CPTU for consolidation properties of Lake Bonneville clay

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ABSTRACT: This paper discusses the use of piezecone penetration test (CPTU) for estimating the consolidation properties of the Lake Bonneville clay in Salt Lake City, Utah. The effectiveness of the CPTU in predicting the virgin compression ratio (CR), 1-D constrained modulus (M), preconsolidation stress (σ'_p) and overconsolidation ratio (OCR) is evaluated. This is accomplished by correlating CPTU parameters with results obtained from high quality sampling and constant rate strain consolidation (CRS) laboratory tests using multiple linear regression (MLR) analyses to develop correlations for CR, M, and σ'_p with CPTU parameters. Subsequently, the estimates from the regression equations are compared with the laboratory test results to evaluate the predictive power and reasonableness of the developed regression equations. These evaluations show that the CPTU can reasonably estimate the consolidation properties of the relatively soft, Lake Bonneville clay deposits. Thus, the proposed Multiple Linear Regression (MLR) equations can be used to reduce the cost and time involved with conventional sampling and laboratory testing of these sediments and to expedite primary consolidate settlement calculations for these deposits.

1 INTRODUCTION

The piezecone test (CPTU) involves measuring the tip resistance, q_c, side friction, f_s, and excess dynamic pore water pressure, u. The use of this device was first developed in Sweden in the early 1970s. Currently, the CPTU is a widespread and very convenient test method that allows for rapid, continuous soil profiling and provides economical estimation of key soil properties for design proposes. Meigh (1987) stated that the two main advantages of CPTU are: (1) providing a continuous, or virtually continuous, record of ground conditions and (2) avoiding sample disturbance that is typically associated with drilling and sampling in a conventional manner. Details of the CPTU procedure are provided in ASTM D3441.

The Utah Department of Transportation (UDOT) funded a study to improve in situ methods and their ability to estimate the consolidation properties for the soft to medium stiff Lake Bonneville clays that are found throughout the Salt Lake Valley, Utah. The objectives of this research were to correlate high quality constant rate of strain (CRS) laboratory results with CPTU measurements so that the latter could be used in future geotechnical evaluations and primary consolidation settlement calculations. Evaluation of the effectiveness of the CPTU in predicting the virgin compression ratio, CR, and the preconsolidation stress, was accomplished by statistical (i.e., regression) analyses and by comparing the results of those analyses with the original CRS laboratory test results.

Undisturbed samples of Lake Bonneville Clay were taken in three locations in the Salt Lake Valley near the Interstate I-15 alignment in down town Salt Lake City. A B-80 mobile drill rig was used for drilling. At the South Temple Street location, two sites were drilled, one underneath the northbound bridge at South Temple Street and one in the embankment median of the interstate, just north of the north abutment of the South Temple Street Bridge. At the North Temple Street site, the drilling was done in a vacant lot northeast of the northbound bridge. For the North Temple Street site, rotary wash drilling was used; for both South Temple Street sites, hollow stem auger drilling methods was used.

CRS tests were performed on high quality undisturbed thin-walled piston samples obtained at these sites. Also, additional Shelby tubes samples were obtained and used for laboratory soil classification and determination of index properties. The overlying and underlying Holocene and Pleistocene alluvium, respectively, were not sampled at the research sites. These units are more granular and not as compressible; hence characterization of these sediments was less important from primary consolidation settlement standpoint.

Generally, the surficial Holocene alluvium at the research sites consists of about 5 m of poorly stratified clay, sand and minor gravel. The Holocene alluvium is underlain by about 15 m of compressible lacustrine deposits originating from the late-Pleistocene Lake Bonneville, which is a fresh-water predecessor of the Great Salt Lake. This upper Pleistocene sequence consists of interbedded clayey silt and silty clay, with thin beds of silt and fine sand found near the middle of the Lake Bonneville sequence. These interbedded sediments divide the major clay units of the Lake Bonneville sediments into the “upper Lake Bonneville clay” and the “lower Lake Bonneville clay,” respectively. The Lake Bonneville sediments are underlain by late-Pleistocene alluvium, which is predominately dense to very dense sands and gravels. Beneath this alluvium are much stiffer clays associated with earlier lakes that predate Lake Bonneville.

A very detailed and continuous classification profile of Lake Bonneville sediments is presented in Bartlett and Ozer (2004) and Ozer (2005). In general, the upper Lake Bonneville clay is more plastic than the lower clay and consists of MH, CL, and ML soils. The interbeds are sediments deposited when the lake levels were very low and therefore have more granular soils representing near-shoreline conditions. The interbeds are predominantly silts (ML), with some beds of clay (CL) and thin layers of medium dense sand (SC). The lower Lake Bonneville clay is mainly CL soils with some silt (ML) layers.

2 REGRESSION MODEL FOR PRECONSOLIDATION PRESSURE

Values of q_c have been used previously to estimate the preconsolidation stress. Tavenas and Leroueil (1979) proposed an equation for determining the preconsolidation stress for Canadian clays, which includes q_c. Mayne (1986) proposed an equation that also depends on q_c using correlations developed from a database with 49 different clays. Later, Mayne and Kemper (1988), using a large CPT data base from 50 research sites, correlated overconsolidation ratio (OCR) with the net cone resistance, q_c-σ_{vo}, where σ_{vo} is the total vertical (i.e., overburden) stress. Tavenas and Leroueil (1987) showed that preconsolidation stress was correlated with the net corrected tip resistance, q_t-σ_{vo}, where q_t is corrected tip resistance, for 11 Canadian clays. Sugawara (1988) developed a relation between OCR and the net corrected tip resistance for Japanese clays. In addition, a relationship between OCR and penetration pore water pressure was proposed by Mayne and Bachus (1988) and in their later research (Mayne and Bachus, 1989) proposed relations between preconsolidation stress and pore water pressure.

The interbeds within the Lake Bonneville clays have interbedded fine sand layers, which must be filtered out of the CPTU data before performing the subsequent regression analysis. (This was done so that these more granular units are not included in the correlations. Also, no CRS testing was done in this zone). The filtering (i.e., removal) of the fine sand layers was done using the soil behavior type index, I_c (Jefferies and Davies, 1993). Data with I_c values less than 2.6 were considered to be granular material and were eliminated from the subsequent statistical analyses.

After this, the remaining CPTU readings were paired by elevation with the laboratory preconsolidation stress results from the CRS tests. For the analysis, the pairing of the CPTU data with the laboratory test data was conducted using a 1-m average of the CPTU readings. This average started 0.5 m above the elevation of each respective CRS sample location and continued 0.5 m below the CRS sample location. These averaged CPTU measurements used in the regression analysis included q_c, f_s, and Δu_c. In addition, average values of σ_{vo} were used in the regression analyses.

Exploratory regression analyses were conducted to find independent variables for the regression model and to see the function form that these variables have with the dependent variable. For example, in these exploratory analyses, CRS determined values of σ'_p (dependent variable) were correlated with the independent variables (e.g., tip resistance, q_c, net tip resistance, (q_c - σ_{vo}), sleeve stress, f_s, corrected tip resistance, q_t, net corrected tip resistance, (q_t-σ_{vo}), total overburden stress, σ_{vo}, and induced excess pore pressure, Δu_c).

Because q_t is calculated from q_c and Δu and is also used widely in the literature, q_t was chosen over q_c and Δu as the primary independent variable to correlate with σ'_p. Further, it was observed that f_s has the lowest correlation (R^2 = 54.3 %) with σ'_p when compared with the other independent variables, thusly values of f_s were eliminated from further consideration in the main regression model.

Ultimately, the independent variables chosen for the final multiple linear regression (MLR) model were: q_t, (q_t-σ_{vo}), and σ_{vo}. These variables were used to predict σ'_p by dividing them into seven different models as presented in Table 1. (From an application standpoint, the regression models should not be dependent on the stress units, so all variables were divided by atmospheric pressure, P_a, to make the regression variables dimensionless.)

All regression analyses shown in Table 1 were performed using Microsoft EXCEL. These models have the general form:

$$y = \beta_o x_1^{\beta_1} x_2^{\beta_2} \tag{1}$$

This can be expressed in a linear form for multiple regression using:

$$\log y = \log \beta_o + \beta_1 \log x_1 + \beta_2 \log x_2 \tag{2}$$

Table 1. Data variables sets and linear regression equations for normalized preconsolidation pressure

Data Set	Independent Variables	R^2 (%)	Equation (From the model given in Equation 1, and regression output by using Microsoft EXCEL, the linear regression can be back transformed to):
A	$\left(\sigma_{vo}/P_a\right)$	87.5	$\frac{\sigma'_p}{P_a} = 0.932\left(\frac{\sigma_{vo}}{P_a}\right)^{0.892}$
B	$\left(q_t/P_a\right)$	88.1	$\frac{\sigma'_p}{P_a} = 0.290\left(\frac{q_t}{P_a}\right)^{0.863}$
C	$\left(\left(q_t-\sigma_{vo}\right)/P_a\right)$	82.9	$\frac{\sigma'_p}{P_a} = 0.429\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{0.798}$
D	$\left(\sigma_{vo}/P_a\right)$, $\left(q_t/P_a\right)$	90.8	$\frac{\sigma'_p}{P_a} = 0.478\left(\frac{\sigma_{vo}}{P_a}\right)^{0.438}\left(\frac{q_t}{P_a}\right)^{0.469}$
E	$\left(\sigma_{vo}/P_a\right)$, $\left(\left(q_t-\sigma_{vo}\right)/P_a\right)$	90.9	$\frac{\sigma'_p}{P_a} = 0.632\left(\frac{\sigma_{vo}}{P_a}\right)^{0.565}\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{0.342}$
F	$\left(q_t/P_a\right),\left(\left(q_t-\sigma_{vo}\right)/P_a\right)$	90.4	$\frac{\sigma'_p}{P_a} = 0.192\left(\frac{q_t}{P_a}\right)^{1.953}\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{-1.046}$
G	$\left(\sigma_{vo}/P_a\right)$, $\left(q_t/P_a\right)$, and $\left(\left(q_t-\sigma_{vo}\right)/P_a\right)$	90.7	$\frac{\sigma'_p}{P_a} = 0.960\left(\frac{\sigma_{vo}}{P_a}\right)^{0.756}\left(\frac{q_t}{P_a}\right)^{-0.693}\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{0.842}$

A comparison of preconsolidation stress predicted from Model E (since it gave highest R^2 value) of above table and laboratory CRS and IL consolidation test results can be seen in Figure 1. The lines represent the results of Model E and dots represent the laboratory test results. Model E provides reasonably close prediction of the laboratory results for the Lake Bonneville clays.

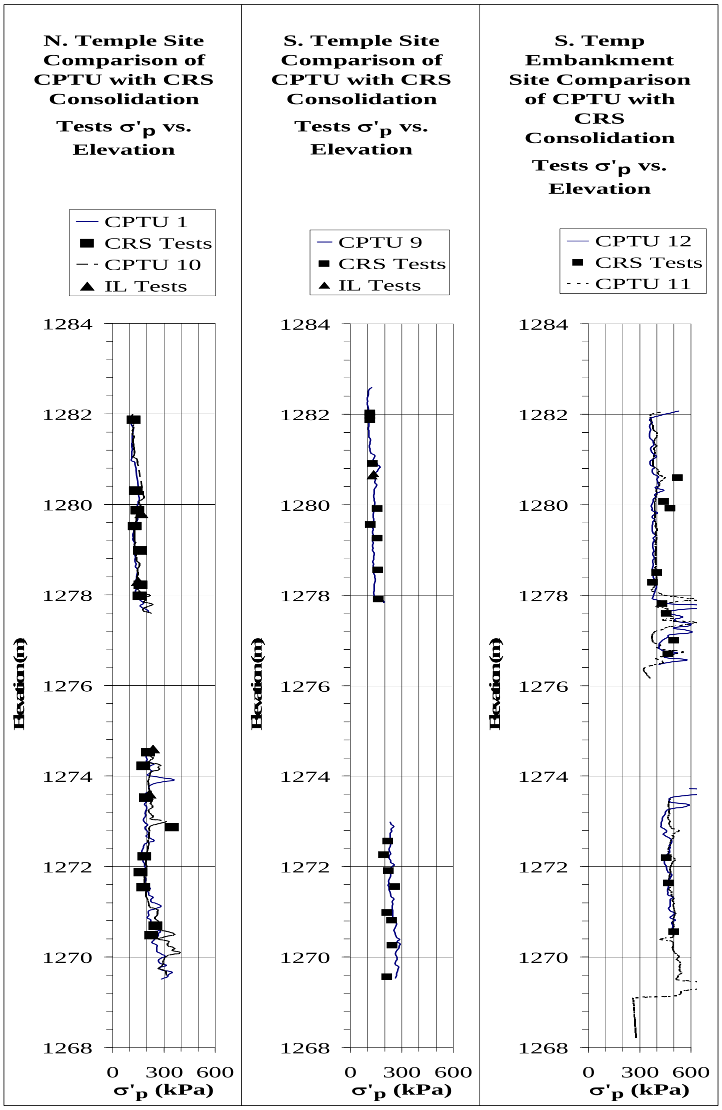

Figure 1. Comparison of preconsolidation stress values with Model E of Table 1

3 CORRELATIONS FOR COMPRESSION RATIO (CR) AND CONSTRAINED MODULUS (M)

Laboratory determined values of compression ratio, CR, were correlated against σ_{vo}, q_t, and (q_t-σ_{vo}), and the R^2 values from those regressions were between 13.5 % and 25.3 %. Due to these relatively low R^2 values for the CR correlations, in an attempt to improve the models' predictive performances, values of CR were converted to the constrained modulus, M, at the preconsolidation stress level. As given below in Equation (3), M can be back-calculated from CR values.

$$M = \sigma'_v \left(\frac{1 + e_o}{C_c} \right) \ln 10 = \sigma'_p \frac{2.3}{CR} \qquad (3)$$

When laboratory determined values of M were correlated against σ_{vo}, q_t, and (q_t-σ_{vo}), and the R^2 values from those regressions were between 81 % and 84 %, which significantly improved the correlations. MLR models were applied to predict M values based on q_t, and (q_t-σ_{vo}), and σ_{vo}. As was done to evaluate the preconsolidation stress in the previous section, independent variables were divided into seven different models and regression analyses were performed. Models attempted for the constrained modulus are given in Table 2.

It was observed that model E of Table 2 has the highest R^2 value. Values of CR can be back-calculated from the using the definition of M given in Equation (3). Comparison of M from Equation presented in Table 2 for Model E, and back calculated CR from Equation (3) from the laboratory results is given in Figure 2. As can be seen in Figure 2, calculated values of M and back-calculated values of CR from Equation (3) are reasonably close to the laboratory values.

Table 2. Data variables sets and linear regression equations for normalized constrained modulus

Data Set	Independent Variables	R^2 (%)	Equation (From the model given in Equation 1, and regression output by using Microsoft EXCEL, the linear regression can be back transformed to):
A	(σ_{vo}/P_a)	85.1	$\frac{M}{P_a}=5.816\left(\frac{\sigma_{vo}}{P_a}\right)^{1.148}$
B	(q_t/P_a)	87.8	$\frac{M}{P_a}=1.252\left(\frac{q_t}{P_a}\right)^{1.125}$
C	$((q_t-\sigma_{vo})/P_a)$	83.3	$\frac{M}{P_a}=2.067\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{1.044}$
D	(σ_{vo}/P_a), (q_t/P_a)	89.5	$\frac{M}{P_a}=2.141\left(\frac{\sigma_{vo}}{P_a}\right)^{0.468}\left(\frac{q_t}{P_a}\right)^{0.704}$
E	(σ_{vo}/P_a), $((q_t-\sigma_{vo})/P_a)$	89.7	$\frac{M}{P_a}=3.240\left(\frac{\sigma_{vo}}{P_a}\right)^{0.655}\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{0.517}$
F	(q_t/P_a), $((q_t-\sigma_{vo})/P_a)$	89.1	$\frac{M}{P_a}=0.828\left(\frac{q_t}{P_a}\right)2.218\left(\frac{q_t-\sigma_{vo}}{P_a}\right)^{-1.049}$
G	(σ_{vo}/P_a), (q_t/P_a), and $((q_t-\sigma_{vo})/P_a)$	89.6	$\frac{M}{P_a}=12.284\left(\frac{\sigma_{vo}}{P_a}\right)^{1.267}\left(\frac{q_t}{P_a}\right)^{-2.212}\left(\frac{q_t-\sigma_{vo}}{P_a}\right)$

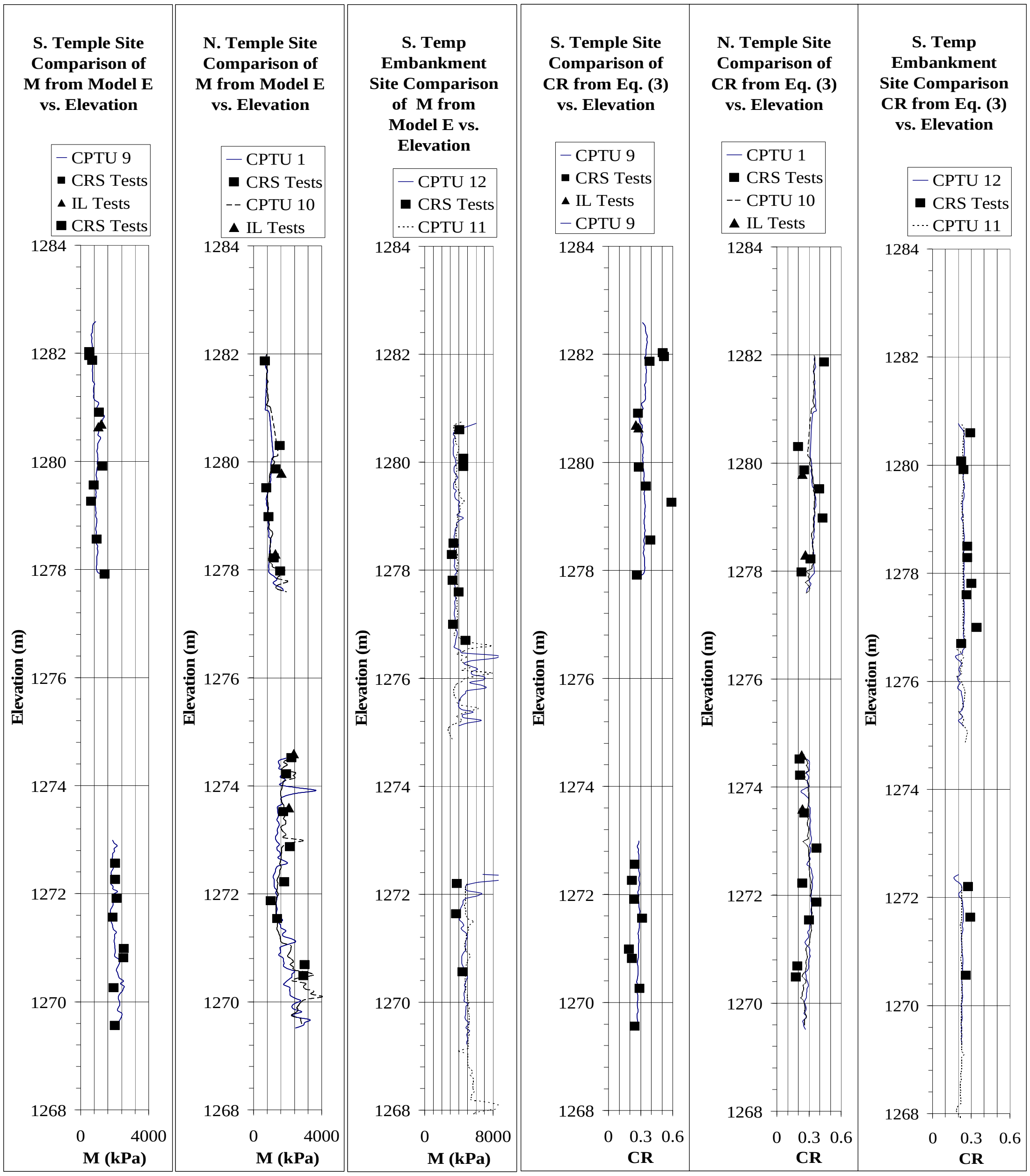

Figure 2. Comparison of M and CR from laboratory consolidation tests and CPTU results

4 CONCLUSIONS

MLR models based on CPTU parameters can adequately predict the preconsolidation stress and constrained modulus of the Lake Bonneville clays. The use of the MLR equations is recommended for geotechnical evaluations and settlement calculations for locations underlain by the silty clay and clayey silt sediments of Lake Bonneville in Utah. These clayey deposits constitute the “deep water deposits” of Lake Bonneville that are found in the lower elevations of many northern Utah valleys in Salt

Lake, Utah, Davis, Weber and Box Elder Counties. Although the recommended correlations were developed specifically for the Salt Lake Valley Lake Bonneville deposits, we expect that the model will have adequate performance for other northern Utah locales where the Lake Bonneville clays is found. This expectation is based on the premise that because these clays have the same geologic origin, they will be reasonably similar in their geotechnical properties, regardless of the specific location. However, it may be prudent to perform additional sampling and CPTU and CRS testing to verify the performance of our models for other Utah locales outside of Salt Lake Valley. Using this approach, and as the statistical basis for the MLR models grows with additional data, we anticipate that the scope of geotechnical laboratory testing can be significantly reduced for many UDOT projects where primary consolidation settlement is a project consideration. The reliability of these models from predicting behavior of other clay deposits of various origins and locations is unknown and should be further researched.

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