CPTU and DMT for estimating soil unit weight of Lake Bonneville clay

A.T. Ozer
Okan University, Istanbul, Turkey

S. F. Bartlett & E. C. Lawton
University of Utah, Salt Lake City, Utah, USA

ABSTRACT: This paper discusses the use of piezecone penetration test (CPTU) and flat-plate dilatometer (DMT) for estimating the soil unit weight of the Lake Bonneville clay in Salt Lake City, Utah. Soil unit weight is required when calculating net cone resistance, normalized cone resistance, pore pressure ratio, and normalized friction ratio from CPTU results, and horizontal stress index from DMT results. To improve the predictive performances of existing correlations additional analysis were carried out. This is accomplished by correlating CPTU and DMT parameters with results obtained from high quality undisturbed sampling using multiple linear regression (MLR) analyses to develop correlations for soil unit weight. MLR analyses showed that the both CPTU and DMT can reasonably estimate the soil unit weight of the relatively soft, Lake Bonneville clay deposits with CPTU giving slightly higher predictive performance. Proposed correlations emerged for estimation of total unit weight in terms of net cone resistance and sleeve friction from CPTU results and P_1 value of DMT. By obtaining reliable estimates of soil unit weight directly from CPTU and DMT results, geotechnical consultants in the Salt Lake Valley would gain benefit for efficient post-processing of the both CPTU and DMT data.

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 flat dilatometer test (DMT) was developed in Italy by Marchetti (1980). It was initially introduced in North America and Europe in 1980 and is currently used in over 40 countries (Marchetti et al., 2006). Test procedures described by Marchetti (1980), Schmertmann (1986), and in ASTM D6635.

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 (Bartlett & Ozer, 2004). The objectives of this research were to correlate high quality constant rate of strain (CRS) consolidation laboratory test results with DMT results (Ozer et al., 2006) and CPTU measurements (Ozer et al., 2010) so that the latter could be used in future geotechnical evaluations and primary consolidation settlement calculations. CRS consolidation tests were performed on high quality undisturbed thin-walled piston samples obtained at research sites. In this paper, data obtained from both DMT and CPTU in UDOT study was used to estimate unit weight of Lake Bonneville clay. Unit weight of the Lake Bonneville clay were measured using CRS test ring prior to the CRS consolidation tests were initiated. Evaluation of the effectiveness of the DMT and CPTU in predicting the soil unit weight was accomplished by statistical (i.e., regression) analyses and by comparing the results of the soil unit weights.

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. CRS tests were performed on high quality undisturbed thin-walled piston samples obtained at these sites. 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 CPTU

Laboratory total unit weights of Lake Bonneville clay is determined using CRS test ring had a height of 25.4 mm and an inner diameter of 63.5 mm. All Shelby tubes collected from the research sites were stored in a humidity room to preserve their original water content. Prior to extrusion, 76.2 mm long sections of the Shelby tube were cut by a band saw. This was done to minimize disturbance of the sample during extrusion. The samples were then extruded using a standard extruder. Trimming of the specimen to fit the CRS consolidation ring was carefully done using a wire saw to minimize disturbance of the sample. Before placing the soil in the CRS consolidation ring, the inner circumference of the ring was lubricated with a low-friction lubricant to minimize disturbance. After soil specimens were placed in the ring, the top and bottom of the specimens were trimmed flush with the ring. Any small voids were carefully filled with remolded soil without disturbing the specimen. The ring and soil specimen was weighed to allow determination of total unit weight.

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 unit weight determination 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 total unit weight results.

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.

2.1 *Existing models*

Estimation of the soil unit weight based on direct measurements of CPTU has a practical value for post processing the CPTU raw data. Soil unit weight is required when calculating net cone resistance (q_n), normalized cone resistance (Q_{tn}), pore pressure ratio (B_q), and normalized friction ratio (F) from CPTU results, so that the engineering properties of the soils can effectively estimated without further need for undisturbed sampling to determine soil unit weight.

Larson & Mulabdic (1991) developed a chart to estimate unit weight based on pore pressure ratio, B_q, and q_n for Swedish clays. Lunne et al. (1997) suggested a method for estimation of soil unit weight based on Robertson's (1986) soil behavior type (SBT) chart. Robertson & Cabal (2010) indicated that even though this method provides reasonable estimates, the SBT zones cover wide range of soil density; consequently it does not capture the change in soil unit weight due to variations in soil density. Robertson & Cabal (2010) developed a contour chart to estimate soil unit weight based on CPT direct measurements, corrected cone resistance, q_t (or cone resistance, q_c) and sleeve friction, f_s. Proposed equation governing the contour chart has been tested with the database collected around the world, and provided reasonable estimates of unit weight. Using an extensive geometarial database, Mayne et al. (2010) proposed an equation based on sleeve friction and effective overburden stress. Mayne et al. (2010)

showed that the proposed equation reasonably estimates the total unit weight of variety of materials including clays, silts, sands, tills, and mixed soil types, however predictive performance did not seem valid for diatomaceous clays and limited applicability on highly calcareous soils. Using effective overburden pressure as an independent variable, which depends on the total unit weight, seems one of the inherent disadvantage of this model when the direct interpretation is considered.

Predictive performances of most recent correlations; Robertson & Cabal (2010), and Mayne et al. (2010) models were performed for Lake Bonneville clays, and a comparison of calculated values versus measured ones are shown in Figures 1 and 2, respectively.

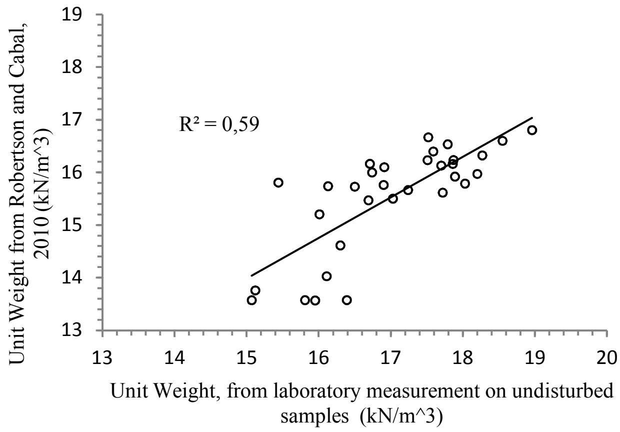

Figure 1. Predictive performance of Robertson & Cabal (2010) model

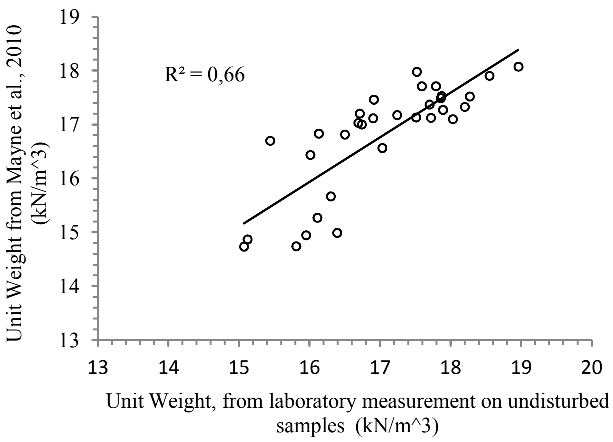

Figure 2. Predictive performance of Mayne et al. (2010) model

As shown from Figures 1 and 2, predictive performances of published correlations showed modest correlation for the soft to medium stiff Lake Bonneville clays. To improve the predictive performance of these correlations additional regression analyses were carried out to find additional factors that might improve the predictive performance.

2.2 *Proposed model*

The independent variables chosen for the multiple linear regression (MLR) model were: q_c, f_s, q_t, net corrected tip resistance, (q_t-σ'_{vo}), and friction ratio, R_f. These variables were used to predict total unit weight by dividing them into nine different models as presented in Table 1. (From an application standpoint, the regression models should not be dependent on the stress units, so all independent variables were divided by atmospheric pressure, P_a, and depended variable was divided by unit weight of water, γ_w, to make the regression variables dimensionless.) All regression analyses shown in Table 1 were performed using Microsoft EXCEL. These models have the general form:

$$y = \beta_o x_1^{\beta_1} x_2^{\beta_2} \quad (1)$$

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

$$log y = log\beta_o + \beta_1 log x_1 + \beta_2 log x_2 \quad (2)$$

A comparison of soil unit weight predicted from Model E (since it gave highest R^2 value) of Table 1 and laboratory results can be seen in Figure 3. 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.

3 REGRESSION MODEL FOR DMT

3.1 *DMT Results*

The average values of I_D, K_D and E_D for the Lake Bonneville clays at the research sites are summarized in Table 2.

Values of P_o and P_1 increase approximately linearly with depth for the upper Lake Bonneville clay, but P_1 did not follow the same trend for the lower Lake Bonneville clay (Ozer et al., 2006). Also in the upper Lake Bonneville clay, the values of P_o and P_1 are very similar. (This might be attributed to very small values of I_D, which is an index of relative spacing between P_o and P_1). The horizontal stress index, K_D, is almost constant both for the upper Lake Bonneville clay with an average value of 3.67 and for the lower Lake Bonneville clay with an average value of 3.05. The dilatometer modulus, E_D, is almost constant for the upper Lake Bonneville clay, except for a silty clay layer at the middle of this zone. Values of E_D increase linearly with depth in the lower Lake Bonneville clay.

Table 1. Data variables sets and linear regression equations for normalized total unit weight

Data Set	Independent Variables	R^2 (%)	Equation (From the model given in Equation 1, and regression output by using Microsoft EXCEL, back transformed linear regression):
A	$\left(q_c/P_a\right)$	77	$\frac{\gamma}{\gamma_w} = 1.274\left(\frac{q_c}{P_a}\right)^{0.156}$
B	$\left(q_t/P_a\right)$	77	$\frac{\gamma}{\gamma_w} = 1.245\left(\frac{q_t}{P_a}\right)^{0.157}$
C	$\left(f_s/P_a\right)$	52	$\frac{\gamma}{\gamma_w} = 1.968\left(\frac{f_s}{P_a}\right)^{0.055}$
D	$\left(R_f\right)$	20	$\frac{\gamma}{\gamma_w} = 1.718\left(R_f\right)^{0.047}$
E	$\left(q_t/P_a\right)$, $\left(R_f\right)$	80	$\frac{\gamma}{\gamma_w} = 1.27\left(\frac{q_t}{P_a}\right)^{0.148}\left(R_f\right)^{0.0144}$
F	$\left(f_s/P_a\right)$, $\left(R_f\right)$	79	$\frac{\gamma}{\gamma_w} = 2.495\left(\frac{f_s}{P_a}\right)^{0.147}\left(R_f\right)^{-0.132}$
G	$\left(\frac{q_t - \sigma'_{vo}}{P_a}\right)$	74	$\frac{\gamma}{\gamma_w} = 1.297\left(\frac{q_t - \sigma'_{vo}}{P_a}\right)^{0.149}$
H	$\left(q_c/P_a\right)$, $\left(f_s/P_a\right)$	78	$\frac{\gamma}{\gamma_w} = 1.369\left(\frac{q_c}{P_a}\right)^{0.132}\left(\frac{f_s}{P_a}\right)^{0.0135}$
I	$\left(q_c/P_a\right)$, $\left(q_t/P_a\right)$, and $\left(R_f\right)$	78	$\frac{\gamma}{\gamma_w} = 5.925\left(\frac{q_c}{P_a}\right)^{-0.192}\left(\frac{f_s}{P_a}\right)^{0.338}\left(R_f\right)^{-0.321}$

Table 2. Summary of DMT Results for Bonneville Clay

DMT Test No. and Location	Average I_D		Average K_D		Average E_D	
	Upper Bonneville	Lower Bonneville	Upper Bonneville	Lower Bonneville	Upper Bonneville	Lower Bonneville
DMT – 1 N. T.	0.468	0.249	3.04	3.03	44.1	31.8
DMT -2 S. T.	0.430	0.330	3.67	3.05	43.7	57.5

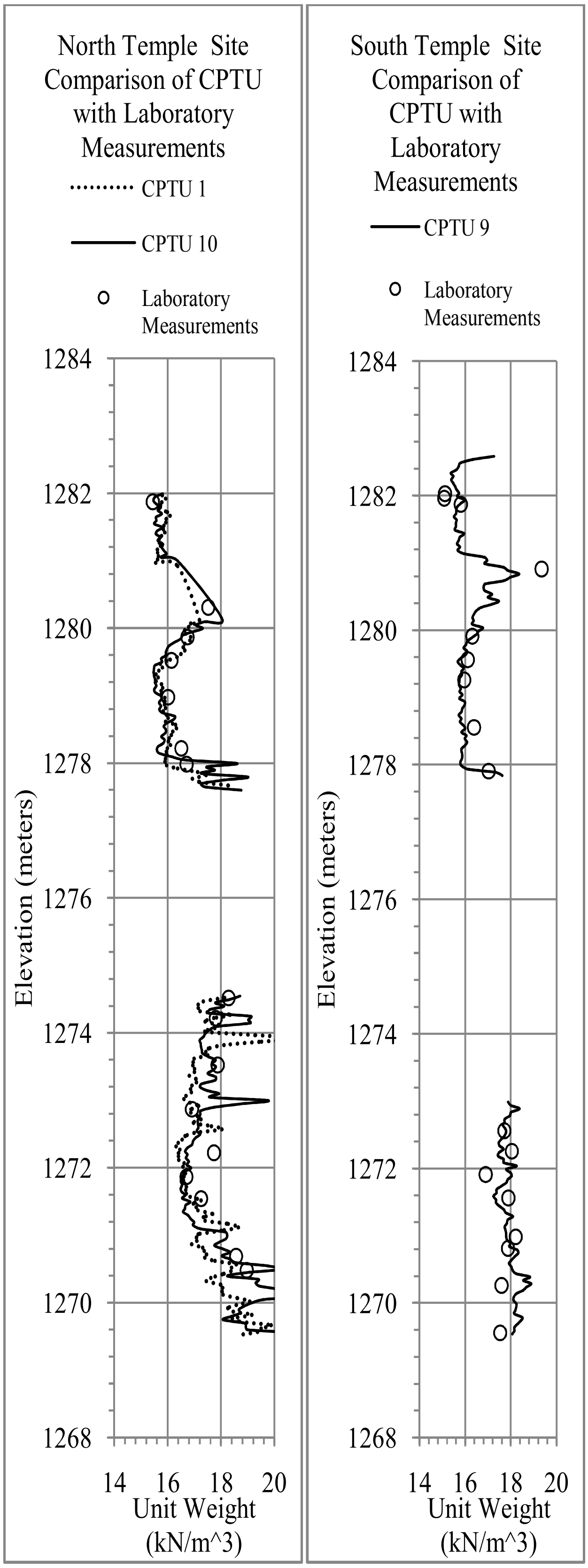

Figure 3. Comparison of unit weight values with Model E of Table 1

3.2 *Existing Model*

Marchetti & Craps (1981) developed a chart for determining soil type and unit weight from DMT material index, I_D, and dilatometer modulus, E_D. Marchetti et al. (2006) indicated that the main scope of this chart is not the accurate estimation of the total unit weight; it generally provides an average value. Unit weight of Bonneville clay determined based on Marchetti & Craps (1981) chart compared with the laboratory measurements (Fig. 4). As shown in Figure 4, predictive performance of Marchetti & Craps (1981) chart showed modest correlation for the soft to medium stiff Lake Bonneville clays. To improve the predictive performance of the chart additional regression analyses were carried out to find additional factors that might improve the predictive performance.

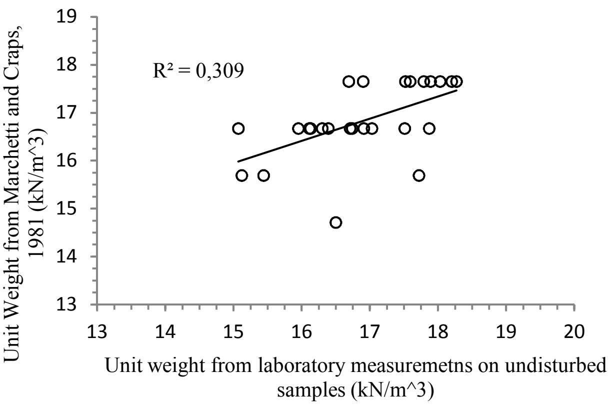

Figure 4. Predictive performance of Marchetti & Craps (1981) chart

3.3 *Proposed Model*

Estimation of the soil unit weight based on direct measurements of DMT has a practical value for post processing the DMT raw data. Soil unit weight is required when calculating horizontal stress index (K_D), from DMT results (Marchetti, 1980). By using K_D, Marchetti (1980) proposed relations to estimate fundamental engineering properties of the soil such as: coefficient of earth pressure at rest (K_o), overconsolidation ratio (OCR), undrained shear strength (s_u), internal friction angle (ϕ), and vertical drained constrained modulus (M). Therefore, reliable estimate of unit weight based on direct DMT measurements without further need for undisturbed sampling can provide reliable post processing.

The independent variables chosen for the multiple linear regressions (MLR) model were: corrected first dilatometer reading, P_o, corrected second dilatometer reading, P_1, and dilatometer modulus, E_D. These variables were used to predict total unit weight by dividing them into four different models as presented in Table 3. (From an application standpoint, the regression models should not be dependent on the stress units, so all independent variables were divided by atmospheric pressure, P_a, and depended variable was divided by unit weight of water, γ_w, to make the regression variables dimensionless.) All regression analyses shown in Table 3 were performed using Microsoft EXCEL. These models have the general form as presented in Equations 1 and 2.

Table 3. Data variables sets and linear regression equations for normalized total unit weight

Data Set	Independent Variables	R^2 (%)	Equation (From the model given in Equation 1, and regression output by using Microsoft EXCEL, back transformed linear regression):
A	(P_1/P_a)	72	$\frac{\gamma}{\gamma_w}=1.31\left(\frac{P_1}{P_a}\right)^{0.161}$
B	(P_o/P_a)	71	$\frac{\gamma}{\gamma_w}=1.35\left(\frac{P_o}{P_a}\right)^{0.159}$
C	(P_1/P_a), (P_0/P_a)	72	$\frac{\gamma}{\gamma_w}=1.32\left(\frac{P_1}{P_a}\right)^{0.091}\left(\frac{P_o}{P_a}\right)^{0,0733}$
D	(E_D/P_a)	16	$\frac{\gamma}{\gamma_w}=1.47\left(\frac{E_D}{P_a}\right)^{0.045}$

As shown in Table 3, predictive performances of the first three models were reasonably close. A comparison of soil unit weight predicted from Model A (since it gave highest R^2 value) of Table 2 and laboratory results can be seen in Figure 4. The lines represent the results of Model A and dots represent the laboratory test results. Model A provides reasonably close prediction of the laboratory results for the Lake Bonneville clays.

4 CONCLUSIONS

MLR analyses showed that the both CPTU and DMT can adequately predict the soil unit weight of the relatively soft, Lake Bonneville clay deposits with CPTU giving slightly higher predictive performance. The use of the MLR equations is recommended for geotechnical evaluations 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.

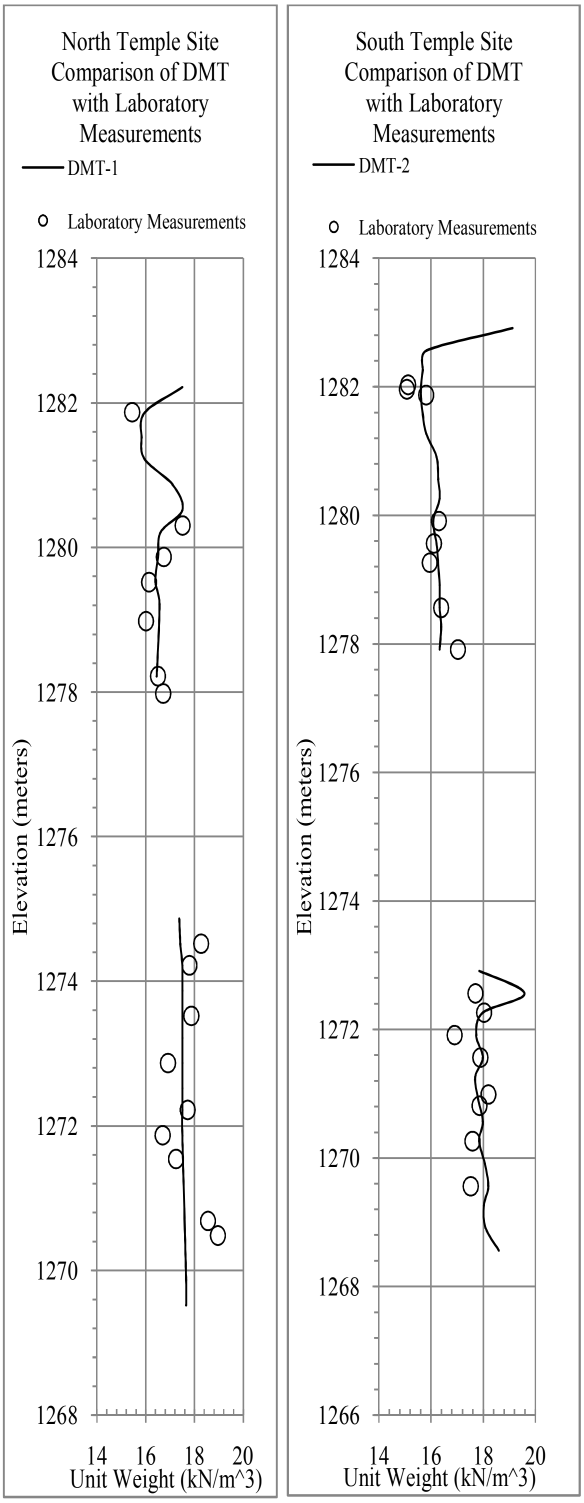

Figure 4. Comparison of unit weight values with Model A of Table 2

However, it may be prudent to perform additional sampling and CPTU and DMT 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, reliable estimate of unit weight based on both CPTU and DMT measurements without further need for undisturbed sampling can provide reliable post processing. 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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