity estimates as input for seepage analyses using blanket theory analysis (BTA). The BTA calculates the average vertical exit gradient (i) at the toe of the levee which is defined as the total head drop in the vertical direction across the levee's landside blanket divided by the blanket thickness measured in the same units as the head drop.

The United States Army Corps of Engineers (USACE) developed Blanket Theory Analyses (BTA) to assist in the assessment of underseepage analyses. These procedures are presented in EM 1110-2-1913 (USACE 2000) Appendix B "Mathematical Analysis of Underseepage and Substratum Pressure."

For this report, the flood elevation used to calculate exit gradient is the 200-year flood.

A sensitivity analysis was performed on the horizontal hydraulic conductivity of the pervious layer by selecting two values in addition to the best estimate. Calculations of exit gradients were performed keeping all other inputs constant and using a low estimate, best estimate, and high estimate for the value of horizontal hydraulic conductivity of the pervious layer.

10 RESULTS

The RD 17 site-specific fines content-I_c correlation presented in this paper resembles the Robertson and Wride (1998) correlation.

Plots of AFC and laboratory fines content versus depth are presented in Figure 5 for CPTs WR0017_001C, WR0017_040C, WR0017_101C, and WR0404_015C. A summary of BTA inputs and results are presented on Table 1.

Table 1. BTA Analyses Results for the San Joaquin River Project

	Hydraulic Conductivity k_f *			Hydraulic Gradient, i		
Exploration	Low Estimate cm/s	Best Estimate cm/s	High Estimate cm/s	Low Estimate	Best Estimate	High Estimate
WR0017_001C	NO BLANKET – BTA NOT APPLICABLE			N/A	N/A	N/A
WR0017_040C	$1.1x10^{-3}$	$3.5x10^{-3}$	$1.1x10^{-2}$	0.20	0.28	0.34
WR0017_101C	$1.1x10^{-3}$	$3.5x10^{-3}$	$1.1x10^{-2}$	0.45	0.48	0.49
WR0404_015C	$7.1x10^{-5}$	$1.4x10^{-4}$	$7.1 x10^{-4}$	0.04	0.06	0.09

*k_f is the horizontal hydraulic conductivity of the foundation layer as defined by USACE (2000).

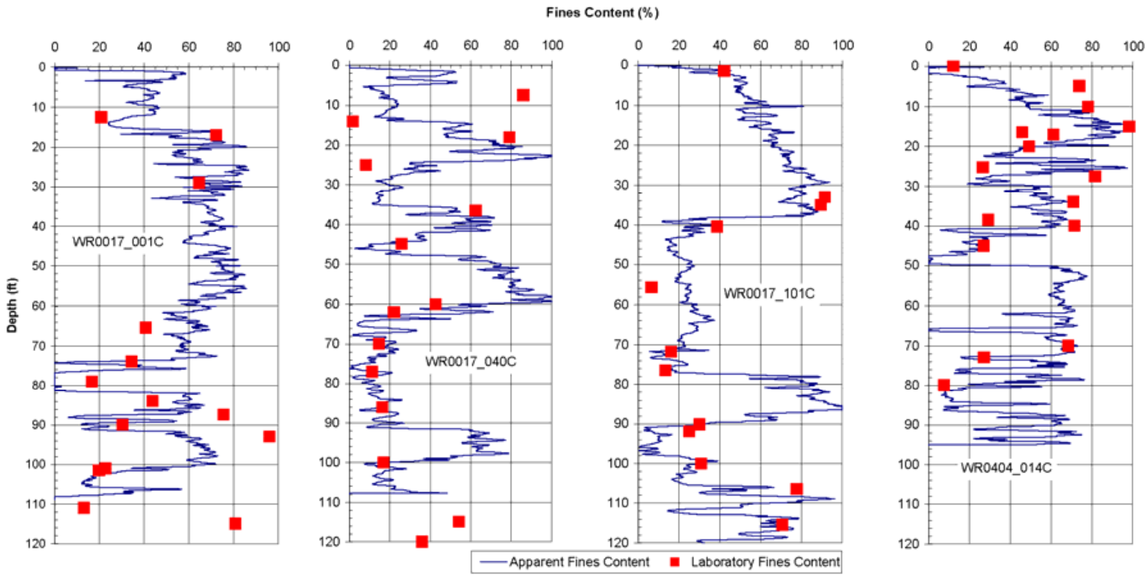

Figure 5. CPT Apparent Fines Content correlation results at San Joaquin River, California.

The three CPT-boring pairs, WR0017_001C, WR0017_040C, and WR0017_010C, compare data used in the regression model. Sounding WR0404_014C is from a near-by site included in the Urban Levee Geotechncial Evaluations Program. The correlation is shown for WR0404_014C to examine the use of the AFC in a similar geologic setting with data not used in the regression analyses.

In general, the AFC correlation appears to make a good prediction of fines content. A notable exception occurs for WR0017_040C with an under prediction of fines content at a depth of 8.5 feet and an over prediction at a depth of 14 feet.

The soil at a depth of 8.5 feet was logged as silt (ML). As the CPT is advanced, completely nonplastic silt may shear as more of a partially drained material rather than an undrained material. Therefore, the soil would behave more like a coarse-grained material than a fine-grained material even if the particles were smaller than 0.075 inches.

The soil at a depth of 14 feet was logged as a poorly graded sand (SP). The over prediction of the fines content of this material may be due to the model inputs. The inputs to the regression model did not include a large sample size of fines contents less than 5%. Therefore, the model will have greater uncertainty in predicting the fines contents of soils with less than 5% fines. The soil at a depth of 14 feet had 2% fines.

In terms of seepage analyses, the AFC appears to provide results accurate enough to perform screening level seepage analyses and define seepage condition trends as defined by USACE ETL 1110-2-569 (USACE, 2005) where seepage conditions are described in terms such as light seepage, medium seepage, heavy seepage, and sand boils. Varying the estimated hydraulic conductivity to a high or low estimate does not change the seepage condition for the sections analyzed.

11 CONCLUSIONS

The site-specific Ic-AFC correlation developed for RD 17 site conditions appears to provide a reasonable prediction of continuous apparent fines content versus depth and therefore a good screening tool for seepage analyses.

Due to the sample set, the model does not appear to accurately predict soils with less than 5% fines and greater than 75% fines. Additionally, the model does not appear to predict fines content well for fine-grained materials when sheared in a drained manner. Nevertheless, the use of the apparent fines content correlation can aid efforts to estimate hydraulic conductivity for seepage model development, and allow more efficient targeting of areas for borings after CPTs have been performed.

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