DMT testing for consolidation properties of the Lake Bonneville Clay

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ABSTRACT:

This paper discusses the use of the flat dilatometer test (DMT) to estimate the compressibility of the Lake Bonneville clay in Salt Lake City, Utah. The DMT is evaluated regarding its effectiveness in predicting the virgin compression ratio (CR), 1-D constrained modulus (*M*), preconsolidation stress (σ'_p) and overconsolidation ratio (*OCR*). This is accomplished by correlating DMT parameters with results obtained from high quality sampling and laboratory constant rate strain consolidation (CRS) tests. Multiple linear regression (MLR) analyses were carried out to develop correlations of CR, M, and σ'_p with DMT parameters. This study shows that the DMT can be successfully used to predict consolidation properties for soft, clayey deposits. These findings can significantly reduce the amount and cost of conventional sampling and laboratory testing performed by geotechnical consultants in the Salt Lake Valley for settlement evaluations in the Lake Bonneville clay.

1 INTRODUCTION AND RESEARCH SITES

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. Test procedures are described by Marchetti (1980) and Schmertmann (1986).

The Utah Department of Transportation funded a study to develop in situ methods to predict consolidation properties of the soft to medium stiff clays found in Salt Lake Valley, Utah. The objectives of this research were to correlate high quality CRS laboratory results with DMT results so that the latter can be used in geotechnical evaluations of the Lake Bonneville clay. Evaluation of the effectiveness of the DMT in predicting the virgin compression ratio, CR, and the preconsolidation stress, σ'_p, was accomplished by comparing the field results with CRS laboratory test results.

Undisturbed samples of Lake Bonneville Clay were taken in three locations of the Salt Lake Valley near the I-15 alignment in downtown 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 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 location, the drilling was done in a vacant lot northeast of the northbound structure. For the North Temple Street site, rotary wash drilling was used and for both South Temple Street sites, hollow stem auger drilling methods were used. The CRS tests were performed on high quality undisturbed samples obtained from piston samples and Shelby tube samples were used for soil classification and determination of index properties purposes. The overlying and underlying Holocene and Pleistocene alluvium, respectively, were not sampled. These units are more granular and not as compressible.

The surficial Holocene alluvium at the research sites consists of about 5 m of interbedded clay, silt, and sand and was not part of the scope of this study. The alluvium is underlain by about 15 m of lacustrine Lake Bonneville deposits. This Pleistocene sequence consists of interbedded clayey silt and silty clay, with thin beds of silt and fine sand found near the middle of the sequence. These interbedded sediments divide the clay into the upper Lake Bonneville clay and the lower Lake Bonneville clay (Figure 1). The upper Lake Bonneville clay is more plastic than

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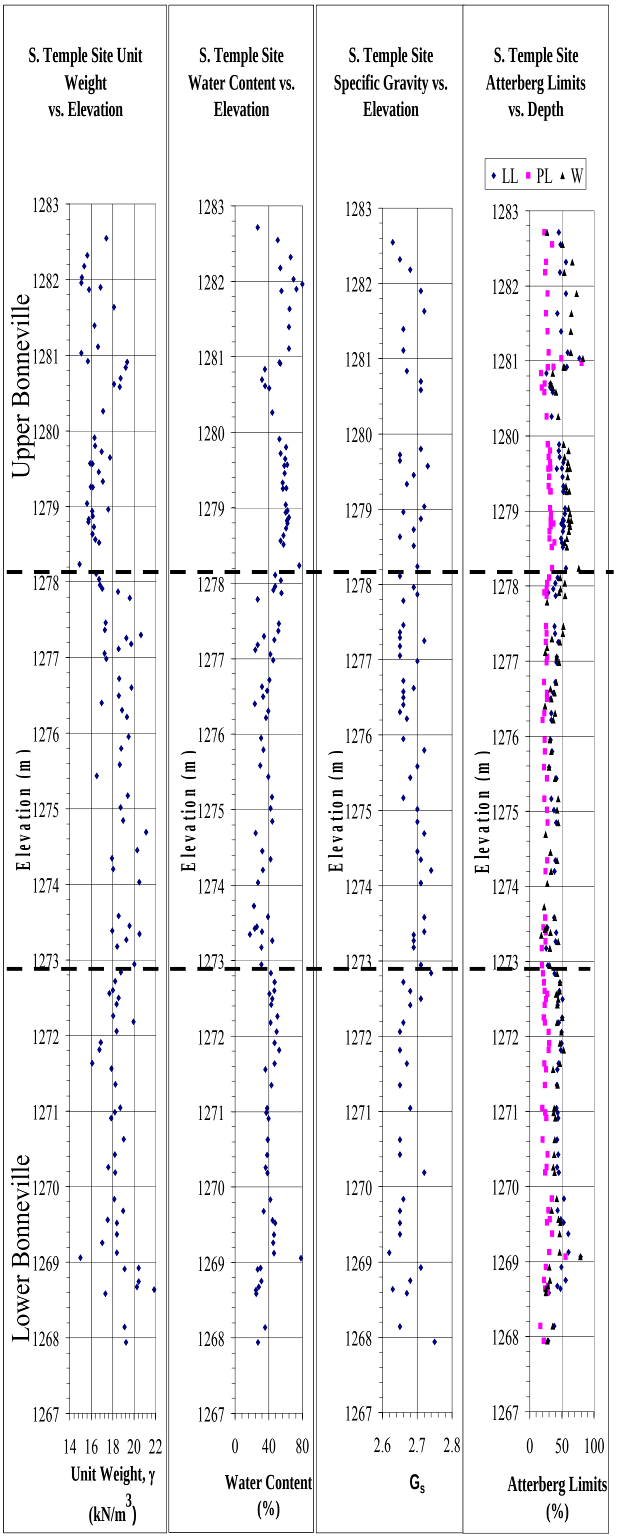

Figure 1. Physical Properties of Lake Bonneville Clay at South Temple Street Research Site

the lower clay and consists of MH, CL, and ML soils. The interbeds represent sediments that were deposited when the lake levels were lower and therefore have more granular soils representing near-shoreline conditions. The interbeds are predominantly silts (ML), with beds of clay (CL) and thin layers of medium dense sand (SC). The lower Lake Bonneville clay is found beneath these interbeds and is mainly CL soils with some silt (ML) layers.

2 DMT RESULTS

The average values of I_D, K_D and E_D for the Lake Bonneville clays at the three different research sites are summarized in Table 1.

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. 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. Values of I_D ranged from 0.22 to 0.4 for this zone). 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.

3 OCR AND σ'_p CORRELATIONS

A comparison of the calculated values of OCR and preconsolidation stress using Marchetti's method and from the CRS consolidation tests showed that Marchetti's method underestimates values of OCR and σ'_p compared to most of the CRS consolidation tests for the North and South Temple Street sites. However, calculated values of OCR and σ'_p from the DMT at the South Temple Street embankment site were close to those calculated from the CRS consolidation tests. The empirical equation for OCR provided by Marchetti (1980) is given in Equation (1).

$$OCR = (0.5K_D)^{1.56} \text{ for } 0.2 \langle I_D \langle 2 \qquad (1)$$

From Equation (1), Marchetti (1980) proposed a functional form to determine the OCR that includes K_D. However, when values of K_D from the DMT were correlated with laboratory determined values of

Table 1. 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
DMT – 3 S. T. Embankment	0.434	---	1.85	---	110	---

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OCR and σ'_p in this study, only modest correlation found. Regression relations correlating OCR and σ'_p with K_D had relatively low R^2 values of 0.458 and 0.526 respectively. To improve the predictive performance of Equation (1), additional regression analyses were carried out to find additional factors that might improve is predictive performance.

In Figure 2, the preconsolidation stress is correlated to the difference between dilatometer contact stress and hydrostatic pore water pressure, $(P_o - u_o)$, and the difference between dilatometer expansion stress and the hydrostatic pore water pressure, $(P_1 - u_o)$. These independent variables are measured by the dilatometer test (DMT) and are related to the total overburden stress, σ_{vo}:

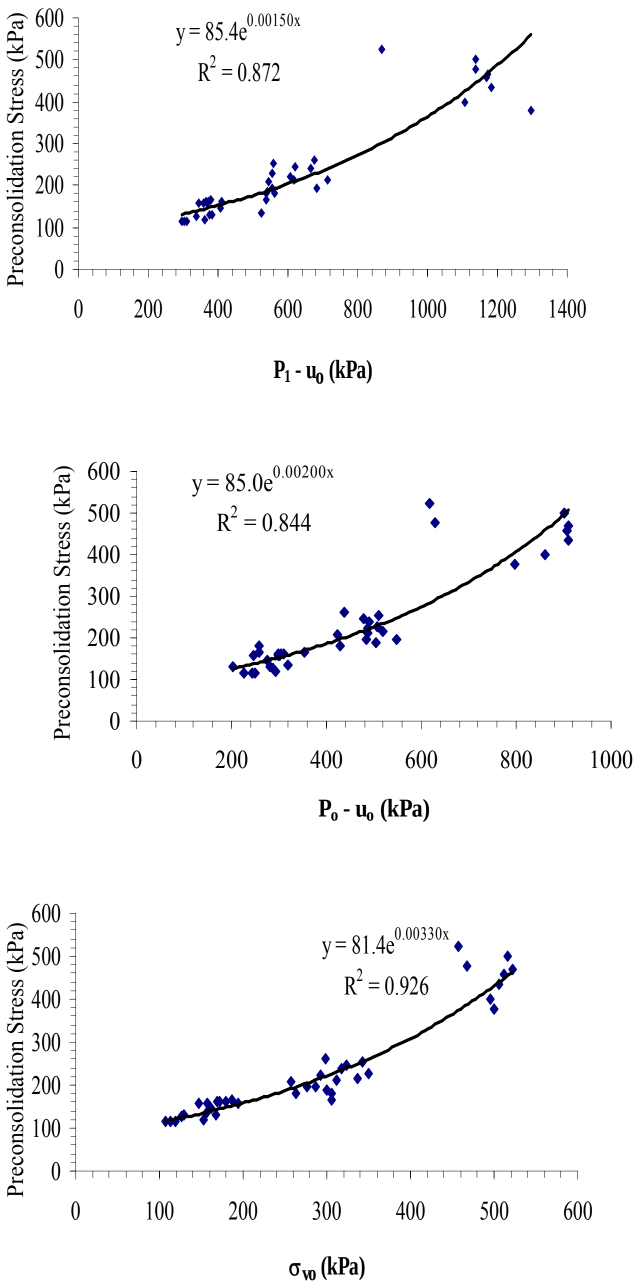

Figure 2. DMT Correlations, Dilatometer $(P_1 - u_o)$ vs. Laboratory Determined σ'_p, Dilatometer $(P_o - u_o)$ vs. Laboratory Determined σ'_p, and Total overburden stress, σ_v vs. σ'_p

$$\cap = \phi[(P_o - u_o),(P_1 - u_o),\sigma_{vo}; B_{P_o - u_u}, B_{P_1 - u_o}, B_{\sigma_{vo}}] \quad (2)$$

where:

$\cap$, is the true response, $B_{P_o - u_u}, B_{P_1 - u_o}$ and $B_{\sigma_{vo}}$ are unknown regression parameters corresponding to $(P_o - u_o),(P_1 - u_o)$, and σ_{vo}.

As can be seen in Figure 2 the simple linear regression models given in Equation 2 have better R^2 values than Equation (1) for the preconsolidation stress of the Lake Bonneville clay. Thus, a MLR model was set up for σ'_p by dividing those factors correlated with σ'_p into seven different models, which are summarized in Table 2. For an application standpoint, it is preferable that a regression model not be dependent on the stress units, so all variables were divided by atmospheric pressure, P_a (1 P_a = 101.325 kPa = 1.01325 Bar), to make the variables dimensionless.

Table 2. Data Variables Sets for Preconsolidation Stress

Data Set	Independent Variables	R^2 (%)
A	$\left(\frac{P_1 - u_o}{P_a}\right)$	88.0
B	$\left(\frac{P_o - u_o}{P_a}\right)$	83.6
C	$\left(\frac{\sigma_{vo}}{P_a}\right)$	85.9
D	$\left(\frac{P_1 - u_o}{P_a}\right)$, $\left(\frac{P_o - u_o}{P_a}\right)$	89.0
E	$\left(\frac{P_1 - u_o}{P_a}\right),\left(\frac{\sigma_{vo}}{P_a}\right)$	89.2
F	$\left(\frac{P_o - u_o}{P_a}\right),\left(\frac{\sigma_{vo}}{P_a}\right)$	88.6
G	$\left(\frac{P_1 - u_o}{P_a}\right)$, $\left(\frac{P_o - u_o}{P_a}\right),\left(\frac{\sigma_{vo}}{P_a}\right)$	87.2

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It was observed that model E, which has gave the highest R^2 value. This model has the general form:

$$y = \beta_o x_1^{\beta_1} x_2^{\beta_2} \quad (3)$$

Equation (3), can be expressed in a linear form for multiple regression using:

$$\log y = \log \beta_o + \beta_1 \log x_1 + \beta_2 \log x_2 \quad (4)$$

From the above model and the regression output by using Microsoft EXCEL, the linear regression can be back transformed to:

$$\frac{\sigma'_p}{P_a} = 0.528\left(\frac{P_1 - u_o}{P_a}\right)^{0.609}\left(\frac{\sigma_{vo}}{P_a}\right)^{0.352} \quad (5)$$

From an application standpoint all of the models shown in Table 2 appear to be adequate for use. Based on R^2, Equation (5) has the best correlation, but is only slightly better than the other models attempted. Also, a strong correlation between the preconsolidation stress and the total overburden stress was found. This correlation was even better than the correlation between preconsolidation stress and the effective vertical stress, which was somewhat surprising and may represent a peculiarity of this particular data set.

Regression models were also attempted using the total overburden stress instead of 1 atmospheric pressure in the denominator of Equation (5). The model has the form:

$$\log\left(\frac{\sigma'_p}{\sigma_{vo}}\right) = \log \beta_o + \beta_1 \log\left(\frac{P_1 - u_o}{\sigma_{vo}}\right) \quad (6)$$

The R^2 value of the regression analysis of Equation (6) was only 5.57 % which is considerably lower than 89.2 % for Equation (5). Thus this model was not further considered. The model given in Equation (5) is recommended as the best model to predict preconsolidation stress for the Lake Bonneville clay.

A comparison of the preconsolidation stress predicted from Equation (5) with that of Equation (1) and the laboratory CRS test results can be seen in Figure 3. Equation (5) shows a better prediction of the laboratory values than Marchetti's (1980) model for the Lake Bonneville clay. Thus, Equation (5) is recommended for these deposits.

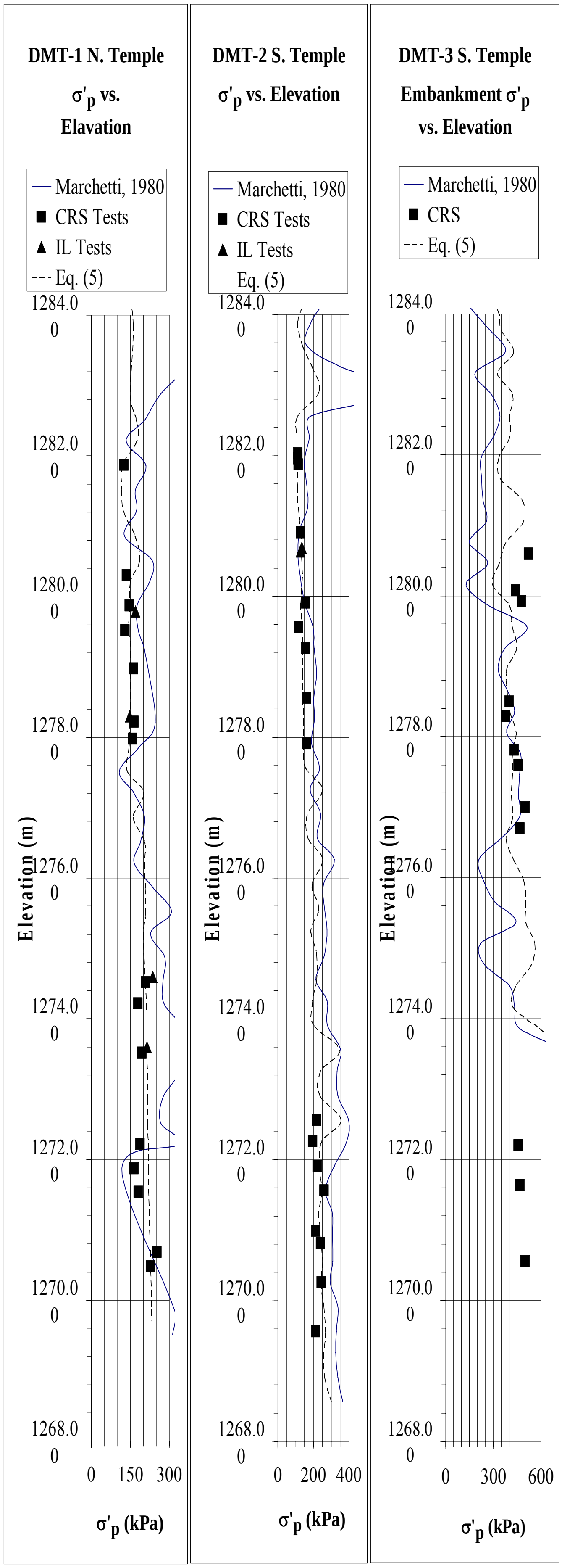

Figure 3. Comparison of Preconsolidation Stress

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

The constrained modulus, M, defined by Marchetti (1980) for the DMT is given in following Equations 7 a, b, c, d, e, and f. From this, Equation (8) can be used to calculate the compression ratio, CR, for virgin compression. Comparison of calculated CR values from DMT results, using the method proposed by Marchetti (1980), with the laboratory CR values is provided in Figure 4. It is obvious that Marchetti's model considerably underestimates CR values for the Lake Bonneville clay.

$$M = R_M E_D \qquad (7)$$

where:

$$\text{If } I_D < 0.6 \quad R_M = 0.14 + 2.36 \log K_D \qquad (7.a)$$

$$\text{If } I_D > 3.0 \quad R_M = 0.5 + 2 \log K_D \qquad (7.b)$$

$$0.6 < I_D < 3.0 \quad R_M = R_{M,o} + \left(2.5 - R_{M,o}\right) \log K_D \qquad (7.c)$$

$$R_{M,o} = 0.14 + 0.15\left(I_D - 0.6\right) \qquad (7.d)$$

$$\text{If } K_D > 10 \quad R_M = 0.32 + 2.18 \log K_D \qquad (7.e)$$

$$\text{Always } R_M > 0.85 \qquad (7.f)$$

$$M = \sigma'_p \left(\frac{1+e_o}{C_c}\right) \ln 10 = \sigma'_p \frac{2.3}{CR} \qquad (8)$$

and CR for normally consolidated clays can be estimated from:

$$M = \sigma'_v \left(\frac{1+e_o}{C_c}\right) \ln 10 = \sigma'_v \frac{2.3}{CR} \qquad (9)$$

According to Equations (7), Marchetti proposed a model to determine CR from K_D. The dilatometer K_D results plotted against laboratory determined CR values are shown in Figure 5. As can be seen in this figure, the correlation between laboratory CR values and K_D values is very low (R^2=5.29 %). This result also explains why Marchetti's model does not agree very well with the laboratory determined CR values, as shown in Figure 4.

Additional regression analyses were performed to improve this predictive performance. Laboratory determined CR values were correlated with $(P_0 - u_o),(P_1 - u_o)$ and σ_{vo}. With these newly included variables, the R^2 values improved, but they are still relatively low (i.e., about 20 %).

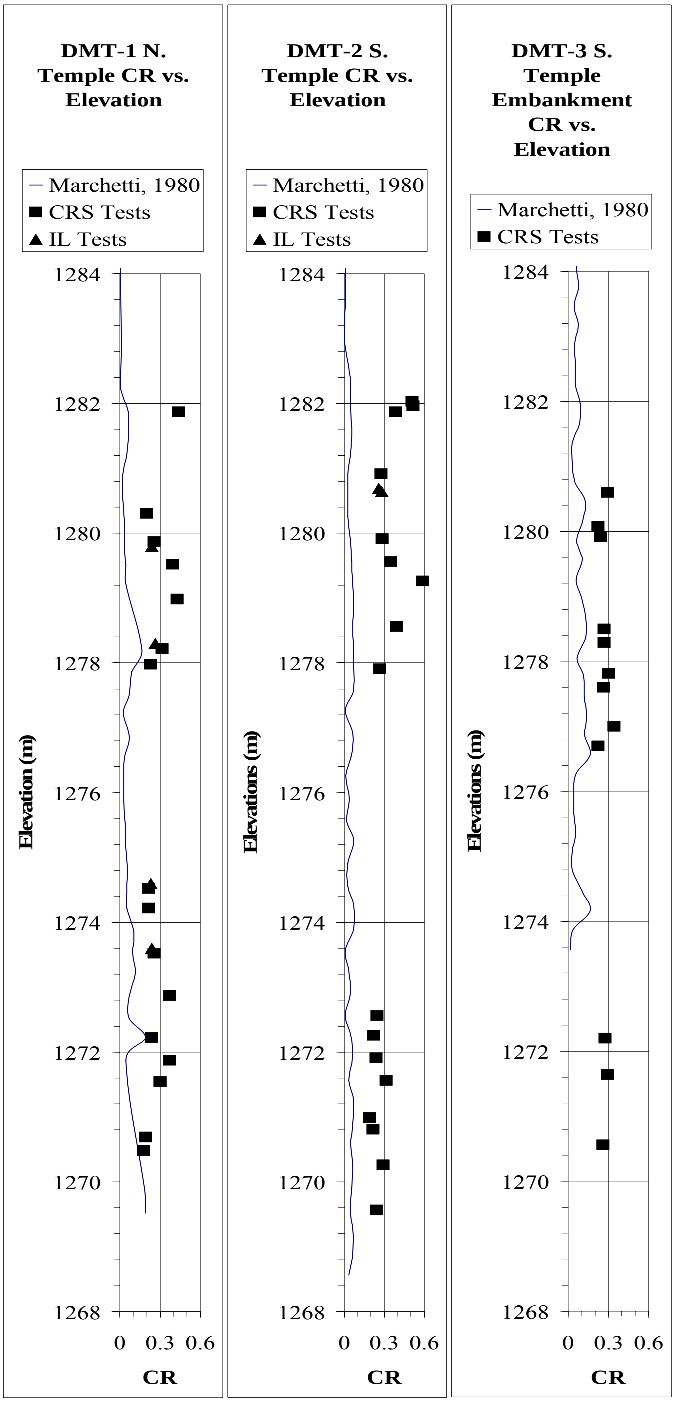

Figure 4. Comparison of laboratory CR values with values determined using Marchetti's (1980) Method

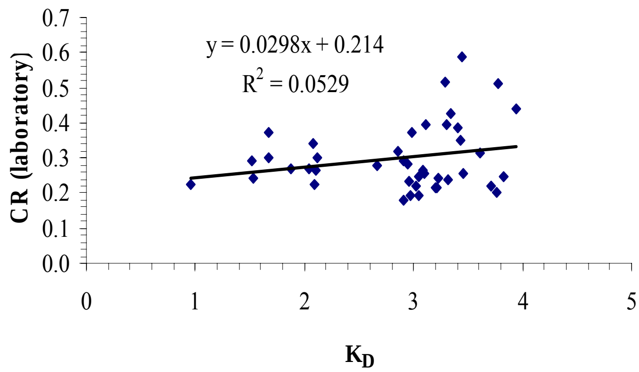

Figure 5. K_D vs. CR

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As given in Equations (8) and (9), one can also back-calculate CR values from the 1D constrained modulus, M, for virgin compression. Because very low R^2 values were obtained for the CR correlations, it was decided to investigate possible correlations between the DMT and laboratory determined M values. As seen in Figure 6, laboratory determined M values plotted against values of $(P_0 - u_o)$, $(P_1 - u_o)$, and σ_{vo} produced significantly better correlation. The R^2 values improved to about 77 to 84 %.

As was done for the preconsolidation stress in the previous section, independent variables were divided into seven different models and regression analyses were conducted. Potential MLR models for M are given in Table 3.

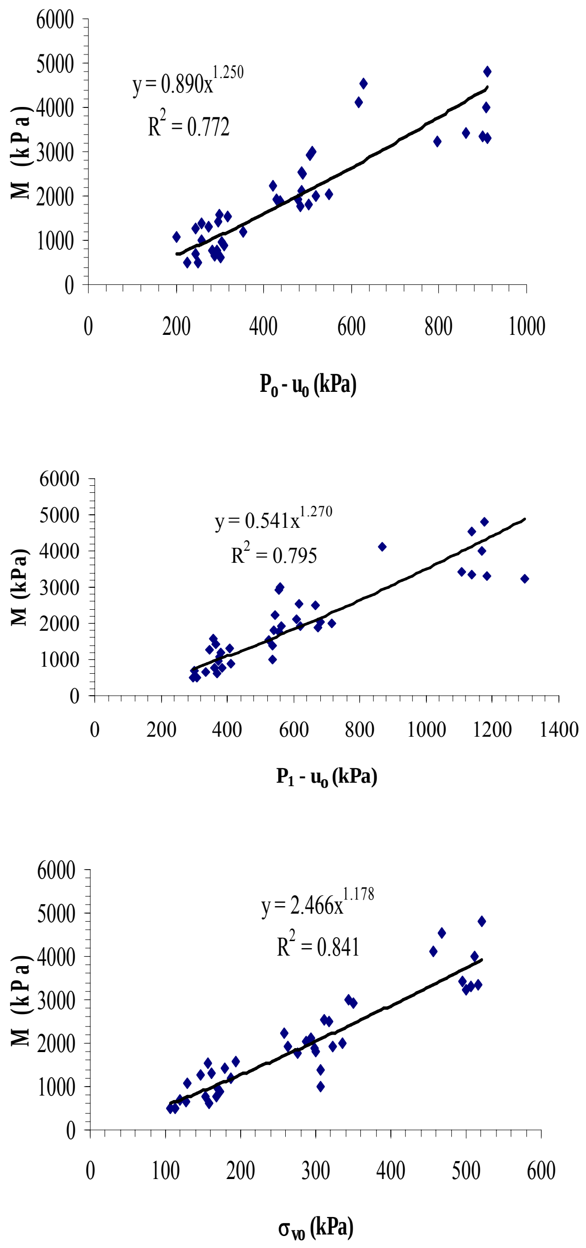

Figure 6. DMT Correlations, Dilatometer $(P_o - u_o)$ vs. Laboratory Determined M, Dilatometer $(P_1 - u_o)$ vs. Laboratory Determined M, and Total Overburden Stress vs. M

Table 3 Data Variables Sets for 1D Constrained Modulus, M

Data Set	Independent Variables	R^2 (%)
A	$\left(\frac{P_1 - u_o}{P_a}\right)$	78.9
B	$\left(\frac{P_o - u_o}{P_a}\right)$	76.6
C	$\left(\frac{\sigma_{vo}}{P_a}\right)$	83.7
D	$\left(\frac{P_1 - u_o}{P_a}\right), \left(\frac{P_o - u_o}{P_a}\right)$	80.2
E	$\left(\frac{P_1 - u_o}{P_a}\right), \left(\frac{\sigma_{vo}}{P_a}\right)$	83.8
F	$\left(\frac{P_o - u_o}{P_a}\right), \left(\frac{\sigma_{vo}}{P_a}\right)$	84.3
G	$\left(\frac{P_1 - u_o}{P_a}\right), \left(\frac{P_o - u_o}{P_a}\right), \left(\frac{\sigma_{vo}}{P_a}\right)$	83.9

Model F produced the highest R^2 value. However, from the analysis of variance (ANOVA) table of model F, it was observed that first independent variable is not significantly contributing to the model (P-value is 11.4 %). The same problem was encountered in models D, E and G. The second independent variable in models D and E was also not significantly contributing to the model, as judged from the ANOVA table, at the 95 percent confidence level. The first two independent variables in model G have also had high P-value of 75.5 and 23.9 %, respectively, which means that these variables are not statistically contributing the models. However, this does not mean that these variables are not correlated with M, it just suggests that this is cross-correlation between the independent variables in a multi variable model.

From a statistical standpoint, Model C, which has the total overburden pressure as an independent variable, is the best one variable model. Thus, for Lake Bonneville clay, M is highly correlated with the total overburden pressure. Correlations were also tried with M and effective vertical stress, but these

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had poorer predictive performance for this particular data set.

It should be noted that the constrained modulus, M, is the modulus calculated at the preconsolidation stress (Equation 8). CRS Laboratory tests indicated that OCR values at the research sites have relatively constant behavior over depth. In other words, since the total overburden stress increases with depth, the preconsolidation stress also increases proportion to the total overburden stress. Since the constrained modulus is the modulus at the preconsolidation stress level, it should produce a relatively high correlation. Model C has the general form:

$$y = \beta_o x_1^{\beta_1} \tag{10}$$

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

$$\log y = \log \beta_o + \beta_1 \log x_1 \tag{11}$$

From the above equation and the MLR output, the linear model back was transformed to:

$$\frac{M}{P_a} = 5.61\left(\frac{\sigma_{vo}}{P_a}\right)^{1.18} \tag{12}$$

However, Equation (12) does not use any DMT parameters, which it not as desirable from an application standpoint. As an alternative to Equation (12), model A from Table 3, was analyzed to develop a relationship between M and DMT parameters. In short, it was found that model A is almost as good as model C from a statistical standpoint and the analysis of variance suggested that the independent variables of both model A and C are also highly correlated with each other. In other words, model A can be used to predict M as well as the total overburden stress, because of the cross-correlation.

Model A has the same general form as model C and is back transformed to:

$$\frac{M}{P_a} = 1.89\left(\frac{P_1 - u_o}{P_a}\right)^{1.27} \tag{13}$$

Ultimately, one can also back-calculate CR values from M using the definition of M from Equation (8):

$$CR_{DMT} = \frac{2.3\sigma'_p}{M\left(from\ Eq.\ 13\right)} \tag{14}$$

Comparison of M from Equations (12) and (13) and the back-calculated CR from Equation (14) with the CRS laboratory results is shown in Figures 7 and 8, respectively.

As can be seen in these figures, calculated values of M from Equations (12) and (13) and back-calculated CR values from Equation (14) closely approximate the laboratory values.

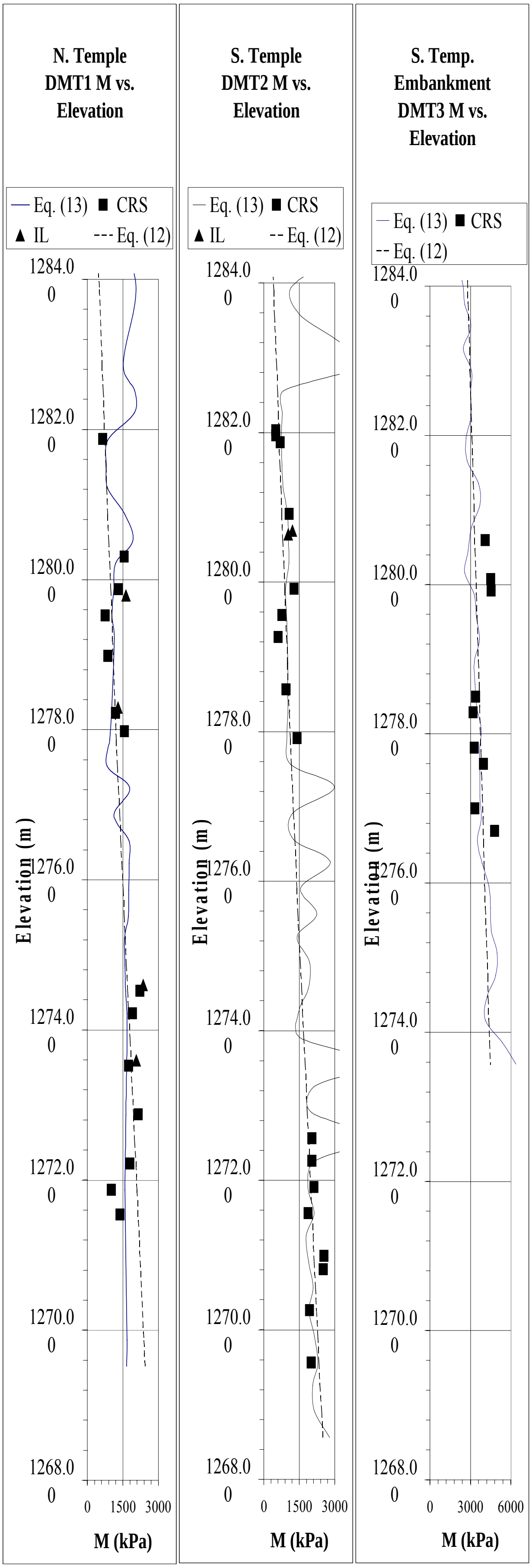

Figure 7. Comparison of constrained modulus

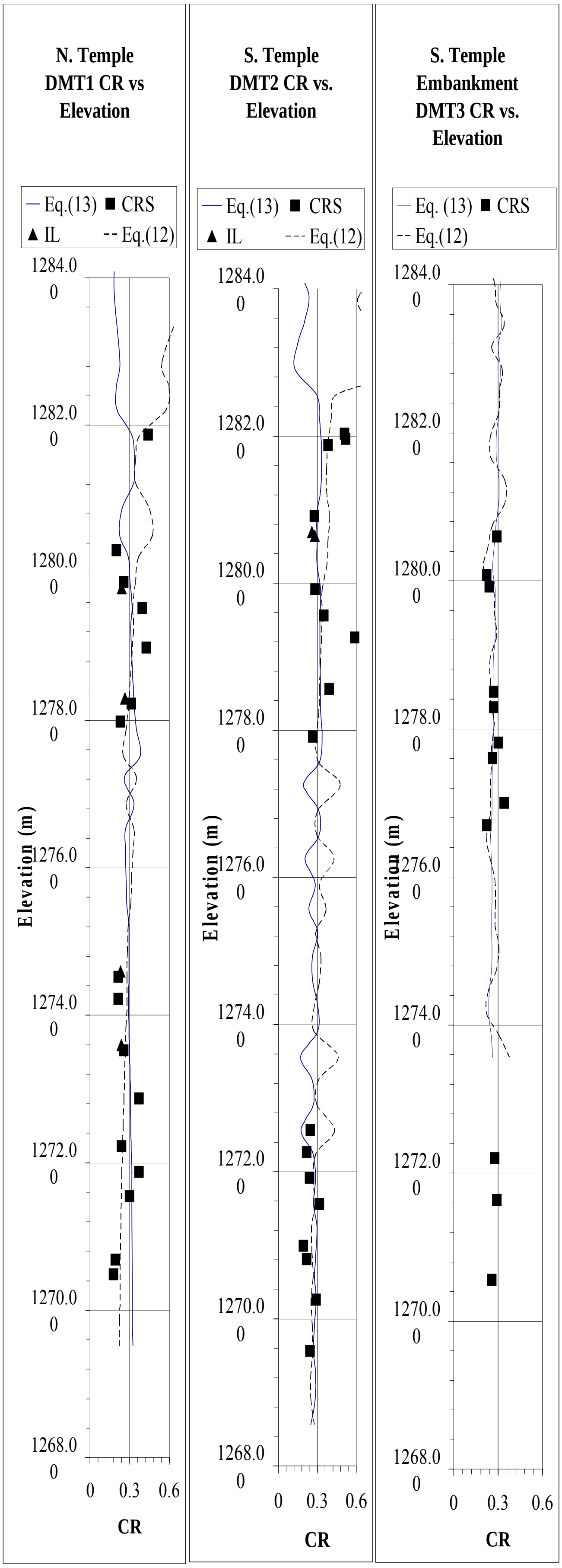

Figure 8. Comparison of compression ratio

5 CONCLUSIONS

The use of the above equations is recommended for geotechnical evaluations for locations underlain by the silty clay and clayey silt sediments of Lake Bonneville. 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 in some cases, to perform a limited sampling and laboratory-test program to verify the performance of our models for other Utah locales outside of Salt Lake Valley. Using this approach, we anticipate that the scope of geotechnical laboratory testing can be significantly reduced for many UDOT projects. The reliability of these models from predicting behavior of clay deposits of other origins and locations is unknown, and should be further researched.

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