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Research Article

The Use of Dynamic Cone Penetrometer to Predict California Bearing Ratio Value of Subgrade Soils

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Abstract

California Bearing Ratio (CBR) is an indirect method mostly used to investigate the strength of subgrade material for highway design. The CBR of subgrade materials can be determined from costly and time-taking laboratory or in situ CBR tests. These limitations suggest the need for an easy and low-cost in situ direct method to estimate the CBR of subgrade materials. Dynamic cone penetration (DCP) is easy, quick, and economical in situ test in geotechnical uses. However, the use of DCP test to evaluate the CBR of subgrade material is condition specific i.e., local conditions should be considered before adopting existing correlations in engineering design. The objective of this study is therefore to develop a correlation that can predict the CBR of subgrade material from the dynamic cone penetration index (DCPI). Several laboratory and field tests including Plasticity index (PI), Liquid limit (LL) and Plastic limit (PL), in situ density, and classification (sieve analysis and hydrometer analysis), CBR (unsoaked), in situ moisture content, and DCP were conducted. The suitability of the existing model to predict CBR from DCPI was checked. The prediction model was then developed using Statistical Package for the Social Sciences (SPSS) software. The result of the SPSS analysis is log (CBR) = 2.954 – 1.496log (DCPI) with R2 = 0.943. The result shows that a good correlation exist between the dynamic cone penetration indexes (DCPI) and unsoaked CBR values.

Keywords

California Bearing Ratio, Dynamic Cone Penetration, Subgrade Soil, Correlation

1. Introduction

1.1. Dynamic Cone Penetration

The DCP test provides a measure of the in-situ strength (stiffness) of the pavement layers through the continuous record of the rate of penetration with depth and thickness of the structural layers (from slope change of the penetration depth (mm) versus cumulative blows plot) [11, 13, 21]. According to [5], the DCP test can be used to investigate the condition of the materials underlying pavement and their in-situ strength (by way of a model that correlates DCPI to the engineering properties of soils). The pavement assessment involves the determination of the compaction level of the granular base layer and pavement edge backfill during construction [5]. The DCP test can be applied to identify the causes of pavement failure if it is related to one of the un-

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derlying unbound layers [20]. DCP can also classify soils based on DCPI values [14].

The DCP test result can be correlated with various pavement strength parameters such as resilient modulus, CBR, unconfined compressive strength, and shear strength [1, 12]. Several studies, e.g., [6, 10, 14, 17, 23, 24, 27] established a relationship between DCPI and CBR values. [9, 16] determined the DCPI relation with shear strength. The study conducted by [8, 26, 17, 19] develop a correlation between DCP and unconfined compressive strength. The relationship between DCP and subgrade resilient modulus was formulated by [7, 16] which relate DCP with dry density and water content. Several factors including materials [16], vertical confinement [18], and side friction [18] affect the DCP test result. The materials effect such as changes in water content, soil type, density, gradation, and maximum aggregate size causes significant variability in DCP test results [16].

The fundamental design of the DCP apparatus has remained the same since the 1950s (initiation of the DCP test). However, several revisions have been made to the falling weight mass and the cone tip. The present version of the DCP was developed by Kleyn of the Transvaal Roads Department, South Africa. Van Vuuren's basic design was used in Kleyn's work with reduced (9kg) hammer weight and increased drop height (576mm). Kleyn explored replaceable 30 and 60 degrees cone angle configurations.

The DCP test result is reported in terms of DCP index: the rate in mm/blow of penetration of the DCP apparatus into the pavement layers (DCPI). The DCPI in general is given as incremental values (Equation 1).

$$DCPI = \Delta DP / \Delta BC \quad (1)$$

Where:
$DCPI$ = penetration index.
ΔDP = Change in penetration depth.
ΔBC = change in blow counts to the ΔDp.

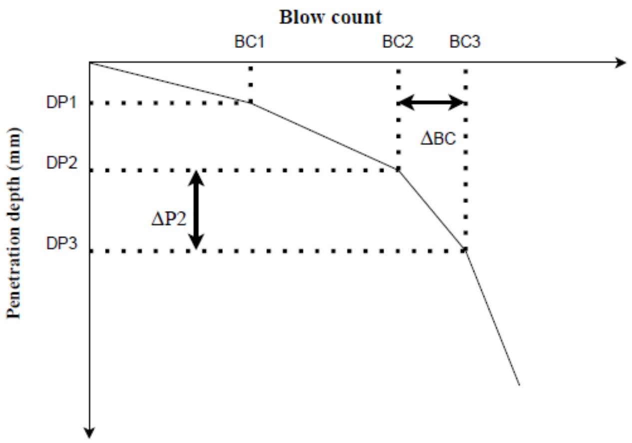

Figure 1. *Typical DCP test results.*

The plot of DCP results expresses the number of blows required to penetrate into a certain depth providing pictorial observation of in-situ material strength (Figure 1). The slope of the curve at any point is described in mm/blow and designated as DCPI which represents the material resistance to penetration; stiffer materials have low DCPI, and vice versa [16].

1.2. California Bearing Ratio

The CBR test was developed by the California State Highways Department in the 1930's. It is an easy penetration test designed to assess strength of subgrade materials. CBR test is not applicable to estimate the standard soil properties (density, consistency, texture, etc.). For pavement design, the CBR test should be determined at the optimum water content [7]. CBR is used as a method to categorize the suitability of soil for a particular application (for example: subgrade or base course material) in highway construction.

The CBR test is used to determine the shearing strength of materials at regulated (moisture and density) environment. The CBR test result (the bearing ratio number) varies with the soil-tested state. The bearing number is the ratio of the pressure (force per unit area) required to penetrate a soil mass to the corresponding penetration of a standard material (crushed stone) with a standard circular piston at the rate of 1.25 mm/min.

$$CBR\ (\%) = \left(\frac{Test\ unit\ load}{Standard\ Unit\ \text{load}}\right) * 100 \quad (2)$$

Although equation 1 yields a percentage value CBR is conventionally expressed as a pure number like 10, 30, and 60. The standard unit loads to be used in the above equation are shown in Table 1.

Table 1. *Penetration corresponding to standard unit load applied to standard gravel [3].*

Penetration (mm)	Standard unit load (MPa)	Remarks
2.54	6.9	Used for highway design and construction purposes
5.04	10.3	“
7.5	13	
10	16	
12.7	18	

For highway applications, the CBR values are calculated at 2.54mm and 5.04mm penetration. Generally, the CBR value at 2.54 mm is expected to be higher than at 5.04 mm. In such a case the reading at the former (2.54mm) shall be taken as CBR for design application; however, if CBR at the latter (5.04) exceeds the test should be repeated. If the same results are obtained the CBR at 5.04 mm penetration should be taken as the CBR of the material tested [15]. Several factors including soil type, density, moisture content, and sample preparation method affect CBR test results [6]. The soil CBR can be determined at dry and soaked conditions. A soaked CBR test is conducted to characterize the strength of the materials under adverse moisture conditions [22].

Road design and construction are based on soaked CBR laboratory tests. The conditioning (soaking) CBR specimen is done for 96 hours or 4 days. On the other hand, pavement design and construction require lots of CBR tests along the length of the road. However, considering the time required (4 days) for sampling and soaking, this will result in a delay in project design and construction and ultimately lead to an increase in project cost. Therefore, to address these limitations it is required to seek alternative easy, fast, and economical approaches.

In doing so, the prediction of CBR from the DCP test has been a viable approach. However, since the existing models were developed based on the local condition they may not apply to others with different soil fabric, geological formation, and climate and environment i.e., they may under or overestimate the strength of the local soil. The former leads to inflated construction costs and the latter leads to fast deterioration or premature failure, and ultimately high life cycle costs. Therefore, the objective of this study is to develop a model to predict the in situ CBR of subgrade soils from the DCP field test result with simple regression analysis using SPSS software.

2. Materials and Methods

The research methodology was developed to address the study objectives. The methodology consists of four steps; literature review; experimental works; results, analysis and discussion, and conclusion and recommendation. In step 1, a comprehensive literature review was conducted aiming to understand the application of DCP and CBR tests for highway engineering, test methods, factors that influence CBR and DCP test results, and the DCP - CBR correlation by different authors. The literature review also helped to set the research objective, develop the test protocol, and select the study site. In step 2 various experiments (field and laboratory) were conducted. In step 3 the test results were analyzed and discussed. Finally, conclusions and recommendations were given.

2.1. Description of the Area

The study is undertaken in the Jimma – Bonga road project, located in the western part of Ethiopia linking the Oromia regional State to Southern Nations, Nationalities, and Peoples' Region. Specifically, the test section extends from km100+200 to km105+050. According to the historical weather record spanning from 2010 to 2020 [2] the area is characterized by an annual rainfall of 1696.05mm and temperature ranging between 15.09℃ and 26℃. The wettest month (May) receives a mean monthly rainfall of 262.53.7mm whereas the driest month (January) receives 38.59mm. The average number of rainy days with rainfall above 1mm or more is 203.01 (55.62%). The warmest month (February) and the coldest month (December) have an average temperature of 30.04℃ and 14.34℃, respectively. The road is functionally classified as a Design Standard 4 Trunk road connecting the capital (Addis Ababa) to South Sudan via the Jimma, Mizan, and Rad routes. Ethiopian Roads Administration (ERA) pavement management system 2023 traffic count record showed that the traffic volume on the Jimma – Bonga road was approximately 538 vehicles per day, with about 33.4% being trucked (which can be subdivided into: Small truck (10.5%), medium truck (9.5%), heavy truck (7.7%) and truck trailer (5.7%)).

2.2. Sampling and Testing

Thirty samples were extracted from the trial pits excavated to a depth ranging from 55cm to 120cm on the chosen 5km length site along Jimma–Bonga road with a sampling interval of 100 to 400m interval. The trial pits were dug using a backhoe excavator in a staggered manner, on the right and left-hand side of the road. A sufficient amount of samples were collected using plastic bags (to avoid moisture loss) and shipped directly to the project laboratory established at Seka village on the same date.

Table 2. *Laboratory test standards.*

Tests	Test method/standard
CBR	BSI 1377
NMC	AASHTO T265(255)
Particle size distribution	AASHTO-T27
LL	AASHTOT89
PL	AASHTOT90
PI	AASHTO T90-96
Hydrometer analysis	ASTMD7928

Laboratory samples for the respective laboratory tests were prepared and tests were carried out following standard procedures (Table 2). The field density tests (FDT) were conducted on each trial pit using the sand cone method, Association of American Highway Transport Officials (AASHTO) T191 test method. The unsoaked CBR tests were done using remolded samples (remolded at the in situ moisture content

(NMC) and field density). The CBR test is conducted according to [4] except that these samples are not exposed to 96 hours soaking, and performed at the in situ density and moisture content. Thus, the 4.5kg rammer method was adopted to compact the soil samples in the molds. The hydrometer analysis test was conducted to classify the soil.

The DCP test was conducted on each trial pit according to the American Standard Testing Method (ASTM)D6951. TRL DCP is used in this study. The DCP has upper and lower shafts. The upper shaft has a 575mm drop height and an 8kg drop hammer having a maximum diameter of 20mm and is connected to the lower shaft through the anvil; the lower shaft contains an anvil and a cone attached at the end of the shaft (Figure 2).

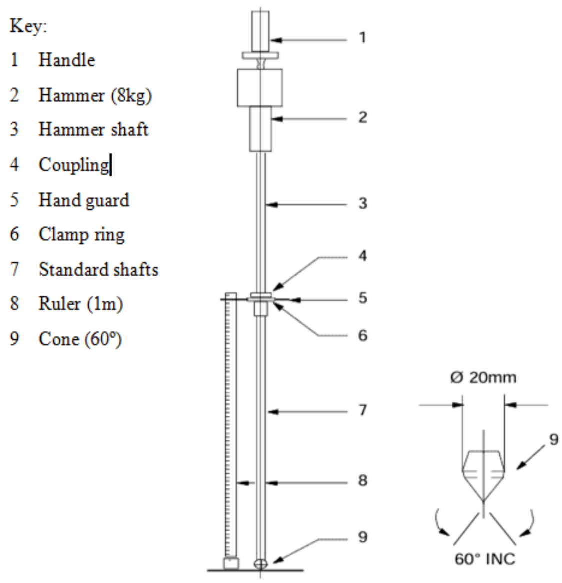

Figure 2. *Layout of DCP device.*

The DCP parts are assembled as shown in Figure 2 and the initial (zero) reading was recorded before the cone was driven to the subgrade soil. The penetration depths were recorded (to the nearest 0.1mm) for each 2 blow counts on the standard data collection form until the test was completed. The penetrometer is then removed by ramming the weight from the handle.

3. Results

The DCP test results were reported in terms of DCPI, the slope of the penetration depth (mm/blow) versus a cumulative number of blows plot. An example of a plot of penetration depth with a cumulative number of blows for the km100+200 trial pit is shown in Figure 3. Table 3 summarizes the laboratory (CBR, PI, LL, and NMC) and field (DCPI and FDT) test results including AASHTO soil classification.

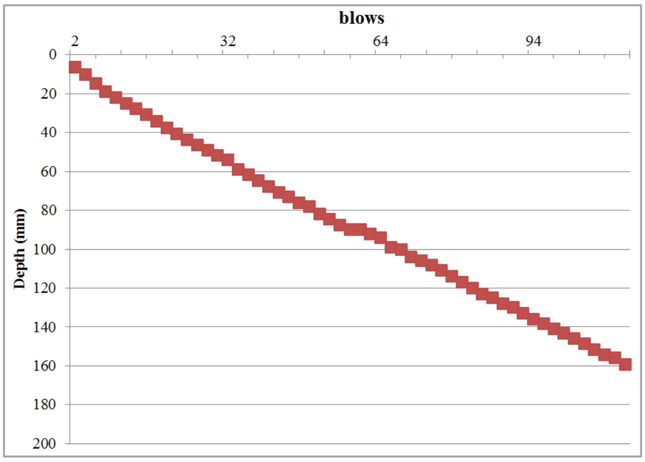

Figure 3. *Variation of penetration depth with cumulative number of blows.*

Table 3. *Summary of field and laboratory tests result.*

Station	Direction	Sampling depth	Lab CBR (%)	DCPI (mm/blow)	PI (%)	LL (%)	FDT (gm/cm3)	NMC (%)	Classification(AASHTO)
100+200	RHS	40-67	18.5	13.8	35	62	1.729	27.3	Red clay(A-7-6)
100+420	LHS	28-55	12.4	18.7	37	66	1.612	34.4	Red clay(A-7-6)
100+600	RHS	38-70	8.86	21.6	35	67	1.536		Red clay(A-7-5)
100+800	LHS	29-67	13.04	17.1	38	69	1.629	21.6	Light brown clay (A-7-5)
101+050	RHS	50-90	13.37	16.6	38	68	1.660	20.2	Brown clay(A-7-5)
101+250	LHS	31-66	18	13.4	34	71	1.731	27.2	Light brown clay (A-7-5)
101+450	RHS	40-70	24	10	32	63	1.847	27.2	Brown clay(A-7-5)
101+650	RHS	48-62	16.75	14.8	34	65	1.703	36.1	Light brown clay (A-7-5)

Station	Direction	Sampling depth	Lab CBR (%)	DCPI (mm/blow)	PI (%)	LL (%)	FDT (gm/cm3)	NMC (%)	Classification(AASHTO)
101+850	RHS	30-70	16.59	15.4	35	65	1.694	25.7	Light brown clay (A-7-5)
102+050	LHS	65-80	6.44	25.1	34	64	1.481	24.1	Brown clay(A-7-5)
102+250	RHS	73-108	12.56	17.3	34	63	1.613	27.6	Brown clay(A-7-6)
102+650	LHS	46-78	10.18	19.8	31	63	1.595	31.7	Dark Red clay(A-7-5)
102+850	RHS	42-67	11.1	19.4	34	64	1.608	38	Brown clay(A-7-5)
103+050	LHS	50-70	16.27	16.3	33	63	1.692	25	Dark Red clay(A-7-5)
103+250	RHS	63-79	34	7.5	32	65	2.09	12.3	Brown clay(A-7-5)
103+450	LHS	49-68	1.15	20.6	35	68	1.587	25.6	Brown clay(A-7-5)
103+650	RHS	39-66	6.28	24.6	37	68	1.415	27.8	Brown clay(A-7-5)
103+850	LHS	34-68	10.16	20.3	32	69	1.588	32.4	Light brown clay (A-7-5)
103+950	LHS	43-77	15.9	24.6	34	67	1.676	26.8	Red clay(A-7-5)
104+050	RHS	53-78	19.5	20.3	34	68	1.736	28.9	Brown clay(A-7-5)
104+150	RHS	39-74	17.97	16.4	58	92	1.713	30.6	Light brown clay (A-7-5)
104+250	LHS	42-76	7.81	13.1	33	65	1.496	31.6	Brown Red clay(A-7-5)
104+350	RHS	48-68	14.69	14.5	32	66	1.670	29.6	Red clay(A-7-5)
104+450	LHS	47-88	8.75	22.5	33	66	1.519	30.6	Light brown clay (A-7-5)
104+550	RHS	49-78	22	16.5	32	66	1.751	31.5	Red silty clay(A-7-5)
104+650	LHS	47-82	18	21.8	32	67	1.721	33.4	Light brown clay(A-7-5)
104+750	RHS	66-106	5.65	13	33	68	1.265	26.8	Brown clay(A-7-5)
104+850	LHS	47-120	22.98	14.3	33	62	1.766	28.6	Brown clay(A-7-5)
104+950	RHS	50-90	9.06	26.5	32	62	1.547	30.5	Brown clay(A-7-5)
105+050	LHS	47-81	16	11.3	37	62	1.692	29.6	Brown clay(A-7-5)

4. Discussion

4.1. Correlation

For this study, a simple regression analysis was adopted. The CBR is the dependent variable whereas DCP is the independent (regressor) variable. SPSS statistical software program was used for the analysis. A scatter plot was employed to visualize the relationship between the two variables. The scatter plot is a visual method that displays the relationship between two variables. Figure 4 shows the scatter plot of the dependent and the regressor variable.

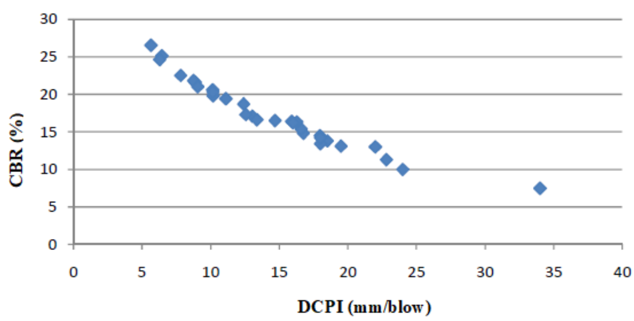

Figure 4. *Scatter Plot of Penetration Index Vs CBR.*

The above scatter diagram was plotted with Microsoft Excel spreadsheet. The representation of the DCPI and CBR values with a dot diagram makes it easy to see the distributions of the individual variables. A thorough examination of the scatter diagram shows that, although no simple curve will pass exactly through all the points, there is a reasonable indication that the points are randomly scattered in an exponential pattern. It also appears that there is an approximation that the two variables are inversely related i.e., an increase in DCPI leads to a decrease in CBR. Therefore, the relationship between CBR and DCPI, based on the scatter plot and previous researches results can be approximated by logarithmic regression models of the form shown below.

$$\text{Log (CBR)} = a + b\ \text{Log (DCPI)} \quad (3)$$

Where:

DCPI = the independent variables (regressors)

a and b = coefficients of the independent variables

CBR = the response (dependent variable)

SPSS is used to explore the relation between the regressor variable and the response. Accordingly, the obtained regression coefficients are a = 2.954 b = (-) 1.496, and R2 = 0.943. Therefore, the DCP-CBR correlation equation becomes:

$$\text{Log (CBR)} = 2.964 – 1.496\ \text{Log (DCPI)}$$

The output of the statistical analysis revealed that DCPI has a significant (significance <0.05) impact on the CBR value of subgrade soil. Thus, 94.3% (R2=0.943) of the CBR value of the subgrade soil could be affected by DCPI and slightly (5.7%) by some other properties of the subgrade soil. The equation also shows an increase in CBR value when DCPI decreases which is agreeable with the consensus: soil with high DCPI has low CBR value.

4.2. Comparison of Laboratory and Predicted CBR

The comparisons of CBR values; laboratory CBR, the CBR predicted with TRL equation (widely accepted correlation in Ethiopia), and CBR predicted with the developed equation were done and shown in Table 4. The actual and percent difference between predicted and measured CBR values is also computed. When the predicted CBR is higher than the measurement the error is positive. On the other hand, a negative error exists when the predicted CBR is lower than the measurement.

Although the number of data points is fairly small, the data (Table 4) falls into two very distinct regions namely DCPI less than 16.5 and DCPI greater than 16.5. For DCPI less than 16.5, a good fit exists between the TRL correlation and the laboratory CBR values for the 14 data points. The average difference between actual CBRs and TRL-predicted CBRs from DCPI values is 0.4 (on the CBR scale) and the average percentage difference is 1.7%. In this region the CBRs are all greater than 15% hence this difference is entirely negligible. For DCPI above 16.5, the correlation between the measured and predicted (using TRL correlation) CBR for 16 data points is very poor. The average difference on the CBR scale is 2.6 with an average percent difference of 30.2. However, though the difference appears small, the actual CBR value in this region is considerably low, and cannot be negligible.

Table 4. *Comparison of CBR values.*

		Predicted CBR		Difference (TRL - Actual CBR)		Difference (Developed - Actual CBR)	
DCPI (A)	Measured CBR (B)	Developed equation (C)	TRL Equation (D)	E= Columns (D) - (B)	Percentage Difference F=(E/B*100)	G= Columns (C) - (B)	Percentage Difference (G/B*100)
		%	%	%	%		
7.5	34	44.1	*35.9*	1.9	5.6	10.1	29.8
10	24	28.7	*26.5*	2.5	10.4	4.7	19.6
11.3	22.8	23.9	*23.3*	0.5	2.1	1.1	4.9
13	22	19.4	*20.1*	-1.9	-8.8	-2.6	-11.9
13.1	19.5	19.2	*19.9*	0.4	2.1	-0.3	-1.7
13.4	18	18.5	*19.4*	1.4	8.0	0.5	2.9
13.8	18.5	17.7	*18.8*	0.3	1.9	-0.8	-4.2
14.2	18	17.0	*18.3*	0.3	1.6	-1.0	-5.6
14.5	17.97	16.5	*17.9*	-0.1	-0.5	-1.5	-8.4
14.8	16.75	16.0	*17.5*	0.7	4.5	-0.8	-4.7

DCPI (A)	Measured CBR (B)	Predicted CBR Developed equation (C) %	 TRL Equation (D) %	Difference (TRL - Actual CBR) E= Columns (D) - (B) %	 Percentage Difference F=(E/B*100) %	Difference (Developed - Actual CBR) G= Columns (C) - (B)	 Percentage Difference (G/B*100)
15.4	16.59	15.0	*16.8*	0.2	1.1	-1.5	-9.3
16.2	16	*13.9*	*15.9*	-0.1	-0.6	-2.1	-12.8
16.3	16.27	*13.8*	*15.8*	-0.5	-2.9	-2.4	-15.0
16.4	15.9	*13.7*	*15.7*	-0.2	-1.3	-2.2	-13.9
16.5	14.69	*13.6*	*15.6*	0.9	6.2	-1.1	-7.6
16.6	13.37	*13.4*	*15.5*	2.1	15.9	0.1	0.6
17.1	13	*12.9*	*15.0*	2.0	15.6	-0.1	-1.0
17.3	12.56	*12.6*	*14.8*	2.3	18.1	0.1	0.7
18.7	12.4	*11.3*	*13.7*	1.3	10.2	-1.1	-9.2
19.4	11.1	*10.7*	*13.1*	2.0	18.4	-0.4	-4.0
19.8	10.18	*10.3*	*12.9*	2.7	26.4	0.2	1.5
20.3	10.16	*10.0*	*12.5*	2.4	23.3	-0.2	-2.0
20.6	10.15	*9.7*	*12.3*	2.2	21.6	-0.4	-4.1
21	9.06	*9.5*	*12.1*	3.0	33.4	0.4	4.4
21.6	8.9	*9.1*	*11.7*	2.8	31.9	0.2	1.9
21.8	8.75	*8.9*	*11.6*	2.9	32.8	0.2	2.2
22.5	7.81	*8.5*	*11.2*	3.4	43.9	0.7	9.3
24.6	6.28	*7.5*	*10.2*	3.9	62.9	1.2	18.9
25.1	6.44	*7.2*	*10.0*	3.6	55.5	0.8	12.5
26.5	5.65	*6.7*	*9.5*	3.8	67.3	1.0	0.2

5. Conclusions

In the present study, 30 tests were conducted with a DCP from Jimma–Bonga road located in the western part of Ethiopia. The measured CBR was compared with the TRL equation and a new correlation was developed to predict laboratory unsoaked CBR values from DCP test results. Accordingly, the below conclusions are made.

1) The CBR test result is inversely related to the values from DCP test i.e., the rise in CBR values will cause a drop in the DCP values.
2) The study proposed DCP-CBR correlation for subgrade soil. The correlation can reliably predict unsoaked CBR from the filed DCP test. For engineering design purposes seasonal variation of the DCP test should be considered.
3) A good fit exists between the laboratory and the predicted CBR values with the TRL equation for a DCPI of less than 16.5. For values above 16.5, the relation is poor.
4) The proposed model as compared to TRL correlation (widely used in Ethiopia) is conservative.

6. Recommendations

The following is recommended for future research.

1) The model can be adopted for Engineering design applications by considering the local conditions.
2) The DCP– CBR relation was modeled with limited data sets. Hence, further data collection is deemed necessary to make the findings more reliable.
3) The study is conducted on clay soil. Hence, different varieties of subgrade materials could be tested.

Abbreviations

AASHTO	American State Highway Transportation Official
ASTM	American Standard Test Method
BSI	British Standard Institute
CBR	California Bearing Ratio
DCP	Dynamic Cone Penetration
DCPI	Dynamic Cone Penetration Index
ERA	Ethiopian Roads Administration
FDT	Field Dry Density
LL	Liquid Limit
NMA	In Situ Moisture Content
PI	Plastic Index
PL	Plastic Limit
SPSS	Statistical Package for the Social Sciences
TRL	Transport Research Laboratory
UCS	Unconfined Compressive Strength

Declarations

Availability of data and materials: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author Contributions

Yitagesu Desalegn Halala: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data curation

Samuel Tadesse Tafesse: Conceptualization, Writing – review & editing

Henok Tsegaye Teferi: Methodology, Data collection

Conflicts of Interest

The authors declare no conflicts of interest.

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