SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I12P102

Volume 12 Issue 12, 12-25, December 2025
© 2025 Seventh Sense Research Group®

Original Article

Correlation between the Dynamic Cone Penetrometer and the California Bearing Ratio for Subgrade Soils

Boris Senin Carhuallanqui Parian[1], Yazmín De la cruz Jeremías[2], Janet Yéssica Andía Arias[2], Víctor Peña Dueñas[3], Albert Jorddy Valenzuela Inga[3*], Rosali Ramos Rojas[3]

[1]*Institute for Statistical Studies and Economics of Knowledge (ISEEK) – HSE University, Russia.*
[2]*Faculty of Engineering, Academic School of Civil Engineering, Universidad Peruana Los Andes, Huancayo, Peru.*
[3]*Faculty of Engineering, Academic School of Civil Engineering, Universidad Continental, Huancayo, Peru.*

[*]*Corresponding Author : 73449915@continental.edu.pe*

Received: 02 October 2025 Revised: 03 November 2025 Accepted: 02 December 2025 Published: 29 December 2025

Abstract *- The assessment of soil bearing capacity is fundamental for pavement design, but the traditional California Bearing Ratio (CBR) test is time-consuming and costly. The Dynamic Cone Penetrometer (DCP) offers a rapid and cost-effective field alternative. This study develops and validates correlation models between CBR and DCP for clayey, granular, and clayey-granular soils. The analysis was based on 15 CBR tests and evaluated against four established DCP correlation models: Kleyn and Van Heerden, TRL Overseas Road Note 8, US Corps of Engineers, and MOPT Colombia 1992. Results demonstrate that a cubic regression model consistently provides the best fit for all soil types, achieving coefficients of determination (R^2) as high as 0.96 for granular soils and exceeding 0.89 for clayey soils. The findings confirm that the DCP test, when paired with the validated cubic correlations, constitutes a precise and efficient tool for estimating CBR, covering efficient on-site testing and information for preliminary design in pavement subgrade.*

Keywords *- Dynamic Cone Penetrometer (DCP), CBR-DCP correlation, Soil characterization, Geotechnical engineering, California Bearing Ratio (CBR).*

1. Introduction

Within the industry of road construction, the acquisition of a soil classification remains a challenge, due to the fact that traditional laboratory methods often require significant time, skilled personnel, and financial resources [1]. This is the main reason why the correlation of the California Bearing Ratio (CBR) test with the Dynamic Cone Penetrometer (DCP) index is needed because it can provide certain advantages for rapid soil diagnosis in the area of work [2]. Thus, establishing accurate correlations is essential to comply with international and national technical standards, such as ASTM D6951 specifications and the Peruvian standard MTC (Manual of codes and test procedures) [4, 5].

The use of CBR is already well established in the entire world, and it is also used as a traditional practice for evaluation before the paving activity [6], and this tool, along with the DCP, is a fundamental and complementary tests in the mechanics of soils [7]. In addition, performing the latter test provides a simple and economical way to evaluate soil strength [8] because it is standardized according to ASTM D6951. This test consists of repeatedly hitting a steel cone with a hammer and then recording the penetration ratio with each blow [9, 10]. Despite its simplicity, the DCP method provides enough information to carry out the refinement of the initial design, quality control, and long-term performance of pre-paving soils.

Previous scientific literature has explored numerous types of relationships between DCP results and CBR values. The found correlations have been established by linking the subgrade modulus to both tests [6]. A study in Brazil [11] demonstrated the effectiveness of correlating CBR values with DCP results for various types of soil by developing predictive equations. Similarly, another previous research has introduced recalibrated correlations that have shown high accuracy for various types of soil groups, which facilitates rapid and reliable CBR estimations [4].

On the other hand, it is also noticed that moisture content and bulk density significantly influence DCP estimates; it has also been proposed that the DCP methodology can be employed for the preliminary road subgrade design so that relative strength can be verified [12]. Likewise, the application of the correlation across different soil types can lead to a generalized relationship between the DCP penetration rate and the CBR test [13].

This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

Despite the fact that the laboratory application of the CBR is time-consuming and resource-intensive, it is a fundamental test. Due to these drawbacks, the CBR test presents the DCP trial as an efficient alternative, even though its reliability depends on a precise correlation with CBR values, and its applicability can vary significantly depending on the soil type. Therefore, the aim of this research is not only to obtain, but also to validate, the correlation equations between the DCP and CBR tests for three types of soils: clayey soils, granular soils, and a combination of the two.

The distribution of this paper is divided into the following sections: first, the section of materials and methods employed, followed by the results obtained through the analysis of the correlations and their applicability, and ending with the conclusions of this study, in which are also proposed future lines of research.

2. Materials and Methods

2.1. Soil Classification and Characterization

The classification of soil is an activity that follows standardized laboratory procedures, and it provides insight into how the material behaves, both physically and mechanically. One of the most important tests for doing the soil classification is the consistency limits test (according to ASTM D4318 [14]). This test is widely used to determine how plastic a fine soil is, and it also defines two key values:

- The Liquid Limit (LL) indicates the point at which the soil changes from behaving as a plastic to behaving as a liquid.
- The Plastic Limit (PL) is the value that marks the point below which the soil no longer deforms plastically.

These two values are fundamental not only for the classification of the type of soil, but also for the anticipation of its behavior in engineering works. Figure 1 shows how this test is performed in the laboratory.

Fig. 1 Atterberg limits test on a clayey soil, (a) Determination of the liquid limit using the Casagrande cup device, (b) Rolling soil threads for the plastic limit test, and (c) Molded threads ready for oven-drying to determine their moisture content.

The particle size distribution is obtained by sieve analysis according to NTP 400.012 [14] and allows us to know how the soil particles are distributed according to their size. This information is key to determining if the material is suitable for different uses in construction. Figure 2 shows the soil fractions separated by size.

Fig. 2 Soil fractions separated by particle size analysis

Water content is one of the parameters that most influence soil behaviour. For this purpose, the samples are dried in an oven at a controlled temperature until a real weight of the sample is reached; this ratio of water and weight gives the moisture content [14]. According to [15], these moisture states can alter both the shear strength and compressibility.

To interpret the results, the USCS and AASHTO classification systems were applied, both of which helped to group the soils according to their grain size and plasticity.

2.2. Modified Proctor Test

The modified Proctor test was performed according to ASTM D1557 [16] and AASHTO T180 [17] to evaluate how the soil is compacted. During this procedure, samples are placed in a mold of five different layers, and each layer is compacted by applying 25 blows with a 4.54 kg hammer from a height of 457 mm. After this, the relationship between dry density and moisture content is plotted; this plotting action allows the identification of two key parameters.

Fig. 3 Manual execution of the modified proctor with a standard tamper on the sample in molds

2.3. Dynamic Cone Penetrometer (DCP) Test

The Dynamic Cone Penetrometer Test (DCP) is one of the most popular methods in geotechnics, which is used to evaluate soil strength directly in the area of work [18]. This technique consists of introducing a standardized cone into the ground by using controlled blows, and then measuring how much it sinks with each impact. According to the ASTM D6951 [9], this method is suitable for application in both fine and coarse soils, but not only that, because it also provides useful information about the density and bearing capacity of these soils in the natural state. A previous study done by Salamanca-Medina and Dominguez [19] showed that the DCP method is effective in characterizing soils with different textures, and this highlights its importance in geotechnical field investigations. Figure 4 shows the equipment schematic, while Figure 5 presents the field test.

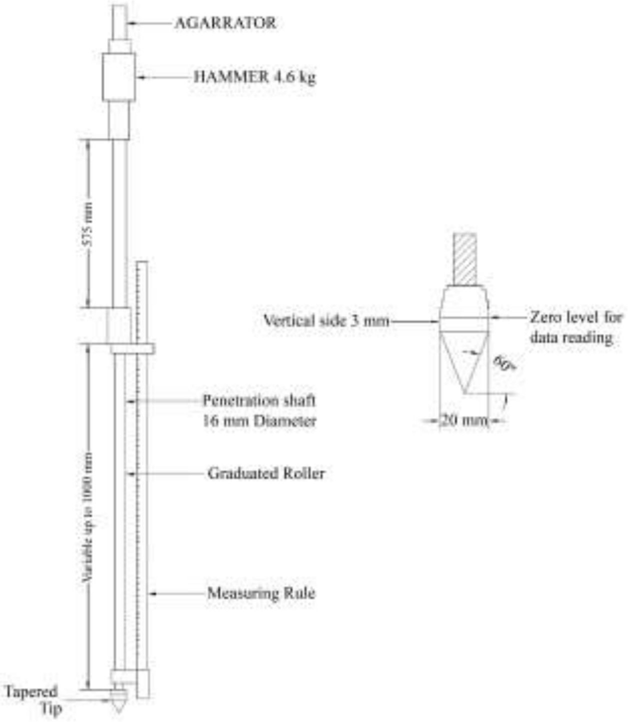

Fig. 4 Schematic of the Dynamic Cone Penetrometer (DCP) apparatus

Fig. 5 Dynamic Cone Penetrometer test (DCP) to evaluate the strength of the soil in its natural state

2.4. California Bearing Ratio (CBR) Test

A very basic test widely used in geotechnical engineering is the CBR (California Bearing Ratio), which permits measuring how resistant a soil or material is when facing loading, especially when pavements or roads are to be built on it. This test was performed according to ASTM D1883 [20], which defines how to measure the CBR value in the laboratory for soil materials such as subgrade, subbase, and base used in pavement construction. According to [21], the test provides key parameters for the design and evaluation of road structures across diverse soil types. The configuration of the apparatus is presented schematically in Figure 6.

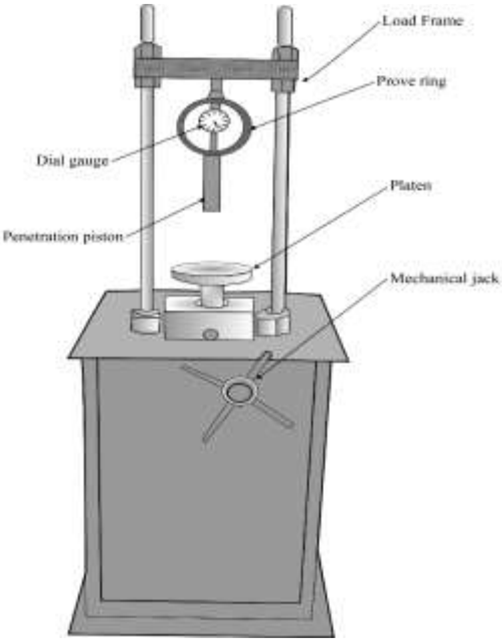

Fig. 6 Schematic diagram of the California Bearing Ratio (CBR) test apparatus

3. Results

Fifteen cylindrical samples with a diameter of 152 mm (6 in) and a height of 178 m (7 in) were elaborated and analyzed under proctor compaction and CBR test.

3.1. Soil Classification

The characteristics of the soil were analyzed using different laboratory tests, with the objective of knowing how it behaves in terms of strength, stability, and bearing capacity. Table 1 shows the consistency limits of three samples (M1, M2, and M3), which were chosen from a group of 16 samples that had similar properties, like their composition, texture, or even their initial conditions. The chosen soils were then classified into three different groups: clayey, granular, and clayey-granular. For the clayey soil, the Liquid Limit (LL) ranged from 36 to 37, the Plastic Limit (PL) was between 11 and 12, and the Plasticity Index (PI) ranged from 25 to 26. On the other hand, the granular soil type had an LL between 35 and 36, a PL from 26 to 27, and a constant PI of 9. The clayey-granular soil type exhibited a constant LL of 29, a PL of 15, and a PI of 14.

Table 2 presents the distribution of the particle sizes, while also highlighting the percentage of different factors, such as gravel, sand, and fines. The clayey soil type presents the characteristic of being predominantly fine-grained, with a content of fines that exceeds 90%. In contrast, the granular soil has the feature to be coarse-grained, with a gravel content near 50% and a content of fines that ranges from 22.43% to 22.64%. On the other hand, the clayey-granular soil shows a mix of the following properties: 67.5% fines, approximately 21% gravel, and 11.5% sand.

Table 3 summarizes three different soil classifications according to the USCS and AASHTO systems. The clayey soil is classified as CL (USCS) and A-6(22) (AASHTO), which indicates that it has plastic behavior. The granular soil is classified as GM (Silty Gravel) and A-2-4(0). These results suggest that it is very suitable as a construction material. Meanwhile, the clayey-granular soil is classified as CL and A-6(7), and this indicates an intermediate bearing capacity.

Table 1. Consistency limits of the soil samples

			Clayey Soil			**Granular Soil**		**Clayey-Granular Soil**	
Sample	LL	PL	PI	LL	PL	PI	LL	PL	PI
M1	37	11	26	36	27	9	29	15	14
M2	37	12	25	36	27	9	29	15	14
M3	36	11	25	35	26	9	29	15	14

Table 2. Particle size distribution of the samples

			Clayey Soil			**Granular Soil**		**Clayey-Granular Soil**	
Composition	M1	M2	M3	M1	M2	M3	M1	M2	M3
%GRAVEL	2.09	2.08	2.08	49.98	49.88	49.97	21.03	21,03	21.04
%SAND	7.86	7.87	7.86	27.45	27.43	26.39	11.47	11.47	11.47
%FINES	90.05	90.05	90.06	22.57	22.43	22.64	67.5	67.5	67.5

Table 3. Soil classification of the samples

Classification	**Clayey Soil**	**Granular Soil**	**Clayey-Granular Soil**
USCS	CL	GM	CL
AASHTO	A-6(22)	A-2-4(0)	A-6(7)

Table 4. Proctor compaction test results for the three soil types

	Clayey Soil		**Granular Soil**		**Clayey-Granular Soil**	
Sample	MDD(g/cm^3)	OMC(%)	MDD(g/cm^3)	OMC(%)	MDD(g/cm^3)	OMC(%)
M1	1.882	13	2.114	8.50	2.074	8.50
M2	1.882	13	2.122	7.00	2.082	8.50
M3	1.874	13	2.122	8.00	2.074	8.50
M4	1.874	13	2.122	7.00	2.074	8.50
M5	1.874	13	2.122	7.00	2.074	8.50
M6	1.874	13	2.122	7.00	2.074	8.50
M7	1.874	13	2.122	7.00	2.074	8.50
M8	1.882	13	2.122	8.00	2.074	8.50
M9	1.882	13	2.122	8.00	2.074	8.50
M10	1.882	13	2.122	8.00	2.074	8.50
M11	1.882	13	2.122	8.00	2.074	8.50
M12	1.882	13	2.114	8.50	2.082	8.50
M13	1.882	13	2.114	8.50	2.082	8.50
M14	1.882	13	2.114	8.50	2.082	8.50
M15	1.882	13	2.114	8.50	2.082	8.50
Mean	1.879	13.00	2.12	7.83	2.077	8.50
Standard Deviation	0.004	0.00	0.00	0.65	0.004	0.00

3.2. Proctor Compaction Test Results

Table 4 summarizes and shows the compaction characteristics, specifically two: the first one is the Maximum Dry Density (MDD), while the second one is the Optimum Moisture Content (OMC). In addition, this table also exhibits these two compaction characteristics in the case of the three types of soils: the clayey, granular, and clayey-granular soils across fifteen different samples. The clayey soil type consistently exhibits an MDD between 1.874 and 1.882 g/cm³, with a constant OMC of 13%. These numbers indicate a relatively low density and high moisture demand. In contrast, the granular soil exhibits a higher MDD, close to 2.114 or 2.122 g/cm³, with an OMC varying between 7.00% and 8.50%; these outcomes reflect that this soil has a lower water retention. The clayey-granular soil, instead, presents intermediate characteristics, with an MDD between 2.074 and 2.082 g/cm³ and a constant OMC of 8.50%. The homogeneous results obtained in the measurements within each soil type, confirmed along with the low standard deviation values, suggest that uniform compaction conditions were achieved.

Table 5 exhibits the values of the laboratory California Bearing Ratio (CBR) that were acquired for the clayey, granular, and clayey-granular soils. All these samples were evaluated at two compaction levels: 95% and 100% of their respective Maximum Dry Density (MDD). On average, the granular soil samples exhibited the highest CBR values, registering 15.02% at 95% MDD and 32.85% at 100% MDD. With respect to the low standard deviations obtained (σ = 2.32 and 0.36, respectively), they were notable. This indicates a high consistency and confirms their superior bearing capacity. Conversely, the clayey soil samples showed the lowest CBR values (averaging 1.50% and 2.81%). These numbers confirm their limited structural strength. In addition, the clayey-granular soils got intermediate results, with average CBRs of 7.51% and 14.01% (σ = 0.74 and 0.46), exhibiting a significant improvement in strength as the compaction level increases as well. When observing all the soil types, a clear increasing trend in CBR values was noticed that goes in line with a higher compaction density. This observation confirms the direct and critical influence that the degree of compaction has on the soil's bearing capacity.

Table 5. CBR test results at 95% and 100% compaction

	Clayey Soil		**Granular Soil**		**Clayey-Granular Soil**	
Sample	CBR at 95% MDD (%)	CBR at 100% MDD (%)	CBR at 95% MDD (%)	CBR at 100% MDD (%)	CBR at 95% MDD (%)	CBR at 100% MDD (%)
M1	1.54	2.81	18.5	32.97	7.9	13.9
M2	1.63	2.81	18.22	32.65	7.8	13.86
M3	1.64	2.78	18.13	32.43	7.71	13.81
M4	1.8	2.75	17.11	32.81	7.87	14.43
M5	1.14	2.72	15.90	32.96	7.94	14.97
M6	1.24	2.7	16.19	33.12	8.05	14.70
M7	1.15	2.69	14.49	33.27	8.06	14.65
M8	1.54	2.74	12.82	32.65	7.70	13.96
M9	1.58	2.74	13.21	32.87	7.70	13.90
M10	1.6	2.71	12.70	33.10	8.10	13.83
M11	1.34	2.76	13.28	33.32	7.91	13.76
M12	1.26	2.89	16.09	33.24	5.83	13.44
M13	1.68	2.97	11.11	32.83	6.22	13.54
M14	1.68	3.06	13.23	32.43	6.31	13.64
M15	1.63	2.97	14.36	32.04	7.61	13.74
Mean	1.50	2.81	15.02	32.85	7.51	14.01
Standard Deviation	0.21	0.11	2.32	0.36	0.74	0.46

3.3. CBR Correlation for Clayey Soils

Figure 7 displays the results obtained from the regression analyses performed on the clayey soil, which correlate the laboratory-measured CBR values (at 100% MDD) with the CBR values estimated from four different DCP-based models. At this stage, five regression types were fitted to the data: exponential, logarithmic, cubic, power, and linear. For all the evaluated models (Kleyn and Van Heerden (Figure 7(a)), TRL Overseas Road Note 8 (Figure 7(b)), US Corps of Engineers (Figure 7(c)), and MOPT Colombia 1992 (Figure 7(d)), the cubic regression model (which is the blue line) reliably provides the best fit to the experimental data. This feature of superiority is indicated by its ability to capture the data's curvature and by achieving the highest coefficient of determination (R^2) in each case. In contrast, the linear, logarithmic, and power models exhibit a more limited ability for the accurate representation of this relationship. Table 6 provides a very detailed summary of the regression equations and their corresponding coefficients of determination (R^2) for each of the models that were fitted to the clayey soil data, and this is visually presented in Figure 7. The cubic models consistently produced the highest R^2 values, and this indicated the best fit for all four DCP correlation methods used in this study.

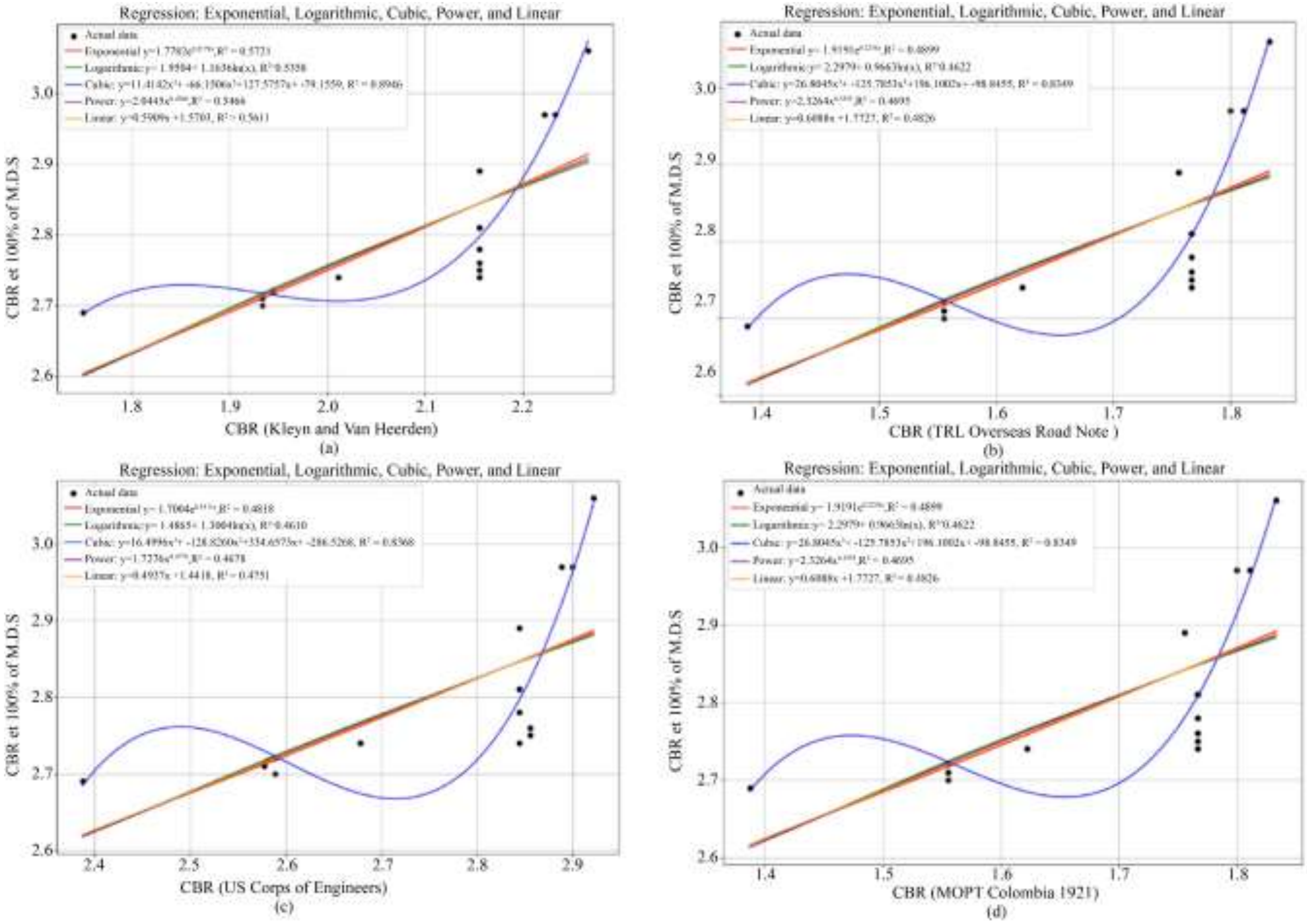

Fig. 7 Correlation plots between laboratory-measured CBR (at 100% MDD) and DCP-estimated CBR for the clayey soil. The analysis evaluates five regression models (exponential, logarithmic, cubic, power, and linear) for four different DCP correlation methods, (a) Kleyn and van heerden, (b) TRL overseas road note 8, (c) US corps of engineers, and (d) MOPT colombia 1992.

Table 6. Regression equations and coefficients for the methods applied to the clayey soil

Method	Model	Equation	R^2
Kleyn and Van Heerden	Linear	$y = 0.5909 * x + 1.5703$	0.5611
	Exponential	$y = 1.7782 * e^{0.2178x}$	0.5721
	Logarithmic	$y = 1.9504 + 1.16\ln(x)$	0.5358
	Cubic	$y = 11.41x^3 - 66.1506x^2 - 127.5757x - 79.1559$	0.8946
	Power	$y = 2.0445x^{0.43}$	0.5466
TRL Overseas Road Note 8	Linear	$y = 0.6088x + 1.7727$	0.4826
	Exponential	$y = 1.9191e^{0.2236x}$	0.4899
	Logarithmic	$y = 2.2976 + 0.9663 * \ln(x)$	0.4622
	Cubic	$y = 26.8045x^3 - 125.7853x^2 - 196.1002 * x - 98.8455$	0.8349

	Power	$y = 2.3264x^{0.3555}$	0.4695
US Corps of Engineers	Linear	$y = 0.4937x + 1.4418$	0.4751
	Exponential	$y = 1.7004e^{0.1811x}$	0.4818
	Logarithmic	$y = 1.4865 + 1.3004\ln(x)$	0.4610
	Cubic	$y = 16.4996x^3 - 128.826x^2 - 334.657x - 286.5268$	0.8368
	Power	$y = 1.7276x^{0.4776}$	0.4678
MOPT Colombia 1992	Linear	$y = 0.6088x + 1.7727$	0.4826
	Exponential	$y = 1.9191e^{0.2236x}$	0.4899
	Logarithmic	$y = 2.2976 + 0.9663\ln(x)$	0.4622
	Cubic	$y = 26.8045x^3 - 125.7853x^2 - 196.1002x - 98.8455$	0.8349
	Power	$y = 2.3264x^{0.3555}$	0.4695

Figure 8 shows a visual comparison of the performance of five regression models. This figure exhibits their coefficients of determination (R^2) for each of the four DCP methods applied to the clayey soil. The results show that the cubic model is superior to the others because it consistently provides the highest R^2 values, ranging from 0.8368 to 0.8946. This result indicates the best fit to the data across all the evaluated methods. On the other hand, the remaining functions (Linear, Exponential, Logarithmic, and Power) demonstrated significantly weaker correlations because their R^2 values generally fell between 0.46 and 0.57. This result also underscores the efficacy of the cubic model in not only describing the soil's performance but also capturing the underlying relationship.

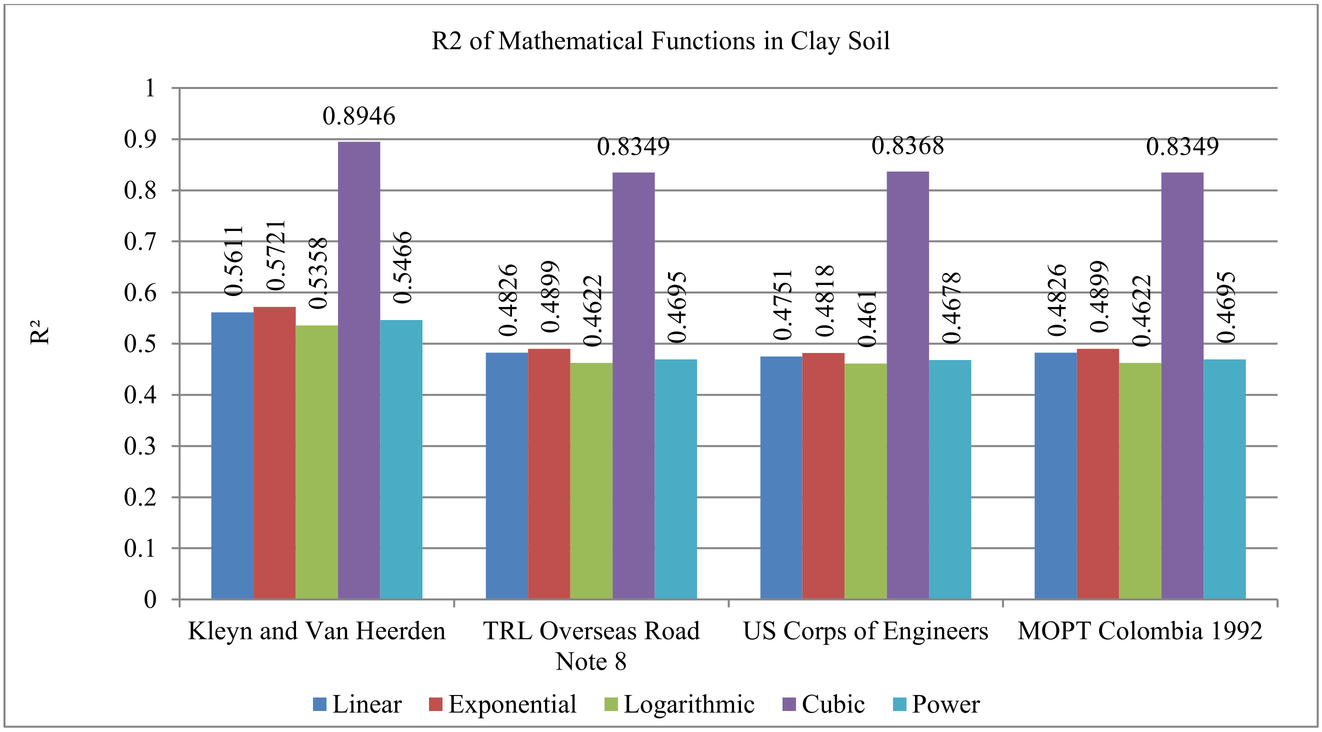

Fig. 8 Comparison of the coefficient of determination (R^2) for five regression models across the four DCP-CBR correlation methods for the clayey soil. The chart highlights the superior performance of the cubic model

Likewise, the validity test was carried out for the model that best fits the prediction (Kleyn and Van Heerden), $R^2 = 0.8946$, obtaining values of less than 10%. These tests were conducted based on the Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), as shown in Table 6.

Table 7. Performance metric for the R2 model with the best fit (clayey soil)

No	CBR AT 100% OF M.D.S.	CBR (Kleyn and Van Heerden)	Prediction
1	2.69	1.75	2.69
2	2.7	1.93	2.72
3	2.71	1.93	2.72
4	2.72	1.94	2.72
5	2.74	2.01	2.71
6	2.74	2.16	2.80
7	2.75	2.16	2.80
8	2.76	2.16	2.80
9	2.78	2.16	2.80
10	2.81	2.16	2.80
11	2.81	2.16	2.80
12	2.89	2.16	2.80
13	2.97	2.22	2.94
14	2.97	2.23	2.97
15	3.06	2.27	3.08
	MAE	**0.03**	**6.67%**
	RMSE	**0.04**	**9.01%**

3.4. CBR Correlation for Granular Soil

Figure 9 presents the regression analyses for the granular soil, correlating the laboratory-measured CBR values (at 100% MDD) with the CBR values estimated from four different DCP-based references. The analyses for the Kleyn and Van Heerden, TRL Overseas Road Note 8, US Corps of Engineers, and MOPT Colombia 1992 methods are shown in Figure 9(a), Figure 9(b), Figure 9(c), and Figure 9(d), respectively. In each subplot, the black dots represent the experimental data, while the colored curves correspond to the different regression models.

The outcomes in this study reveal that for the granular soil, the cubic regression model (blue line) is the one that consistently provides the best fit to the data, achieving the highest R² values, which reach up to 0.9687. While other models also show strong correlations for this type of soil, the cubic model is the one that most effectively captures the data's trend. In addition, the specific equations and coefficients of determination (R²) for each model are detailed in Table 8.

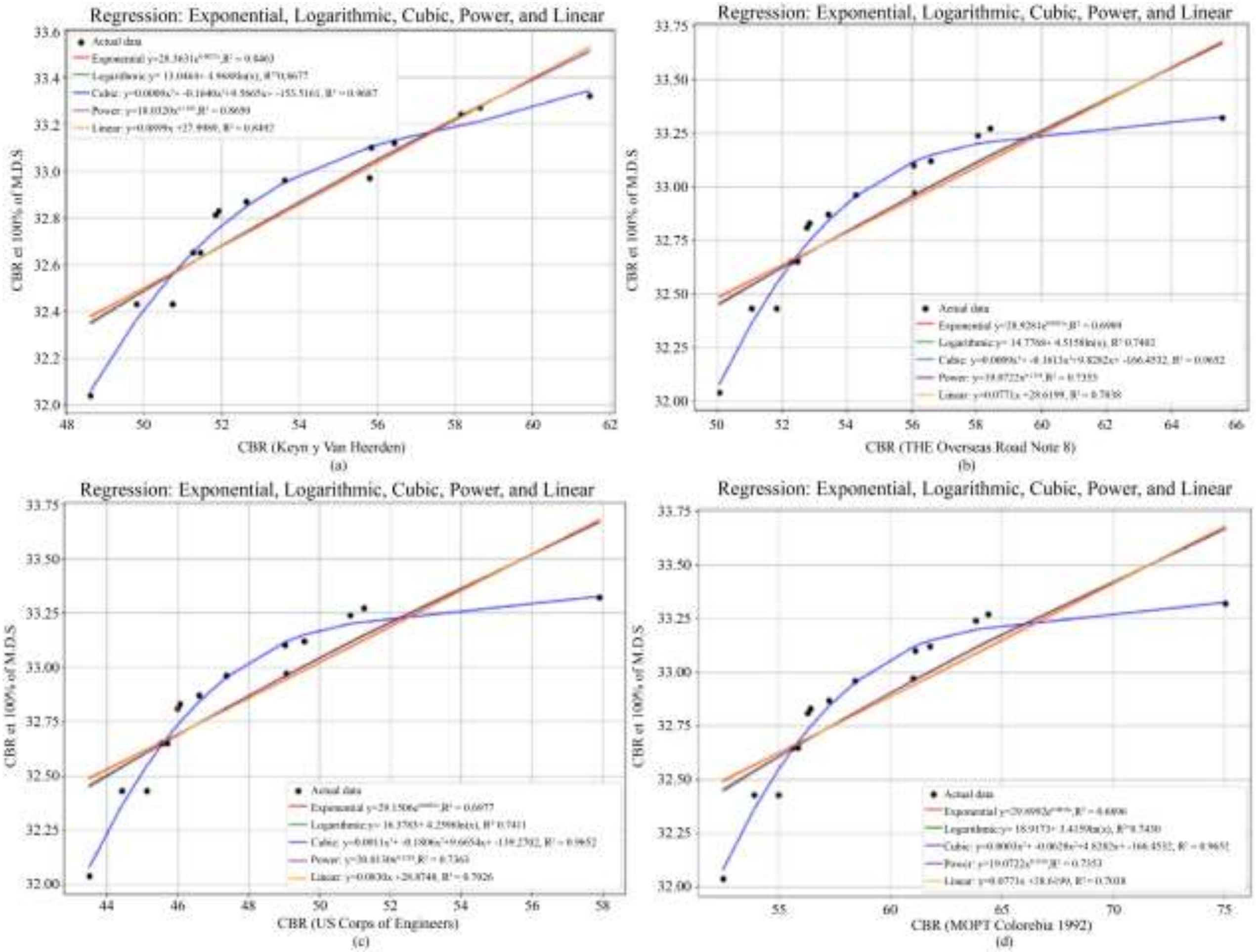

Fig. 9 Correlation plots between laboratory-measured CBR (at 100% MDD) and DCP-estimated CBR for the granular soil, (a) Kleyn and van heerden, (b) TRL overseas road note 8, (c) US corps of engineers, and (d) MOPT colombia 1992.

Table 8. Regression equations and coefficients for the methods applied to the granular Soil

Method	Model	Equation	R^2
Kleyn and Van Heerden	Linear	$y = 0.0899x + 27.9989$	0.8492
	Exponential	$y = 28.3631e^{0.0027x}$	0.8463
	Logarithmic	$y = 13.0464 + 4.9688 * \ln(x)$	0.8677
	Cubic	$y = 0.0009x^3 - 0.1640x^2 + 9.5665x - 153.5161$	0.8687
	Power	$y = 18.0320x^{0.1505}$	0.8650
TRL Overseas Road Note 8	Linear	$y = 0.0771 * x + 28.6199$	0.7038
	Exponential	$y = 28.9281 * e^{0.0023x}$	0.6989
	Logarithmic	$y = 14.7768 + 4.5158 * \ln(x)$	0.7402
	Cubic	$y = 0.0009 * x^3 - 0.1613 * x^2 + 9.8282 * x - 166.4532$	0.9652
	Power	$y = 19.0722 * x^{0.1358}$	0.7353
US Corps of Engineers	Linear	$y = 0.0830 * x + 28.8748$	0.7026
	Exponential	$y = 29.1506 * e^{0.0025x}$	0.6977
	Logarithmic	$y = 16.3783 + 4.2596 * \ln(x)$	0.7411
	Cubic	$y = 0.0011 * x^3 - 0.1806 * x^2 + 9.6654 * x - 139.2702$	0.9652
	Power	$y = 20.0130 * x^{0.1281}$	0.7363
MOPT Colombia 1992	Linear	$y = 0.0528 * x + 28.7178$	0.6946
	Exponential	$y = 29.8992 * e^{0.0016x}$	0.6896
	Logarithmic	$y = 18.9173 + 3.4159 * \ln(x)$	0.7430
	Cubic	$y = 0.0003 * x^3 - 0.0628x^2 - 4.2690 * x - 63.5150$	0.9648
	Power	$y = 21.6012 * x^{0.1028}$	0.7381

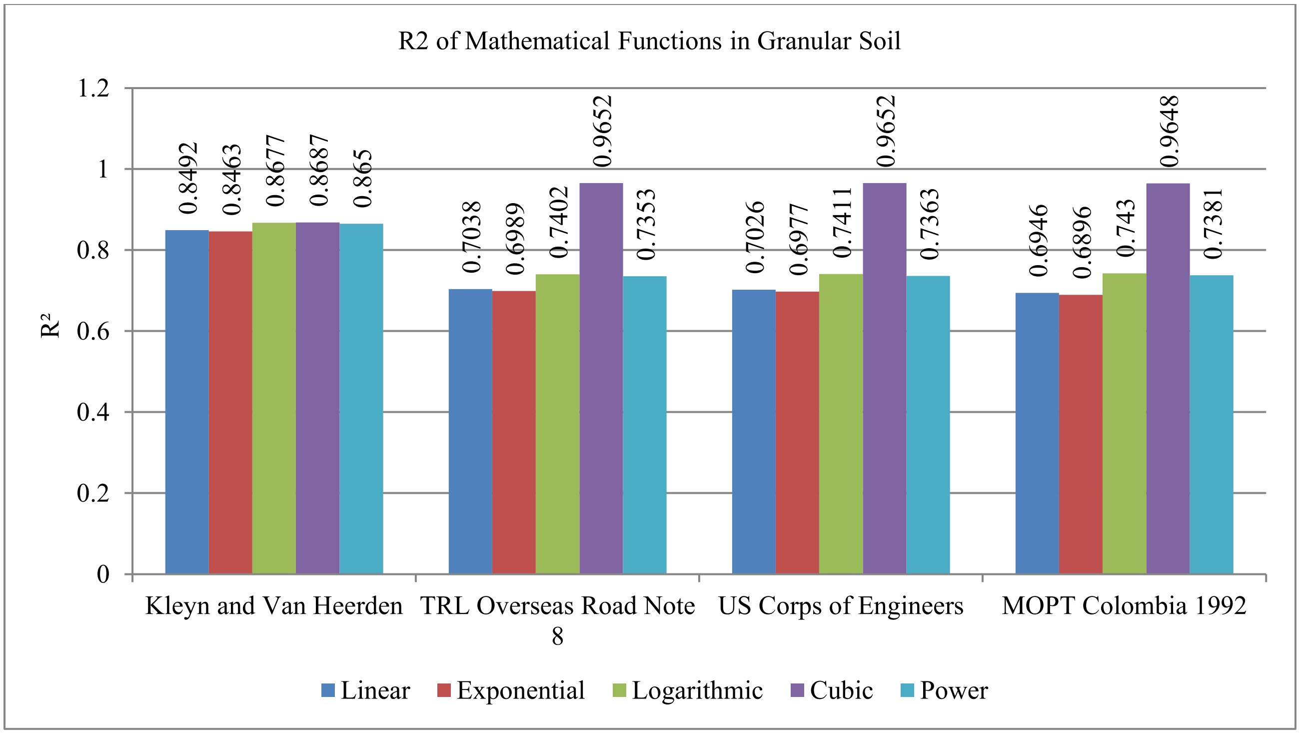

Fig. 10 Comparison of the coefficient of determination (R²) for five regression models across the four DCP-CBR correlation methods for the granular soil. The chart clearly shows the superior fit of the cubic model

Table 9. Performance metric for the R2 model with the best fit (granular soil)

Nº	CBR AT 100% OF M.D.S.	CBR (TRL Overseas Road Note 8)	Predicción
1	32.04	50.07	34.24
2	32.43	51.07	34.66
3	32.43	51.84	34.95
4	32.65	52.29	35.11
5	32.65	52.48	35.17
6	32.81	52.77	35.27
7	32.83	52.85	35.29
8	32.87	53.44	35.48
9	32.96	54.28	35.72
10	32.97	56.08	36.16
11	33.1	56.05	36.16
12	33.12	56.60	36.28
13	33.24	58.03	36.58
14	33.27	58.43	36.66
15	33.32	65.59	38.22
	MAE	**2.88**	**6.67%**
	RMSE	**2.96**	**6.84%**

Figure 10 exposes a visual comparison of the performance of the five regression models used in this study by plotting their coefficients of determination (R²) for each of the four DCP methods applied to the granular soil. The cubic function is the one that consistently produced the highest R² values across all methods, and particularly for the TRL Overseas Road Note 8 and the US Corps of Engineers correlations, where it reached a maximum of 0.9652.

This indicates an excellent fit to the data. In contrast, the Linear, Exponential, Logarithmic, and Power functions yielded lower R² values, generally ranging from 0.69 to 0.87, signifying a comparatively weaker performance in modeling the data.

Likewise, the validity test was performed for the model that best fits the prediction (TRL Overseas Road Note 8), R2 = 0.9652, obtaining values of less than 10%. These tests were performed based on the Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) as shown in Table 9.

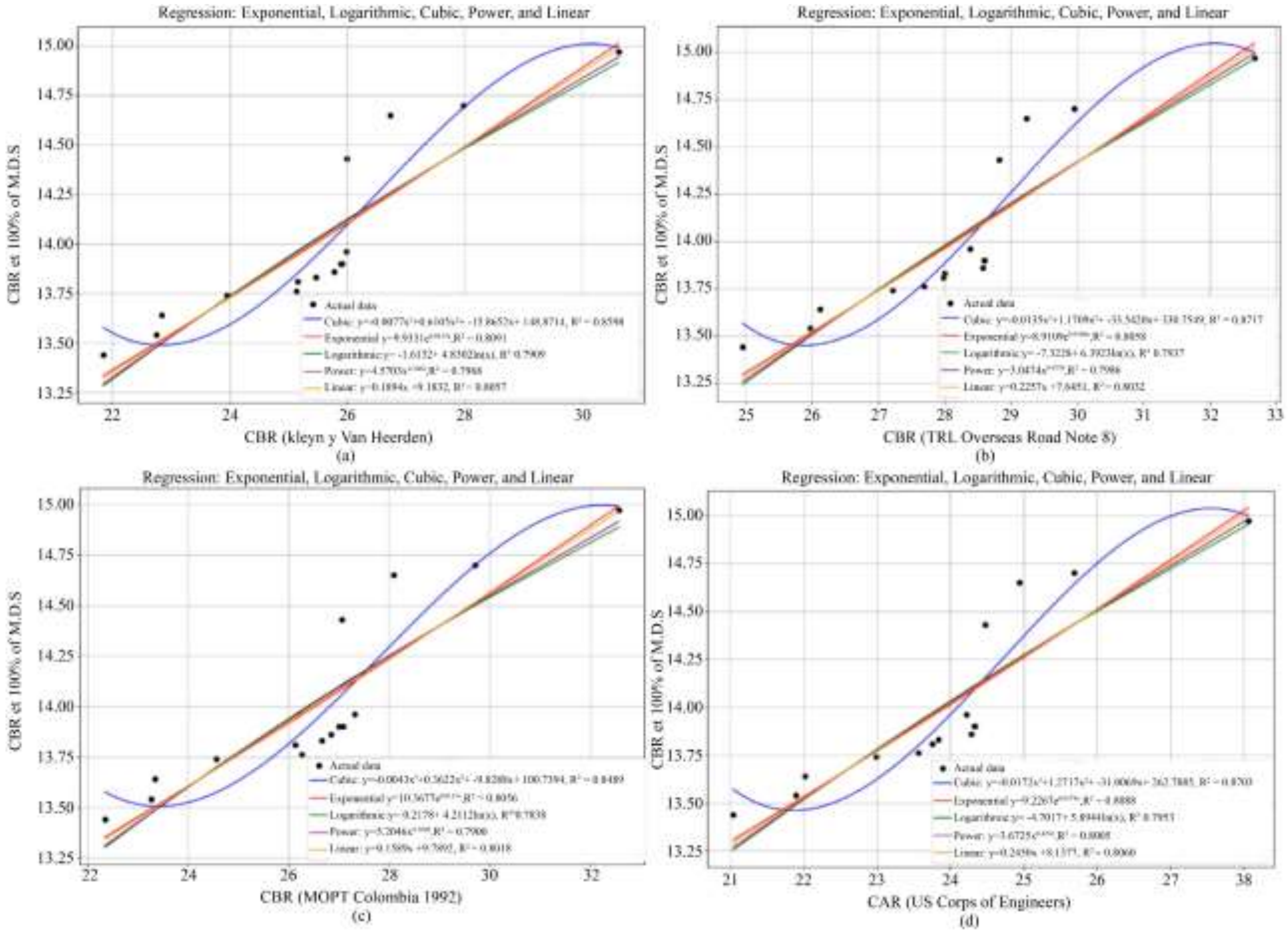

Fig. 11 Correlation plots between laboratory-measured CBR (at 100% MDD) and DCP-estimated CBR for the clayey-granular soil. The analysis evaluates five regression models for four different DCP correlation methods, (a) Kleyn and van heerden, (b) TRL overseas road note 8, and (c) MOPT colombia 1992, and (d) US corps of engineers.

3.5. CBR Correlation for Clayey-Granular Soil

The regression analyses for the clayey-granular soil are presented in Figure 11. These plots correlate laboratory-measured CBR values (at 100% MDD) with CBR values estimated from four different DCP-based methods: Kleyn and Van Heerden (Figure 11(a)), TRL Overseas Road Note 8 (Figure 11(b)), MOPT Colombia 1992 (Figure 11(c)), and US Corps of Engineers (Figure 11(d)). In each subplot, it can be seen that the black dots represent the experimental data, while the colored curves show the different regression models. Among these, the cubic regression model (blue line) consistently provides the best fit, achieving the highest R² values, which reach up to 0.8717. While the other models also show reasonable correlation, they exhibit lower precision, with R² values as low as 0.7838. Table 10 provides a detailed summary of the regression equations and their corresponding coefficients of determination (R²) for each model fitted to the clayey-granular soil data, as visually presented in Figure 11. The results confirm that the cubic models consistently yielded the highest R² values, indicating the best fit across all four DCP correlation methods.

Table 10. Regression equations and coefficients for the methods applied to the clayey-granular soil

Method	Model	Equation	R²
Kleyn and Van Heerden	Linear	$y = 0.1894x + 9.1832$	0.8057
	Exponential	$y = 9.9331e^{0.0135x}$	0.8091
	Logarithmic	$y = -1.6132 + 4.8302 * \ln(x)$	0.7909
	Cubic	$y - 0.0077 * x^3 + 0.6105 * x^2 - 15.8652 * x + 148.8714$	0.8598
	Power	$y = 4.5703 * x^{0.3462}$	0.7698
TRL Overseas Road Note 8	Linear	$y = 0.2257 * x + 7.6451$	0.8032
	Exponential	$y = 8.9109 * e^{0.0160x}$	0.8058
	Logarithmic	$y - 7.3228 + 6.3923 * \ln(x)$	0.7937
	Cubic	$y = -0.0135 * x^3 + 1.1709 * x^2 - 33.5420 * x + 330.7549$	0.8717
	Power	$y = 3.0474 * x^{0.4570}$	0.7986
US Corps of Engineers	Linear	$y = 0.2450 * x + 8.1377$	0.8060
	Exponential	$y = 9.2267 * e^{0.0174x}$	0.8088
	Logarithmic	$y = -4.7017 + 5.8944 * \ln(x)$	0.7953
	Cubic	$y = -0.0172 * x^3 + 1.2717 * x^2 - 31.0069 * x + 262.7885$	0.8703
	Power	$y = 3.6725 * x^{0.4216}$	0.8005
MOPT Colombia 1992	Linear	$y = 0.1589 * x + 9.7892$	0.8018
	Exponential	$y = 10.3677 * e^{0.0113x}$	0.8056
	Logarithmic	$y = 0.2178 + 4.2112 * \ln(x)$	0.7838
	Cubic	$y = -0.0043 * x^3 + 0.3622 * x^2 - 9.8288 * x + 100.7394$	0.8489
	Power	$y = 5.2046 * x^{0.3022}$	0.7900

Figure 12 presents a grouped bar chart comparing the performance of the five mathematical functions (Linear, Exponential, Logarithmic, Cubic, and Power) by plotting their R² values for the four DCP methods applied to the clayey-granular soil. The analysis shows that R² values range from 0.7698 to 0.8717. The cubic function consistently yields the best results in terms of data fit, reaching a peak R² value of 0.8717. The Linear, Exponential, Logarithmic, and Power functions demonstrate a similar, but weaker, performance, with R² values generally ranging from 0.7698 to 0.8091. This suggests that while these models are effective, they do not achieve the level of precision offered by the cubic function in this context.

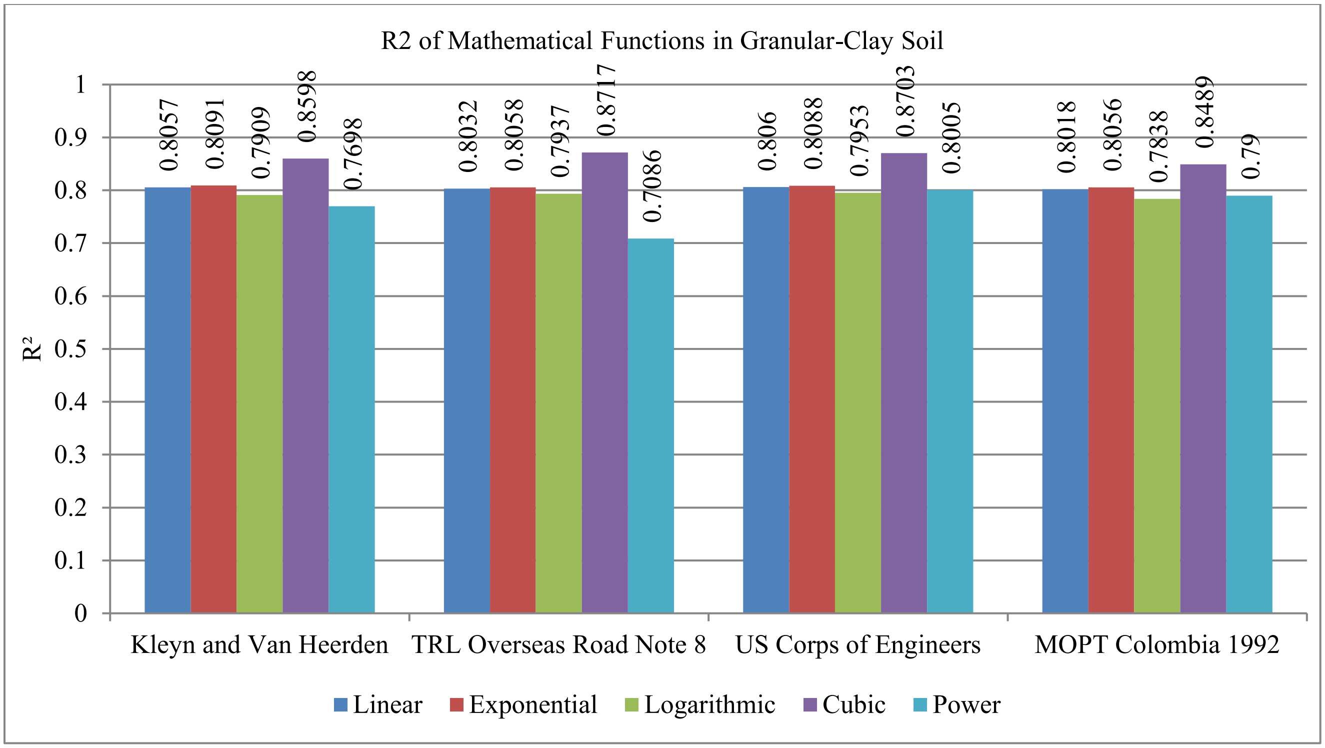

Fig. 12 Comparison of the coefficient of determination (R²) for five regression models across the four DCP-CBR correlation methods for the clayey-granular soil

In the same way, the validity test was carried out for the model that best fits the prediction (TRL Overseas Road Note 8), $R^2 = 0.8717$, obtaining values of less than 10%. These tests were carried out based on the Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) as shown in Table 11.

Table 11. Performance metric for the R2 model with the best fit (clayey-granular soil)

Nº	CBR AT 100% OF M.D.S.	CBR (TRL Overseas Road Note 8)	Predicción
1	13.44	24.96	13.10
2	13.54	25.98	12.92
3	13.64	26.13	12.92
4	13.74	27.22	13.03
5	13.76	27.70	13.14
6	13.81	27.99	13.21
7	13.83	28.00	13.22
8	13.86	28.58	13.39
9	13.90	28.61	13.40
10	13.90	28.60	13.39
11	13.96	28.38	13.33
12	14.43	28.83	13.46
13	14.65	29.24	13.59
14	14.70	29.96	13.80
15	14.97	32.67	13.94
	MAE	**0.69**	**6.67%**
	RMSE	**0.72**	**6.96%**

4. Discussion

The findings of this research demonstrate the feasibility of using the Dynamic Cone Penetrometer (DCP) test to estimate the California Bearing Ratio (CBR) in various soil types, with the cubic regression model consistently emerging as the best fit.

A particularly significant finding was observed in the granular soil (AASHTO A-2-4(0)). While a study in Brazil [10] reported a power-law orrelation with an R² of 0.86 for an A-2-4 soil, our research achieved a superior fit using a cubic model, reaching an R² of 0.9652 with the equation: y=0.0009x^3-0.1613x^2+9.8282x-166.4532 (where y = CBR at 100% MDD, x = CBR from TRL Overseas Road Note 8). This result not only confirms the strong correlation between DCP and CBR reported by others [5] but also suggests that a higher-order model can capture the relationship with greater accuracy for this material type.

For the clayey soils, our study found a strong cubic correlation (R² = 0.8946), which is consistent with research reporting high correlation coefficients for fine-grained soils [4]. A study in Saudi Arabia [22] obtained an even higher logarithmic correlation (R² = 0.96) for clay soils. While the obtained value is slightly lower, the robustness of the cubic model in our case demonstrates its reliability. Unlike studies that explore soil improvement with additives like natural fibers [23], this research focused on establishing reliable correlations for soils in their natural state, providing an essential baseline for engineering practice. In addition, a significant correlation was found with the US Corps of Engineers methodology, where it has been one of the institutions that performed the DCP test for a wide variety of soils, making it a normative procedure.

On the other hand, when performing the RMSE and MAE analysis by means of cross-analysis, the results were less than 10%, however, this margin of variation is due to the fact that these models may present performance problems at the extremes of the predictive model [24]. It is noteworthy that the cubic model provided the best fit across all soil types analyzed in this study, in contrast to other research that reports logarithmic [5, 20], or power-law [10] models as most suitable. This preference for a higher-order model may indicate that the DCP-CBR relationship is not simply monotonic but may feature inflections that only a third-degree polynomial can effectively model, reflecting complex transitions in soil behavior. Our study employed four established DCP correlation methods (Kleyn and Van Heerden, TRL, US Corps of Engineers, and MOPT Colombia), in accordance with the ASTM D6951 standard [25, 26], lending broad validity to this finding.

Other research [1], where the correlation between the CBR - DCP test was used, a correlation coefficient R2 = 0.69 was obtained, compared to the research R2 = 0.87, this difference lies in the fact that the test was performed for a soil type where the clay fraction facilitated the penetration of the soil during the DCP test and the contribution of the gravel fraction was less incidental. On the other hand, the DCP test is standardised as ASTM D6951/D6951M, but it is used as a way of estimating soil strength; however, for it to be adopted in construction standards, it should be adopted based on local information from each area [4].

Finally, the mathematical functions derived from the DCP test showed a high correlation with the laboratory-obtained CBR values, which fall within the ranges required by the MTC Highway Manual [27]. Given its low cost, speed of application, and demonstrated statistical accuracy, it is strongly recommended that the MTC consider the formal adoption of the DCP test and the cubic correlation functions validated herein as a reliable alternative method for the in-situ evaluation of subgrade, subbase, and base layers in road projects.

5. Conclusion

Derived from the results and discussion acquired and presented in this study, the following conclusions are drawn:

- The integration of CFD simulations allows for evaluating the surface runoff and turbulence patterns.
- This research results demonstrated that highly reliable mathematical correlations can be established between Dynamic Cone Penetrometer (DCP) test values and California Bearing Ratio (CBR) test results, particularly for the soil types studied in this paper (clayey, granular, and clayey-granular).
- The cubic regression model is the one that consistently provided the best fit for all three soil types, since it outperformed linear, exponential, logarithmic, and power models. This finding suggests that the relationship between the DCP and the CBR tests has a complex, non-linear nature.
- The strongest correlation was found for the granular soil sample, where the cubic model achieved a coefficient of determination (R^2) of 0.9652. While for the clayey soil sample, a strong correlation was also obtained (R^2 = 0.8946). These results validate the efficacy of the cubic model across a wide range of materials.
- The DPC test is suitable for the estimation of in-situ soil strength because it provides information for the pre-design stage of road projects, such as the subgrade layer.
- The incorporation of these cubic correlation functions into the national technical standards, such as the MTC Highway Manual, is recommended because it will permit formalizing the use of the DCP as a complementary or alternative method for pavement design and quality control. Furthermore, future research should focus on validating these models studied in this research across a broader range of geographical conditions and soil types to achieve a generalization of their applicability.

References

[1] İnan Keskin, and Metehan Alp Memiş, “Prediction of Soil Strength and Dynamic Properties through the Dynamic Cone Penetration Index,” *Discover Civil Engineering*, vol. 2, no. 1, p. 1-14, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] Mohammad Reza Elyasi, Daryoosh Daryaee, and Fatemeh Sarabi, “Presenting a CBR Estimation Model and Compaction Characteristics of Base Layer of Pavement Using a Dynamic Cone Penetrometer (DCP) Test,” *Journal of Testing and Evaluation*, vol. 52, no. 4, pp. 2335-2349, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Jong-Sub Lee et al., “Assessing Subgrade Strength Using an Instrumented Dynamic Cone Penetrometer,” *Soils and Foundations*, vol. 59, no. 4, pp. 930-941, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[4] Jirawat Chokkerd et al., “Recalibrated Correlations between Dynamic Cone Penetrometer (DCP) Data and California Bearing Ratio (CBR) in Subgrade Soil,” *Eng*, vol. 5, no. 3, pp. 1173-1182, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Eimar Andres Sandoval Vallejo, and William Albeiro Rivera Mena, “Correlation of CBR with Unconfined Compressive Strength,” *Science and Engineering in New Granada*, vol. 29, no. 1, pp. 135-152, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Varghese George, Nageshwar Ch. Rao, and R. Shivashankar, "PFWD, DCP and CBR Correlations for Evaluation of Lateritic Subgrades," *International Journal of Pavement Engineering*, vol. 10, no. 3, pp. 189-199, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[7] Adel Hassan Yahya Habal, and Mohammed Amin Benbouras, "California Bearing Ratio and Compaction Parameters Prediction Using Advanced Hybrid Machine Learning Methods," *Asian Journal of Civil Engineering*, vol. 26, no. 1, pp. 121-146, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[8] Favio Paul Portilla Yandún, "Correlation between Laboratory CBR, DCP Index and Physical and Mechanical Properties of Granular Soils," *ConcienciaDigital*, vol. 5, no. 4.1, pp. 49-59, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] ASTM D4429-09A: Standard Test Method for CBR (California Bearing Ratio) of Soils in Place (Withdrawn 2018), ASTM International, 2018. [Online]. Available: https://www.astm.org/d4429-09a.html

[10] Hugo Florencio Torres Merino et al., "Correlation between the Dynamic Cone Penetrometer and the California Support Relationship in the Field for the Sub-Rasant Floor of the Portoviejo-Manta Road," *Technical Gazette*, vol. 21, no. 1, pp. 27-43, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Fernando Feitosa Monteiro et al., "CBR Value Estimation Using Dynamic Cone Penetrometer-A Case Study of Brazil's Midwest Federal Highway," *The Electronic Journal of Geotechnical Engineering*, vol. 21, pp. 4649-4656, 2016. [Google Scholar]

[12] Jemal J. Muhammed, and Murad M. Abdella, "Evaluation of Subgrade Capacity of Jimma Soils Using DCP Test: A Correlation of CBR and DCPI," *Malaysian Journal of Civil Engineering*, vol. 30, no. 3, pp. 457-467, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[13] Kundan Meshram, "Estimation of Field CBR from DCP for Subgrade Soils," *Arabian Journal of Geosciences*, vol. 15, no. 9, pp. 1-5, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] National Institute of Quality (INACAL): We are the National Benchmark in Quality Matters - Technical Standardization, Accreditation and Metrology - and we Manage the National Quality System, Gob.pe, 2021. [Online]. Available: https://www.inacal.gob.pe

[15] Ruben D. Tovar-Valencia et al., "Effect of Base Geometry on the Resistance of Model Piles in Sand," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 147, no. 3, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] ASTM D1557-12(2021): Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)), ASTM International, 2021. [Online]. Available: https://www.astm.org/d1557-12r21.html

[17] AASHTO T 180: Standard Method of Test for Moisture–Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop, American Association of State Highway and Transportation Officials (AASHTO), 2020. [Online]. Available: https://standards.globalspec.com/std/14316821/aashto-t-180

[18] Miguel Angel Benz Navarrete, Pierre Breul, and Roland Gourvès, "Application of Wave Equation Theory to Improve Dynamic Cone Penetration Test for Shallow Soil Characterisation," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 1, pp. 289-302, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[19] Edgar Leonardo Salamanca Medina, and Juan José López Dominguez, "Super Heavy Dynamic Penetration Test (DPSH) Equivalence for the Standard Penetration Test (SPT) in Colombia," *Engineering Research and Development*, vol. 21, no. 2, pp. 47-56, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[20] ASTM D1883-21: Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils, ASTM International, 2021. [Online]. Available: https://www.astm.org/d1883-21.html

[21] Blaise Dabou, Christopher Kanali, and Zachary Abiero-Gariy, "Structural Performance of Laterite Soil Stabilised with Cement and Blue Gum (Eucalyptus Globulus) Wood Ash for Use as a Road base Material," *International Journal of Engineering Trends and Technology*, vol. 69, no. 9, pp. 257-264, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] C.P. Sagar et al., "Prediction of CBR using Dynamic Cone Penetrometer Index," *Materials Today: Proceedings*, vol. 60, pp. 223-228, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] David Miranda Carlos et al., "Potential Application of Natural Fibres for the Reinforcement of Unpaved Forest Roads-Response after RL-CBR Tests," *Applied Sciences*, vol. 14, no. 3, pp. 1-12, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[24] Max Kuhn, and Kjell Johnson, *Applied Predictive Modeling*, Springer New York, NY, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[25] Yoshinori Fukubayashi, Atsushi Koyama, and Daisuke Suetsugu, "Evaluation of Base Course Consisting of Soil Bags Filled with Fine-Grained Soil Using the Dynamic Cone Penetration Test," *E3S Web of Conferences: 4th African Regional Conference on Geosynthetics (GeoAfrica 2023)*, vol. 368, pp. 1-8, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[26] Nada Amer Yousif, Alaa M. Shaban, and Raid R. Almuhanna, "Evaluating Strength Characteristics of Unsaturated Sand Soils Using Dynamic Cone Resistance," *AIP Conference Proceedings: 5th International Conference on Engineering Sciences – ICES21*, vol. 2631, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[27] *Highway Manual: Soils, Geology, Geotechnics and Pavements*, 1st ed., Macro Publishing, 2014. [Publisher Link]