Estimation of four-day soaked CBR using index properties

K Jayamali
University of Moratuwa, Geotech (Pvt) Ltd

Udeni P. Nawagamuwa
University of Moratuwa, University of Wollongong, udeni@uow.edu.au

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Estimation of four-day soaked CBR using index properties

Abstract

California Bearing Ratio (CBR) is an important parameter used to evaluate the strength of subgrade and sub-base soils for design of flexible pavements and hence it plays a significant role in road and highway constructions. Obtaining CBR is heavily time consuming and it is difficult to acquire a representative CBR value. Therefore, many correlations have been developed by various researchers worldwide to predict the CBR. Due to differences in soil formations in the tropical environment, these existing global correlations found to be not satisfactory with local soils in Sri Lanka. Hence, this study was carried out to develop empirical correlations between CBR and index properties those best suit for local soils, using the data obtained from Atterberg limits and sieve analysis tests together with compaction tests. The new correlations were established using the method of regression analysis in the form of empirical equations representing the role of index properties. Robust regression by the method of least absolute residuals using MATLAB was considered in the analysis to reduce the impact of outliers along with traditional multiple regression using Microsoft Excel. As a final verification, several laboratory tests were conducted to compare the results with proposed regression equations.

Disciplines

Engineering | Science and Technology Studies

Publication Details

ESTIMATION OF FOUR-DAY SOAKED CBR USING INDEX PROPERTIES

K.V.S. Disna Jayamali[1,2], Udeni P. Nawagamuwa[1,3] and Buddhima Indraratna[3]

[1]Department of Civil Engineering, University of Moratuwa, Sri Lanka
[2]Geotech (Pvt) Ltd., Nugegoda, Sri Lanka
[3]Centre for Geomechanics and Railway Engineering, University of Wollongong, Australia

ABSTRACT

California Bearing Ratio (CBR) is an important parameter used to evaluate the strength of subgrade and sub-base soils for design of flexible pavements and hence it plays a significant role in road and highway constructions. Obtaining CBR is heavily time consuming and it is difficult to acquire a representative CBR value. Therefore, many correlations have been developed by various researchers worldwide to predict the CBR. Due to differences in soil formations in the tropical environment, these existing global correlations found to be not satisfactory with local soils in Sri Lanka. Hence, this study was carried out to develop empirical correlations between CBR and index properties those best suit for local soils, using the data obtained from Atterberg limits and sieve analysis tests together with compaction tests. The new correlations were established using the method of regression analysis in the form of empirical equations representing the role of index properties. Robust regression by the method of least absolute residuals using MATLAB was considered in the analysis to reduce the impact of outliers along with traditional multiple regression using Microsoft Excel. As a final verification, several laboratory tests were conducted to compare the results with proposed regression equations.

1 INTRODUCTION

Large scale road and highway constructions are taking place throughout Sri Lanka for developing infrastructure facilities. Almost the entire Sri Lankan road network consists of flexible unbound pavements. In many parts of the world, California Bearing Ratio (CBR) is one of the important parameters used for the design of highway, airport, parking lot and other pavement designs besides other uses of the CBR, for example, for backfill specifications. For pavement design purposes, the resilient stiffness of compacted cohesive subgrade soils are commonly characterized by the CBR (Brown et al, 1990). Cocks et al (2015) summarized the use of natural base course materials such as lateritic gravel for the application of soaked and unsoaked CBR values in the design of pavements for heavy and low traffic conditions. Considering the observations of upward hydraulic gradient in the groundwater at the Guildford formation in Perth, Australia, Hillman et al (2003) recommended the adoption of soaked conditions for the evaluation of subgrade CBR.

Many pavement design specifications require CBR sampling to be undertaken at close intervals, e.g. every 100 m sampling is not uncommon. Though the procedure for evaluating the CBR is relatively simple, it is often time consuming and impractical at the planning and the concept stages of a project, given the highly variable sources of materials considered in typical earthworks and infrastructure project undertakings. Therefore, for preliminary design, alternative tools for predicting the CBR value can be considered prudent and of paramount benefit in a practical point of view. One of the methods to overcome this situation is by developing a correlation between CBR values with the index properties of the soils. There are several correlations to predict the CBR using different index properties that have been published by different researchers since 1960s. Rallings (2014) highlighted the reproducibility and repeatability of the laboratory CBR emphasizing the CBR's special place within pavement technology. However, it is important to verify the applicability of these published correlations developed elsewhere for the local soil deposits in Sri Lanka due to the obvious implications of empiricism captured in their developments. Therefore, an attempt has been made in this study to correlate the CBR with soil index properties, as an expedient alternative for predicting CBR.

The aim of the present study is to generate correlations which could describe the relationships among soil index properties, compaction parameters and the California Bearing Ratio (CBR) of Sri Lankan soils used in sub-base and sub-grade layers in pavement systems, as an attempt to reduce the amount of CBR testing typically conducted or recommended in industry. CIDA (2009) recommends the limiting requirement of CBR for the construction of road embankments, subgrades and sub-bases based on soils compacted using the modified compaction effort. Similar conditions have been proposed by Austroads (2004, 2015) for various working platforms, specially the use of 4 day soaked CBR condition for environments with median annual rainfall between 600-800mm. This study considers only the soils compacted to maximum dry density (D_M) and the corresponding optimum moisture content (M_e) using modified compaction effort.

Although number of correlations found in literature have defined the relationships with CBR and several soil parameters, only the relationships with the parameters obtained from typical index tests (i.e. Atterberg limits carried out according to BS 1377:Part 2 and Grain Size Analysis excluding the Hydrometer Analysis carried out according to ASTM D 422) were

considered in this study. Having conducted a comprehensive literature review on already published correlations, a summary of some selected relationships is presented in Table 1. For the sieve analysis parameters in Table 1, P denotes % passing and R denotes % retaining through/on particular sieve sizes in micron meters.

Table 1: Some of the correlations found in literature between CBR and index properties

Author/s	Proposed correlations
de Graft – Johnson and Bhatia (1969)	$CBR = 35 \ (R_{2600}/(\ W_L \ Log \ I_P)) - 8$
Agarwal and Ghanekar (1970)	$CBR = 2 - 16 \ log \ M_0 + 0.07 \ W_L$
Ayodele et al (2009)	$CBR = -0.0004(P_{075})^3 + 0.0759 \ (P_{075})^2 - 4.6629 \ (P_{075}) + 97.4206$
Haupt (1980)	$CBR = 97.7 - 17.1 log \ [I_P \ (P_{425})^{0.5}] - 30.7 \ log(P_{075})$
	$CBR = 119.6 - 33 \ log \ [W_L^{0.7}(P_{425})^{0.3}] - 33.2 \ log(P_{075})$
	$CBR = 90 - 47.4 \ log \ (P_{075})$
NCHRP (2001)	$CBR = 28.09 \ (D_{60})0.358$
	$CBR = 75/(1 + 0.728 \times I_P \times P_{075})$
Patel and Desai (2010)	$CBR = 43.907 - 0.093(I_P) - 18.78 \ D_M - 0.3081 M_0$
Roy et al (2009)	$Log \ (CBR) = Log \ (D_M / \gamma_w) - Log \ M_0$
Breytenbach (2009)	$Log \ CBR = -0.0068 \ (W_L + W_P + P_{075}) + 2.10$
Sood et al. (1978)	$CBR = 50.05 - 0.35(R_{2360}) - 1.11(P_{075}) + 0.25(I_P)$
Vinod and Cletus (2008)	$CBR = - 0.889 \ (W_L \ (1 - R_{425}/100)) + 45.616$
Agrawal et al (2011)	$CBR = -1.3407 M_0 + 28.623$
	$CBR = 38.38 D_M - 61.95$
	$CBR = 0.022 \ W_L + 7.025$
	$CBR = 0.108 \ W_P + 5.085$
	$CBR = -0.044 \ I_P + 8.274$
	$CBR = 0.26 \ M_0 + 42.55 \ D_M - 73.62$
	$CBR = 0.24 \ M_0 + 49.79 \ D_M + 0.33 \ W_L - 97.94$
	$CBR = 0.62 \ M_0 + 58.9 \ D_M + 0.11 \ W_L + 0.53 \ W_P - 126.18$
	$CBR = 0.63 \ M_0 + 59.1 \ D_M - 40.94 \ W_L + 41.59 \ W_P + 41.05 \ I_P - 126.76$
	$CBR = 0.18 \ M_0 + 42.13 \ D_M + 0.11 \ I_P - 72.69$

Lloyd (2014) reanalyzed a method for estimating CBR based on particle size distribution and linear shrinkage which is not a very common index test in Sri Lankan construction industry and hence, it is not compared in this study. McGough (2010) proposed a graphical method based on laboratory data with a fine material factor (FMF) of the soil which is the product of the raw plasticity index and the proportion of the soil passing the 0.425mm sieve.

2 METHODOLOGY

This study covers only soils compacted to Maximum Dry Density at Optimum Moisture Content obtained according to ASTM D 1557 using modified effort in predicting CBR values provided in ASTM D 1883. The data on CBR value and its physical properties of soil were collected from a number of Sri Lankan projects to compare with the published correlations and to develop new regression based models. Data sets of 255 soil samples were considered for this study. From the collected data, several parameters including CBR(%), $D_M(Mg/m^3)$, $M_0(\%)$, liquid limit ($W_L \ \%$), plastic limit ($W_P \ \%$), plasticity index ($I_P \ \%$), % of gravel, % of sand, % passing 75µm, 425µm, 2360µm (screens referred to as P_{075}, P_{425} and P_{2360}) and particle size (in mm) corresponding to 60%, 50%, 30% and 10% finer in the grain size distribution respectively denoted as D_{60}, D_{50}, D_{30} and D_{10} were included into the database.

Having plotted the scattered CBR values and omitted the outliers, filtered data of CBR below 50% were considered for further analysis. As the initial step, filtered data (243 Nos.) were basically categorized as coarse grained and fine-grained soils based on the fines content (i.e. % passing 75µm sieve). Accordingly, there were only 4 sets of data available in the

category of fine grained soils, hence they were too omitted in further analysis due to lack of representation. Thereafter, coarse grained soils only were further categorized into the different soil groups based on Unified Soil Classification System (USCS) according to ASTM D 2487 as illustrated in Figure 1.
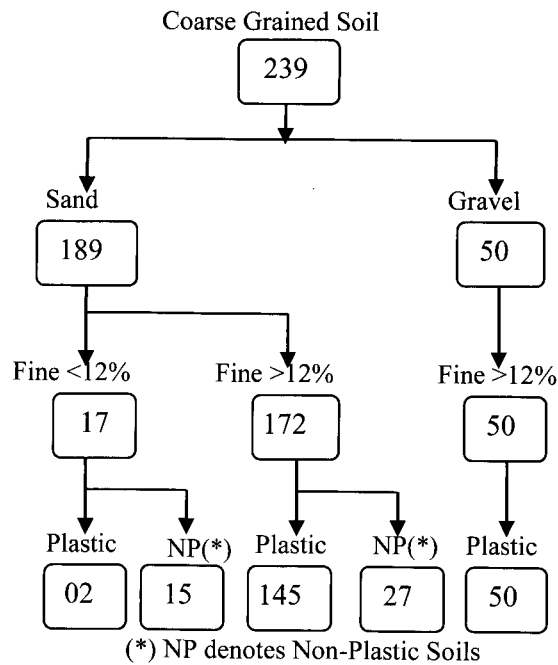
Coarse Grained Soil

239

Sand   Gravel

189   50

Fine <12%   Fine >12%   Fine >12%

17   172   50

Plastic   NP(*)   Plastic   NP(*)   Plastic

02   15   145   27   50

(*) NP denotes Non-Plastic Soils

Figure 1:   Hierarchical chart of data grouping for coarse grained soils based on USCS

Each group of the above soil groups were not considered in detail due to the lack of availability of data. The detailed analysis and comparisons were carried out only for the three group of soil categories identified as;

- Non-plastic sandy soils which contain fines content less than 12%, (i.e. soil having symbols of SP, SW, SW-SM and SP-SM according to USCS);
- Plastic and non-plastic sandy soils which contain fines content greater than 12%   (i.e. soil having symbols of SM, SC and SC-SM according to USCS); and
- Plastic gravelly soils which contain fines content greater than 12% (i.e. soil having symbols of GM,GC and GC-GM according to USCS);

The consideration was first given to the determination of relationships between CBR and individual soil parameters for each soil group identified above. This was executed by Microsoft Excel and MATLAB graphical representation methods using scatter plots. The regression types for each plot were determined according to the trend line option which gives the maximum coefficient of determination, R^2. Thereafter, several analyses were performed to evaluate the applicability of existing published correlations using local soil data by single and multiple linear regression analysis. The evaluation was differentiated based on the broad groups of soils, i.e. coarse-grained and fine-grained. However, due to the limitation in the availability of data, some of the published correlations had to be omitted in the scope of this study.

Multiple regression analysis was initially carried out using Microsoft Excel Regression method with least square estimate according to Miles and Shevlin (2001), assuming that CBR has a linear relationship with soil index properties; and analysis was made on different types of soil groups separately. However, it was noticed that the effect of outliers could spoil the predictions as spotted by Huber (1973). MATLAB solutions on robust regression using linear absolute residuals (Thanoon, 2015) were too utilized in this analysis due to the presence of significant number of outliers.   By the Linear Regression using Microsoft Excel, the coefficients of linear equations were estimated with more independent variables that best predict the value of the dependent variable. Regression analysis was conducted to obtain different equations by correlating CBR values with different groups of soil properties. MATLAB analysis was further utilized in evaluating different order relationships, especially among CBR, D_M and M_0. However, it was limited to maximum second order parabolic equations considering the complexity to be used in industry applications. At the end of analysis, new correlations were proposed and laboratory tests were carried out to validate the new correlations generated with the compiled data for verification purpose.

3 RESULTS & DISCUSSION

The regression types for each plot determined according to the trend line option (which gives maximum R^2 value) resulted that the individual soil parameters do not offer a strong relationship with CBR, since the R^2 values obtained were significantly low. The scattered plots between D_M and CBR for sandy soils with fines content greater than 12% resulted in a liner relationship with R^2 of 0.136 for plastic soils; whilst power relationship with R^2 of 0.209 for Non-Plastic (NP) soils. Similar, poor relationships were obtained for the other soil categories as well when the individual parameter analysis was carried out. Further, according to the results obtained from the analysis done with existing published correlations using local soil data, the existing correlations also do not possess strong relationships with local soil data as they were also resulted in low correlation coefficient (R^2) values and it poorly fitted the models.

Since the individual index test parameters do not possess worthy correlations with CBR, multiple regression analysis was performed using MS Excel Regression method. In this regression, it is assumed that the soil parameters have a linear relationship with CBR value. In the analysis, all the soil parameters considered for evaluation of existing published correlations with local soils data were used for the development of new correlations. Further analysis was conducted considering second order regressions in 3D with MATLAB. Analysis was carried out initially for major three categories of soils identified earlier. Of these, sandy soils with fines greater than 12% consisted both plastic and non-plastic soils. Therefore, these two categories were analyzed separately.

3.1 PLASTIC GRAVELLY SOILS WITH FINES

In the case of linear estimation for multiple parameter regression, initial analysis was conducted on the plastic gravelly soils with fines content greater than 12%. The analysis was performed on 50 sets of data which consisted of Silty Gravel, Clayey Gravel and Clayey-Silty Gravel having the USCS symbol of GM, GC and GC-GM respectively. Regression analysis with five different variables and an intercept using two types of index information (i.e sieve analysis and Proctor compaction) was performed by omitting the parameters with highest P value which is used to interpret the t-stat until the P-value of almost all the parameters were reduced below 0.1, while reducing the Standard Error of the entire model. Further, the F-factor which shows the quality of the entire model has increased while reducing the Significance-F below 0.1 according to the Analysis of Variance (ANOVA) of the regression. Assuming that the model is statistically significant, a new correlation was developed to predict CBR value of plastic gravelly soils with fines greater than 12% as given in Equation (1).

$$CBR = -65.52 - 0.73G_P + 50.97D_M + 2.75M_0 - 0.44P_{425} + 1.94D_{50} \tag{1}$$

CBR value is well predicted by the above correlation with a tolerance of around ±5%. The graph between actual and predicted CBR values based on Equation (1) is plotted in Figure 2. This was further analyzed using MATLAB and a 3D second order represenation of the relationship is proposed for CBR with D_M and M_0 as given in Equation 2 which results in R^2 of 0.72. These findings are presented as a 3D and countour plots in Figure 3.

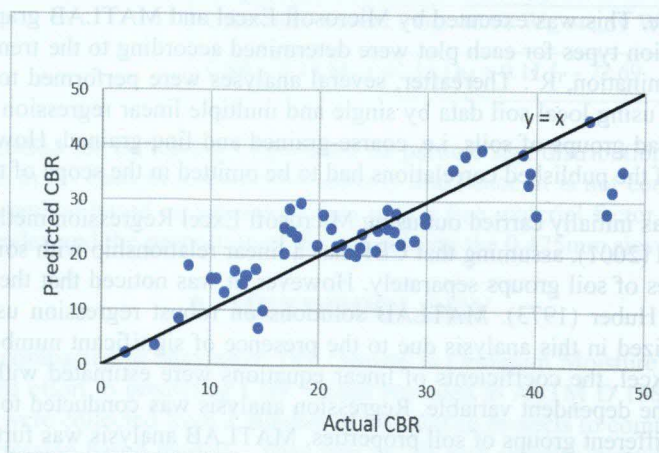$$CBR = 23.1 + 8.3DM + 8.7M0 - 1.2DM2 + DM M0 + 1.9M02 \tag{2}$$

Figure 2: Comparison of Equation (1) for plastic gravelly soils with fines >12%
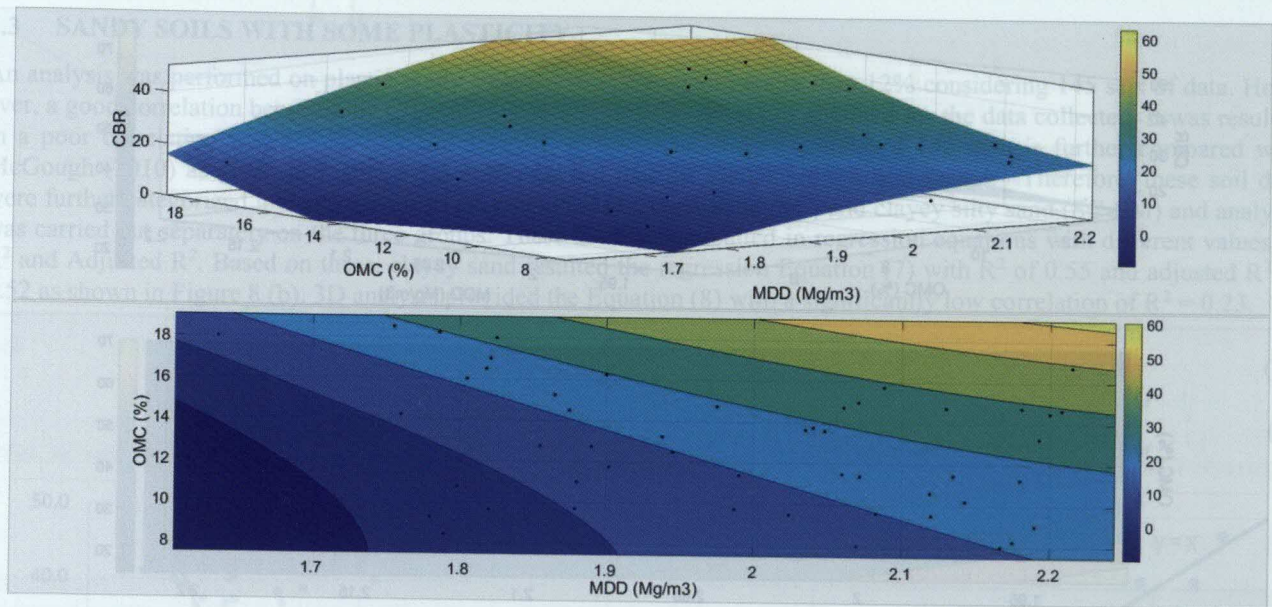
Figure 3:   3D and contour representation of CBR as predicted in Equation (2).

3.2   NON-PLASTIC SANDY SOILS

Similarly, several other correlations were developed for sandy soils as well; with applying constraints in some cases in order to obtain a best-fit model.   Accordingly, initial analysis was carried out for non-plastic sandy soils which are categorized based on the fines content and the analysis was conducted separately for:
  a) Non-plastic sandy soils with fines content greater than 12 % (USCS symbol of SM); and
  b) Non-plastic sandy soils with fines content less than 12% (USCS symbols SP, SW, SP-SM and SW-SM).

The category (a) above was analyzed with 27 sets of data, and the Equation (3) was obtained with R^2 of 0.8372 and Adjusted R^2 of 0.7985.

$$CBR = -99.76 - 0.25P_{075} + 75.77D_M + 1.89M_0 - 0.32P_{2360} - 24.99D_{60} \tag{3}$$

The relationship between actual CBR and predicted CBR using Equation (3) is plotted in Figure 4 and a further 3D analysis is available in Figure 5 with a relationship proposed in Equation (4).

$$CBR = 29.5 - 0.4\,D_M - 3.8\,M_0 + 1.2\,D_M{}^2 + 2.9\,D_M\,M_0 + 1.2\,M_0{}^2 \tag{4}$$
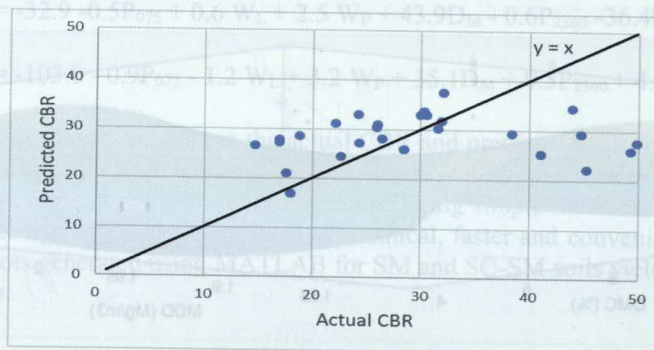

Figure 4:   Comparison of Equation (3) for non-plastic sandy soils with fines >12%

Similarly, for the non-plastic sandy soils in the category (b) mentioned above, the analysis was carried out considering 15 sets of data, and the equation (5) was obtained with R^2 of 0.881 and Adjusted R^2 of 0.815.

$$CBR = 82.0 - 1.96G_P - 2.01S_P - 1.79M_0 + 1.2P_{2360} + 66.55D_{50} \tag{5}$$

Predicted CBR values were plotted against the actual CBR values according to Equation (5) for comparison as shown in Figure 6 and a further 3D analysis is available in Figure 7 with a relationship proposed in Equation (6).

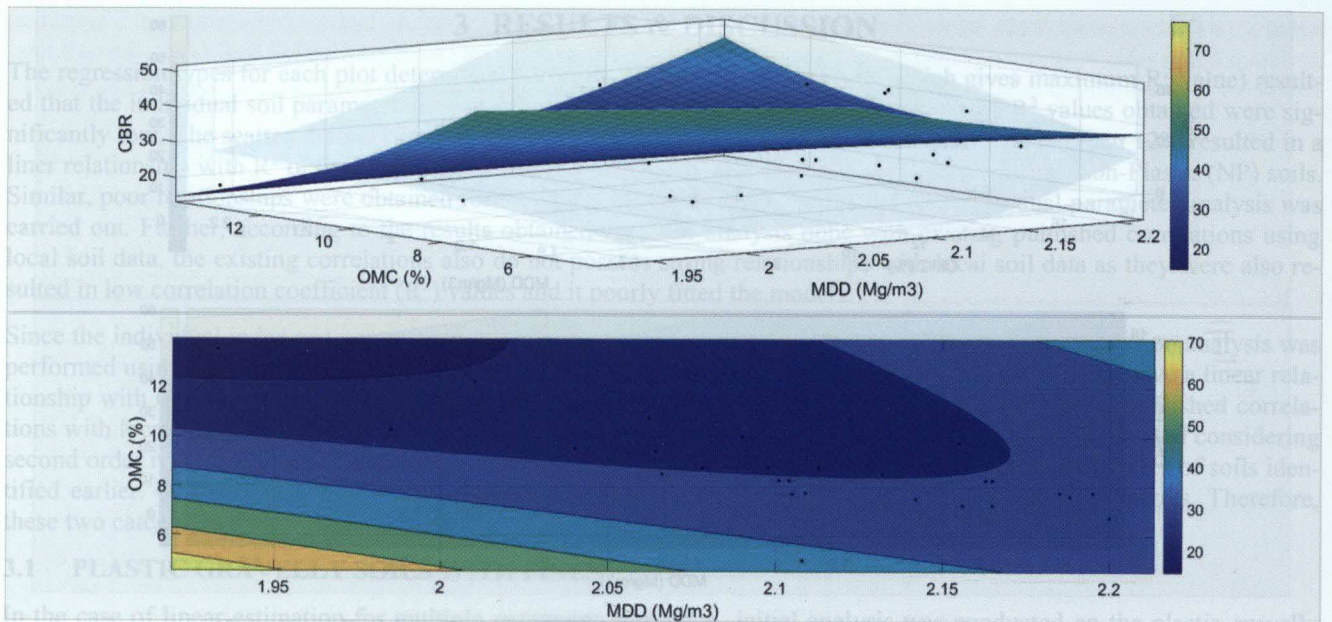$$CBR = 23.0 - 1.2D_M - 4.7M_0 + 1.8D_M{}^2 - 0.6\,D_M\,M_0 - 3.0M_0{}^2 \tag{6}$$

Figure 5:   3D and contour representation of CBR as predicted in Equation (4).
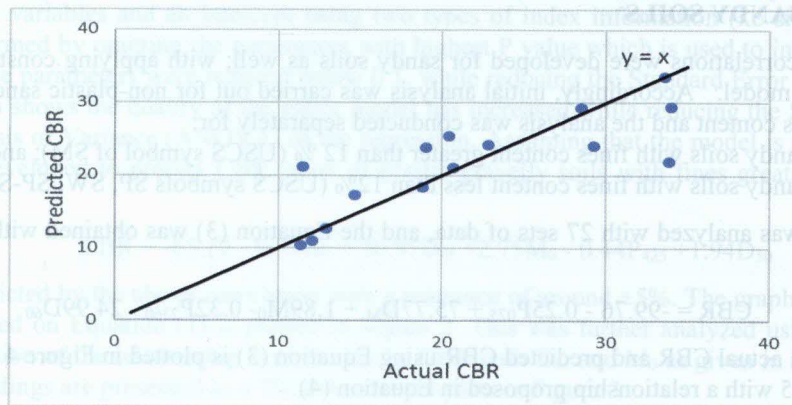

Figure 6:   Comparison of Equation (3) for non-plastic sandy soils with fines <12%
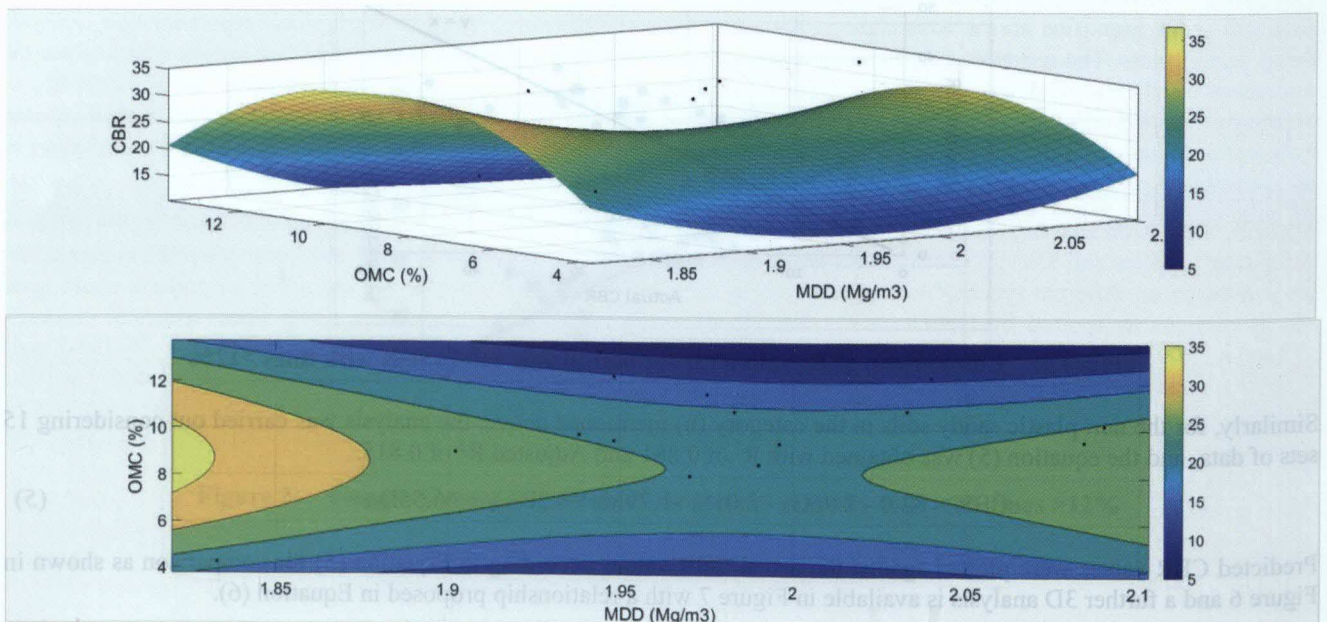

Figure 7:   3D and contour representation of CBR as predicted in Equation (6).

3.3   SANDY SOILS WITH SOME PLASTICITY

An analysis was performed on plastic sandy soils with fines content greater than 12% considering 145 sets of data. However, a good correlation between the CBR and the index properties was not obtained for the data collected. It was resulted in a poor correlation with R^2 of 0.20 and adjusted R^2 of 0.168. The entire set of 145 data is further compared with McGough (2010) as given in Figure 8 (a) and observed that the results were too scattered.   Therefore, these soil data were further categorized into sub groups as silty sand (SM), clayey sand (SC) and clayey silty sand (SC-SM) and analysis was carried out separately on the three groups. These have been resulted in regression equations with different values of R^2 and Adjusted R^2. Based on these, clayey sand resulted the regression Equation (7) with R^2 of 0.55 and adjusted R^2 of 0.52 as shown in Figure 8 (b). 3D analysis provided the Equation (8) with a significantly low correlation of $R^2 = 0.23$.

$$CBR = 39.8 - 1.7\,W_L + 2.4\,W_P + 0.9\,I_P - 2.4M_0 + 1.4D_{60} \tag{7}$$

$$CBR = 20.4 + 2.2D_M - 5.1M_0 - 0.4D_M{}^2 + 0.6D_M\,M_0 + 2.8\,M_0{}^2 \tag{8}$$
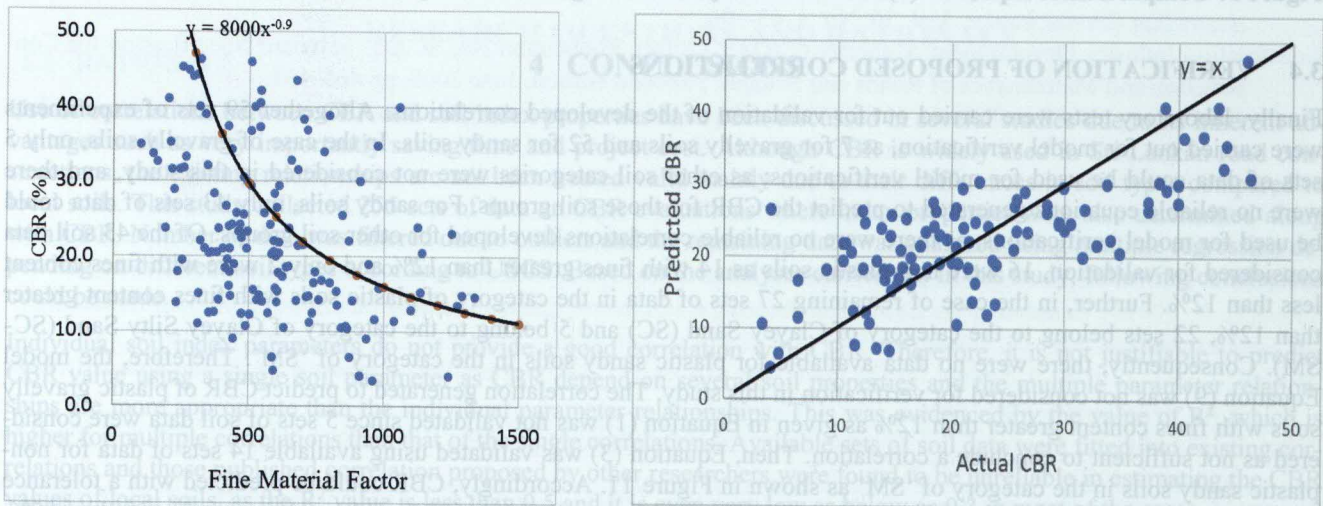

Figure 8: (L) Comparison of CBR with McGough (2010)   (R) Comparison of Equation (7) for Clayey Sand

Nevertheless, very good correlations could be established on SM and SC-SM soils respectively, according to the proposed Equation (9) with R^2 of 0.99 and adjusted R^2 of 0.98 and Equation (10) with R^2 of 0.72 and adjusted R^2 of 0.63.

$$CBR = -32.9 - 0.5P_{075} + 0.6\,W_L + 2.5\,W_P + 43.9D_M - 0.6P_{2360} - 36.4D_{60} + 46.0D_{50} \tag{9}$$

$$CBR = -103.0 - 0.9P_{075} - 1.2\,W_L + 3.2\,W_P + 35.1D_M + 0.5P_{2360} + 4.0D_{60} + 6.9D_{50} \tag{10}$$

Figures 9 and 10 illustrate the relationship between the actual CBR and predicted CBR for equations (9) and (10) respectively. In Figures 9 and 10, most of the data lies near the best fit line with a tolerance of ±5%. The CBR values are well predicted by most of the above correlations with several variables using simple index test information (i.e sieve analysis, Atterberg limits and Proctor compaction) which are more economical, faster and convenient to perform than CBR test. It has to be noted that the 3D plots generated using MATLAB for SM and SC-SM soils yielded very low R^2 values and they are not presented in this paper.
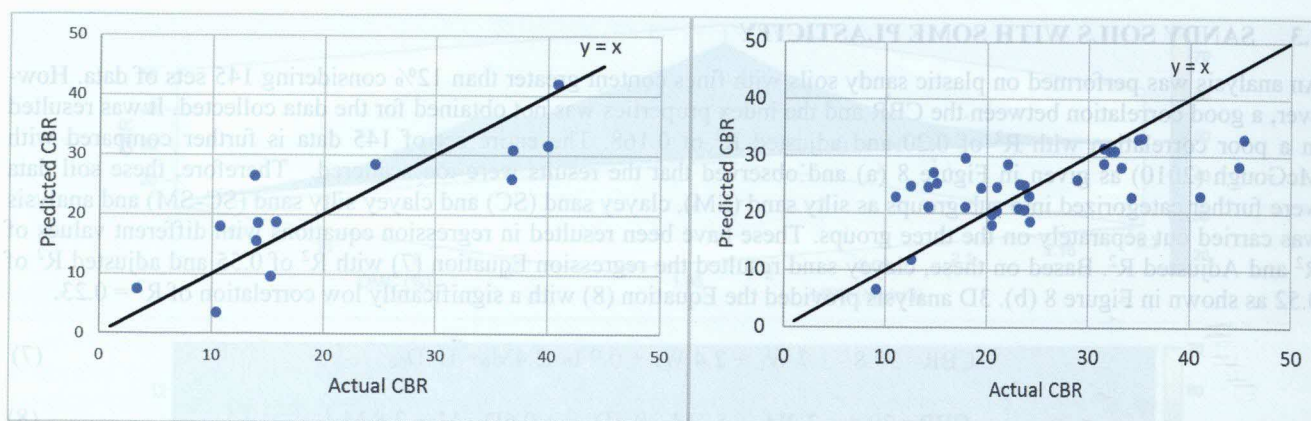
Figure 9: Comparison of Equation (9) for Plastic Silty Sand   Figure 10: Comparison of Equation (10) for SC-SM

3.4   VERIFICATION OF PROPOSED CORRELATIONS

Finally, laboratory tests were carried out for validation of the developed correlations. Altogether 59 sets of experiments were carried out for model verification, as 7 for gravelly soils and 52 for sandy soils. In the case of gravelly soils, only 5 sets of data could be used for model verifications; as other soil categories were not considered in this study, and there were no reliable equations generated to predict the CBR for those soil groups. For sandy soils, only 43 sets of data could be used for model verifications; as there were no reliable correlations developed for other soil. Of the 43 soil data considered for validation, 16 were non-plastic soils as 14 with fines greater than 12% and only 2 were with fines content less than 12%. Further, in the case of remaining 27 sets of data in the category of plastic soils with fines content greater than 12%, 22 sets belong to the category of Clayey Sand (SC) and 5 belong to the category of Clayey Silty Sand (SC-SM). Consequently, there were no data available for plastic sandy soils in the category of 'SM'. Therefore, the model Equation (9) was not considered for verification in this study. The correlation generated to predict CBR of plastic gravelly soils with fines content greater than 12% as given in Equation (1) was not validated since 5 sets of soil data were considered as not sufficient to conclude a correlation. Then, Equation (3) was validated using available 14 sets of data for non-plastic sandy soils in the category of 'SM' as shown in Figure 11. Accordingly, CBR could be predicted with a tolerance of ±5% for most of the data. However, only few data were over predicted the CBR with a tolerance of more than +5%. Equation (5) was not validated as only 2 sets of data were available for non-plastic sandy soils in the category of 'SP-SM' and 'SW-SM'.
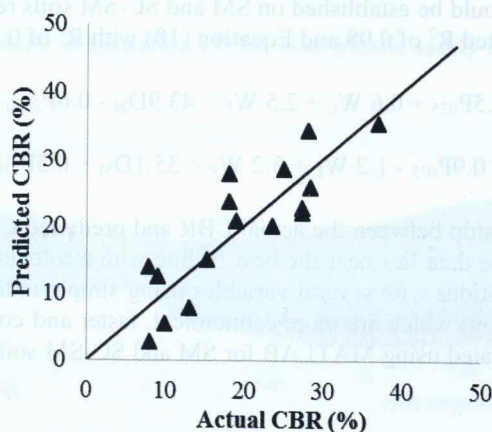

Figure 11:   Verification of proposed correlations on non-plastic SM soils – Equation (3)

The proposed equations were validated to predict the CBR of plastic sandy soils with fines content greater than 12%. Equation (9) developed for soil category of 'SM' could not be validated due to the absence of test data.   Figure 12 illustrates the model verification for clayey sands (SC) with 22 sets of data. In this case also, most of the predicted CBR was located within the limit of ±5% tolerance; whilst about 6 values lie outside these tolerance limits. Equation (10) was also not validated since 5 sets of soil data were considered as not sufficient to conclude a correlation.
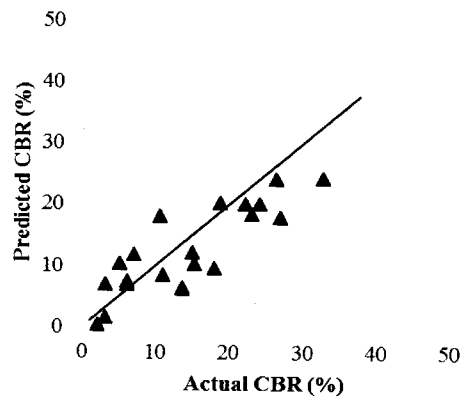
Figure 12: Verification of proposed correlations on SC soils –Equation (7)

4 CONCLUSIONS

Use of correlations between CBR and soil index properties have been discussed in several studies due to its inherent advantages such as very importantly saving time and project cost. Although CBR is widely used in Sri Lankan road constructions, the existing relationships are not been treated valid mainly due to their differences in soil types compared to local soils. This study collected 255 sets of data on CBR evaluations where index properties were also determined along with CBR. Number of data was filtered due to outliers and the remaining data was analyzed using multiple regression depending on different soil types according to USCS. Based on the analyses carried out in this study, following conclusions could be made.

Individual soil index parameters do not provide a good correlation with CBR. Therefore, it is not justifiable to predict CBR value using a single soil parameter as CBR depend on several soil properties and the multiple parameter relationships are more appropriate than the individual parameter relationships. This was evidenced by the value of R^2, which is higher for multiple correlations than that of the single correlations. Available sets of soil data were fitted into existing correlations and those published correlation proposed by other researchers were found to be unreliable in estimating the CBR values of local soils, as the R^2 value is less than 0.5 and it is even very low as below as 0.3 in most of the cases.
No correlation could be developed to predict CBR with R^2 or adjusted R^2 of or nearly 1.0 using the collected data set. Based on the new correlations developed in this study assuming linear relationship only, CBR has significant compatibility with soil index properties with limited index test parameters. CBR can be predicted from the developed new correlations with a tolerance of ±5%. However, in some cases CBR was predicted with the tolerance up to around ±10%. Based on these, it can be assumed that soils behave in a non-liner relationship between CBR and index properties. Therefore, 3D analysis was conducted using MATLAB considering only MDD and OMC and it was found that in some cases, reliable second order relationships could be developed. This study proposes that the developed correlations could be used to predict the CBR for preliminary design purposes and to avoid multiple tests on similar soils. These relationships could be further enhanced by frequent updates of databases and validation of the relationships.

5 ACKNOWLEDGEMENTS

6 REFERENCES

Austroads (2004), 'Austroads Pavement Design Guide– A guide to the Structural Design of Road Pavements', Austroads Inc., Sydney, Australia.

Austroads (2015), Austroads guide to pavement technology part 2; Pavement structural design, Roads and Maritime Austroads guide, publication no 11.050, Jan 2015.

Agarawal D.K., Rathore S.S., Saklecha P.P., Katpatal Y.B., (2011), Spatial Correlation of Mechanical Properties of Subgrade Soil for Foundation Characterization, International Journal of Computer Applications (0975 – 8887), Volume 36– No.11.

Agarwal, K.B. and Ghaneka, K.D., 1970, Prediction from plasticity characteristics of soil, Proceedings of 2nd South-East Asian conference on soil engineering, Singapore, 571-576.

American Standard Test Methods for CBR of Laboratory-Compacted Soils. ASTM D1883-92, Laboratory Compaction Characteristics of Soil Using Modified Effort. ASTM D 1557, Particle-Size Analysis of Soils. ASTM D 422-63, Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM D2487 – 06.

Ayodele A.L., Falade F.A. and Ogedengbe M.O. (2009), Effect of fines content on some engineering properties of lateritic soil in Ile-Ife, Department of Civil Engineering, Obafemi Awolowo University, Ile-Ife.

Breytonbach, I.J, (2009), The relationship between index testing and California Bearing Ratio values for natural road construction materials in South Africa, MSc Dissertation, Department of Geology, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa.

British Standards Institution (1990). Methods of test for soils for civil engineering purposes-Classification tests, London, BS 1377: Part 2.

Brown, S.F., O'Reilly, M.P., and Loach, S.C., (1990), The relationship between CBR and elastic stiffness for compacted clays, *Ground Engineering*, October, pp 27-31.

Cocks, G., Keely, R., Leek, C., Foley, P., Bond, T., Cray, A., Paige-Green, P., Emery, S., Clayton, R., McInnes, D., and Marchnat, L., (2015), The use of naturally occurring materials for pavements in Australia, *Australian Geomechanics*, Vol. 50, No. 1, 43-106.

Construction Industry Development Authority (CIDA), (2009), Publication No. SCA/5: Standard Specification for Construction and Maintenance of Roads and Bridges"; Second edition, June 2009, pp 466-468.

De Graft-Johnson, J.W.S. and Bhatia, H.S., (1969), The engineering characteristics of the lateritic gravels of Ghana, *Proceedings of the 7th International conference on soil mechanics and foundation engineering*, Mexico. Vol 2, 13-43.

Haupt, F J., (1980), Moisture conditions associated with pavements in Southern Africa. MSc thesis, University of the Witwatersrand, South Africa.

Hillman, M., Cocks, G and Ameratunga, J., (2003), Guildford formation, *Australian Geomechanics*, Vol. 38, No. 4, 31-39

Huber, P.J. (1973), Robust regression: asymptotics, conjectures, and Monte Carlo, the annals of statistics 1, 799-821

Lloyd, E. R., (2014), Estimating the Californian Bearing Ratio from Particle Size Distribution and Atterberg Limits, *REAAA Journal*, Vol. 18, 11-19.

McGough, P.G., (2010), A method for the prediction of soaked CBR of remoulded samples from standard classification tests, *Australian Geomechanics*, Vol. 45, No. 4, 75-86.

Miles, J., and Shevlin, M., (2001), Applying regression and correlation: A guide for students and researchers: A guide to regression analysis using MS Excel 2010.

National Cooperative Highway Research Program (NCHRP), (2001), Correlations of CBR values with soil index properties, Transportation Research Board, National Research Council, submitted by ARA, Inc., ERES Division, Illinois.

Patel, R. S., and Desai, M.D., (2010), CBR Predicted by Index Properties of Soil for Alluvial Soils of South Gujarat, *Indian Geotechnical Conference*, Proc. IGC, Vol. I, 79-82.

Rallings, R. (2014), The CBR test – A case for change? *Australian Geomechanics*, Vol. 49, No. 1, 41-55

Roy, T.K., Chattopadhyay, B.C., and Roy, S.K., (2009), Prediction of CBR from Compaction Characteristics of Cohesive Soil, *Highway Research Journal*, July-Dec., 77-88.

Sood, V.K., Lal, N.B. and Dhir, M.P. (1978). Estimation of CBR values of moorums from index properties. Indian Highways, 6, (11), 28-31.

Thanoon, F.H., (2015), Robust regression by least absolute deviations method, *International Journal of statistics and applications*, 2015, 5(3):109-112

The Highway Agency, (1994), Design Manual for Roads and Bridges. Volume 7: Section 2 Part 2 HD 25/94. London: Stationery Ltd.

Vinod, P.; and Cletus R., (2008), Prediction of CBR value of Lateritic Soils using Liquid Limit and Gradation Characteristics Data, *Highway Research Journal*, Vol. I, No. 1, 89-98.