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BI-LOGARITHMIC CORRELATION EQUATION TO EVALUATE THE CBR WITH DCP INDEX OF QUARRY MATERIAL

* Ignacio Fructuoso Solís Quispe†[1], José Carlos Solís Tito[2], José Felipe Marín Loayza[3] and Martin Washington Esquivel Zamora[4]

[1] Faculty of Civil Engineering, Universidad Nacional de San Antonio Abad del Cusco, Perú; [2,3,4] Universidad Nacional de San Antonio Abad del Cusco, Perú

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ABSTRACT: The purpose of this research was to establish a correlation between the DCP Index measured with the Dynamic Cone Penetrometer (DCP) device and the CBR laboratory test results of the Vicho quarry soil, evaluated on the same compacted specimens, which allows the evaluation of the in situ CBR of the pavement subbase courses constructed with material from the Vicho quarry, during the construction process of road projects in the city of Cusco. The bi-logarithmic correlation equation, determined based on the laboratory test results, between the DCP Index and the CBR values for the Vicho quarry soil is Log(CBR)= 2.6838 - 1.21189 Log(DCP) with a reliably coefficient of determination of R^2= 95.91%. This coefficient represents that the equation is appropriate for evaluating the in situ CBR value of the subbase course in road pavements of Cusco city constructed with the Vicho quarry soil, allowing also the evaluation of the adequate functional and structural performance of the pavement structural layer according to the provisions of the project design. The test specimens were compacted with certain percentages of the modified Proctor compaction energy, and then the DCP Index values were evaluated on the compacted specimens previously tested with the CBR laboratory tests. As part of the laboratory test results, the physical properties of the material from the Vicho quarry, to construct the subbase course of pavements, are: w = 5.67 %, LL = 23.74%, LP = 18.09%, PI = 5.65%, thus, the soil is type A-1-a(0) according to the AASHTO soil classification system, and the results of the modified Proctor compaction test are: $\gamma_{d(max)}$ = 21.87 KN/m^3 and w_{opt} = 7.10 %.

Keywords: California Bearing Ratio (CBR), Dynamic Cone Penetrometer (DCP), DCP Index, Correlation Equation, Vicho Quarry

1. INTRODUCTION

The design (based on resistance), construction, evaluation, and rehabilitation of pavements require the evaluation of the properties of the respective pavement layers. This information is obtained based on laboratory and field tests such as the California Bearing Ratio (CBR) test, whose adequate results will guarantee the adequate functional and structural performance of the pavement structure [6].

The control of the CBR of compacted material of the subbase courses can be evaluated with several devices and many test methodologies, among which the most traditional to determine the in situ CBR of the soil is the field CBR test; however, the limitations of this test are usually its availability, cost, speed of execution of the test (many times the results are obtained in times that are not compatible with the deadlines for the execution of the work) and do not allow the evaluation of the pavement structure based on the depth. Therefore, other options can be used, such as the DCP test, which allows evaluating estimated measurements of the in situ CBR, efficiently and economically, for more continuous sections and with greater performance in the speed of execution of the tests during the evaluation process of the construction of a road, whose procedure is non-destructive [5,15].

The Dynamic Cone Penetrometer (DCP) is a device used to evaluate the in-situ resistance of undisturbed and compacted soils by measuring the DCP Index, which can be correlated with other in-situ resistance values, such as CBR [4].

With the record obtained from the penetration depth readings as a function of the number of blows, a curve can be drawn. The curves represent the number of blows necessary to reach a certain depth. The slope of the curve expressed by the ratio between the depth of penetration and the number of blows to reach it (mm/blow) is called the DCP Index, which represents the in situ resistance of the pavement structure layer. Depending on the type of material, that makes up the layer of the pavement structure, its moisture content, and density conditions a change in the slope of the curve will be observed [5], for example, soils that present a greater DCP Index (with a more vertical curve slope) correspond them less resistance [21]. The layer thickness can be defined by the intersection of lines representing the average slope of adjacent layers. Once the layer thicknesses have been defined, the average DCP Index per layer is calculated [4]. For the research, the maximum penetration depth was controlled as a function of the height of the CBR mold, which determines the height of the compacted specimens.

In the city of Cusco, there are different available soil quarries for the construction of the subbase course of pavements for road works, such as the Vicho quarry.

The main objective of the research was to establish a correlation equation between the DCP Index measured with the Dynamic Cone Penetrometer (DCP) device and the CBR evaluated in the laboratory of the Vicho quarry soil on the same compacted specimens. The correlation equation will allow evaluating the in situ CBR during the compaction process of the subbase course of the pavement with practical, economical, and reliable procedures.

This correlation was established based on CBR laboratory test results on compacted specimens, controlling the moisture content and the density of each compacted specimen, correlating these results with the DCP Index values obtained from the tests on the same compacted specimens, previously tested with CBR laboratory tests. The tests were developed in the Soil Mechanics Laboratory of the Universidad Nacional de San Antonio Abad del Cusco, by the technical specifications set out in the ASTM D6951 and ASTM D1883 standards. Therefore, the Dynamic Cone Penetrometer (DCP) device using the correlation equation determined, allows us to control the quality of compaction during the compaction process specifically of the subbase courses constructed with material from the Vicho quarry, for different road projects carried out in Cusco city. It's important to consider that the determined correlation was established through laboratory tests results with representative samples from the Vicho quarry, so that is recommendable to investigate and propose correlation equations for the different soils from other quarries in the Cusco city used in the construction of road pavements, considering that each material has particular physical and mechanical properties that would require specific correlations for each of them, so that, each of the equations is representative of the evaluated material.

The correlation of test results is desirable to estimate values between tests of the same material. These correlations are approximations and should be used as such. The values of the test results depend on the method of performing the test, the moisture content, and the density of the material. When estimating the resistance values of soil, without considering these factors, it is common to generate erroneous assumptions [22].

Exist various investigations were developed to correlate the value of the DCP Index (mm/blow) and the measurement of the CBR (%). These correlations vary according to the test conditions, in which it is prioritized that both tests consider the same conditions of moisture content, dry unit weight, soil compaction energy, as well as the angle of the conical tip of the DCP device (some correlations are for 30º cones and others for 60º cones), as well as the test execution sites, whether in the laboratory, field or both [5]. Although exist different correlation equations published in the technical literature, a specific correlation for the soil of the Vicho quarry that is representative and considers local conditions (specifically the type of soil) is required.

Many organizations have some type of proprietary DCP device and have established their correlations between DCP Index values and some other measure of soil strength. Such correlations are obtained through regression analysis of the results [9]. These models show that there is an inverse relationship between the DCP Index and the CBR for soil tests [13].

The data can be analyzed through linear, logarithmic, exponential, or bi-logarithmic (log x log) models. Of these four models, the log x log version is the one that best describes this relationship, and has the following form [1]:

$$\log(CBR) = a + b \times \log(DCP) \quad (1)$$

Where CBR is expressed as a percentage (%), DCP is expressed in mm/blow, and a and b are constants obtained through regression analysis.

In the technical literature exist different investigations on correlation equations to evaluate the CBR based on the DCP Index; some of them present the models according to bi-logarithmic equations as shown in Table 1.

Table 1 Correlation equations published in the technical literature

Correlation Equation		Material tested	Type of test	Reference
$\log(CBR) = 2.62 - 1.27 \times \log(DCP)$	(2)	Unknown	Laboratory CBR tests and laboratory DCP tests	Kleyn [14]
$\log(CBR) = 2.56 - 1.15 \times \log(DCP)$	(3)	Subgrade soil type clay	In situ CBR tests and situ DCP tests	Smith and Pratt [18]
$\log(CBR) = 2.20 - 0.71 \times [\log(DCP)]^{1.5}$	(4)	Granular and	Laboratory CBR tests	Livneh [16]

Correlation Equation		Material tested	Type of test	Reference
		cohesive soil	and laboratory and in situ DCP tests	
$\log(CBR) = 2.81 - 1.32 \times \log(DCP)$	(5)	Clay, well-graded sand, and gravel	Laboratory CBR tests and laboratory DCP tests	Harison [9]
$\log(CBR) = 2.669 - 1.065 \times \log(DCP)$	(6)	Gravel base course material	Field and laboratory test	Ese et al. [8]
$\log(CBR) = 2.809 - 1.288 \times \log(DCP)$	(7)	Clayey and sandy soil type lateritic.	Laboratory CBR tests and laboratory DCP tests	Lima [15]
$\log(CBR) = 2.38393 - 0.975 \times \log(DCP)$	(8)	Silty gravel and silty gravel with sand	Laboratory CBR tests and laboratory and in situ DCP tests	Viscarra [21]
$\log(CBR) = 2.55 - 1.26 \times \log(DCP)$	(9)	Subgrade soil type lateritic clay	Laboratory CBR tests and laboratory DCP tests	Berti [5]
$CBR = 269 / DCP$	(10)	Subgrade soil	Insitu CBR test and Insitu DCP test	Hasim, Mustafa and Kasim [10]
$CBR = 249 \times DCP^{-1.1284}$	(11)	Subgrade soil type silty sand, clay with sand, silty clay, and poorly graded sand with clay.	In situ CBR tests and situ DCP tests	Tupia and Alva [20]
$CBR = \frac{292}{(DCP)^{1.12}}$	(12)	All soils, except for CL soils with CBR less than 10 and CH soils	Unknown	ASTM D6951 [4]
$CBR = \frac{1}{(0.017019 \times DCP)^2}$	(13)	CL soils with CBR of less than 10	Unknown	ASTM D6951 [4]
$CBR = \frac{1}{0.02871 \times DCP}$	(14)	CH soils	Unknown	ASTM D6951 [4]
$CBR = 187.77 \times DCP^{-0.95}$	(15)	Subgrade soil type aeolian sand, gravelly granular, sandy silt, and clayey silt.	Laboratory CBR tests and laboratory and in situ DCP tests	Injante [11]
$CBR = \frac{112.03}{(DCP)^{0.803}}$	(!6)	Subgrade soil is predominantly clayey	Laboratory CBR tests and in situ DCP tests	Jove, Feria and Hernandez [12]

The correlation equations published in the technical literature have been proposed for different materials evaluated with different types of tests, under specific conditions. Therefore, it is important to consider the local characteristics under which the correlations obtained have been determined because these factors change the empirical values obtained [16].

2. RESEARCH SIGNIFICANCE

A recurring problem that occurs in road works in Cusco city is that some of them are deteriorated before reaching the pavement design life, possibly due to deficiencies in the adequate control and supervision of the construction process, specifically the control of the CBR of the sub base courses. This has motivated the evaluation of the field CBR values in a practical, efficient, and lower-cost way during the compaction process of the subbase course of the pavement structure in the field for different road projects developed in the region of Cusco. For which, we established a correlation between the DCP Index values measured with the Dynamic Cone Penetrometer (DCP) device and the laboratory CBR test results evaluated on the same compacted specimens with material from the Vicho quarry, which allows evaluating the in situ CBR of the subbase course of pavement structures constructed with material from the Vicho quarry, during the compaction process.

3. MATERIALS AND METHODS

3.1 Physical properties of quarry material

The research began with the visit and reconnaissance of the Vicho quarry to later proceed with the collection of disturbed soil samples in the quantities required for the proposed tests and their corresponding transport to the Soil

Mechanics Laboratory of the Universidad Nacional de San Antonio Abad del Cusco and their respective storage to later carry out the respective laboratory tests to evaluate the physical and mechanical properties of the quarry soil.

To determine the maximum dry density and the optimum water content of the quarry soil were compacted specimens according to the modified Proctor compaction test [2], establishing the respective compaction curve for the quarry soil.

3.2 CBR laboratory tests and the respective DCP tests

To establish the correlation equation were developed CBR laboratory tests [3] with specimens compacted at different pre-established percentages of the compaction energy, according to method C of the modified Proctor compaction test [2]. For the compaction were considered different values of the compaction energy per unit volume, which come to be different compaction efforts per unit volume of the quarry soil [7] adding the optimum water content to all specimens. The CBR laboratory test results were compared with the DCP Index (mm/blow) [4] evaluated on the same compacted specimens in the CBR molds at different percentages of the compaction energy with the same optimum water content.

For the CBR laboratory tests, a total of 11 specimens were compacted with different compaction energies established according to the number of blows applied to each specimen, with the respective compaction hammer [3], establishing 11 percentages of the compaction energy (Table 2), considering for all compaction tests the optimum water content, previously determined from the compaction curve, reaching minor values of maximum dry unit weight.

Table 2 Percentages of modified Proctor test compaction energy established for the specimens evaluated

Test No.	Number of blows	$\%E_{comp}$
1	56	100
2	50	89.3
3	44	78.6
4	37	66.1
5	31	55.4
6	25	44.6
7	22	39.3
8	19	33.9
9	16	28.6
10	13	23.2
11	10	17.9

The percentages of the compaction energies of the modified Proctor test less than 100% were considered to control CBR values lower than the design specifications that could be reached during the sub base construction process, thus road works construction field conditions are reproduced.

Subsequently, the respective 11 Dynamic Cone Penetrometer (DCP) tests were performed on the specimens previously tested with the CBR laboratory tests, determining the DCP Index (mm/blow) for different values of dry unit weight with the same optimum water content. The DCP penetration was located to one side of the indentation left by the CBR piston during the bearing test (Fig. 1).

Fig.1 DCP perforation to one side of the CBR indentation.

3.3 Correlation equation

The correlation equation between the test results obtained with the Dynamic Cone Penetrometer (DCP) device (DCP Index values) and the corresponding CBR laboratory test results was established by regression analysis through a bi-logarithmic model. The DCP Index values and the respective CBR values were plotted in a bi-logarithmic graph (Log x Log) with the respective correlation curve between both results.

The results of the DCP Index (mm/blow) with the respective CBR (%) measured on each compacted specimen of Vicho quarry soil made it possible to establish an adequate correlation equation for the conditions established in the test procedure.

4. RESULTS AND DISCUSSION

The laboratory test results of the Vicho quarry soil samples analyzed are shown in Table 3, which allows the classification of the soil as A-1-a(0) according to the AASHTO soil classification system. The same table also shows the results of the modified Proctor compaction test.

Table 3 Physical properties of the Vicho quarry soil.

Property	Value
w (%)	5.67
LL (%)	23.74
LP (%)	18.09
PI (%)	5.65
Fines (%)	6.38
Sand (%)	32.02
Gravel (%)	61.60
$\gamma_{d(max)}$ (KN/m^3)	21.87
w_{opt} (%)	7.10

The particle size distribution curve of the Vicho quarry soil is shown in Fig. 2. The grading conforms to grading envelope A, for subbase material [17].

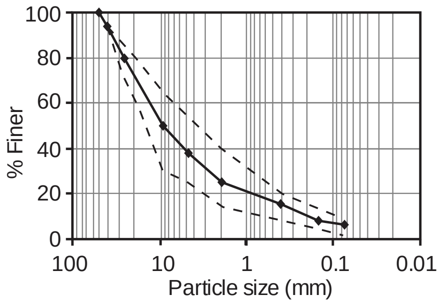

Fig.2 Particle size distribution curve of the Vicho quarry soil.

The compaction curve for the Vicho quarry soil tested according to the modified Proctor compaction test procedure is shown in Fig. 3, where it can be observed the maximum dry density and the optimum water content of the quarry soil.

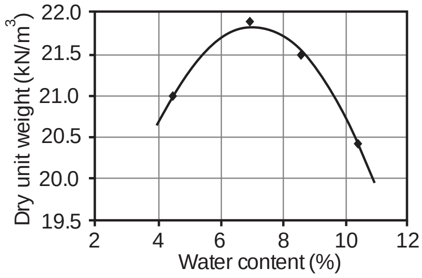

Fig.3 Compaction curve of Vicho quarry soil.

The CBR laboratory test results and the corresponding DCP Index values evaluated with the Dynamic Cone Penetrometer (DCP) device are shown in Table 4. The DCP Index values were evaluated on the same specimens that were compacted according to the percentages of compaction energy established in Table 2.

Table 4 California Bearing Ratio (CBR) laboratory test results and corresponding results of the Dynamic Cone Penetrometer (DCP) tests.

Test No.	CBR (%)	DCP (mm/blow)
1	76.4	5.15
2	68.78	5.21
3	58.85	5.32
4	56.18	5.34
5	49.81	6.22
6	40.55	7.69
7	39.61	7.70
8	38.31	7.81
9	37.87	7.95
10	31.10	9.88
11	23.71	11.88

The plot of results obtained with the Dynamic Cone Penetrometer (DCP) device (DCP Index values) and the corresponding CBR laboratory tests results, in a bi-logarithmic graph (Log x Log), with the respective correlation curve between both results [19] are shown in Fig. 4.

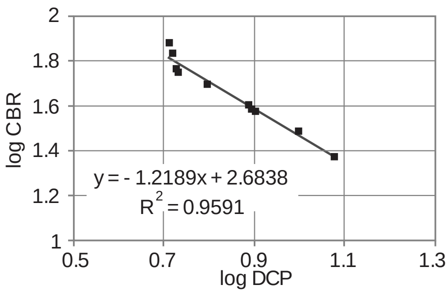

Fig.4 Correlation curve and correlation equation between DCP Index values and CBR laboratory test results.

According to the established correlation, the correlation equation between the DCP Index and the CBR for the Vicho quarry soil evaluated is as follows.

$$\mathrm{Log(CBR)} = 2.6838 - 1.21189\,\mathrm{Log(DCP)} \qquad (17)$$

The results of the CBR laboratory tests and the corresponding DCP Index values determined with the Dynamic Cone Penetrometer (DCP) device, on the same samples, allowed us to establish the correlation equation of the Eq. (17) with an adequate determination coefficient for the soil quarry studied.

The correlation curve, shown in Fig. 4, shows a good fit with the experimental data, with a coefficient of determination (R^2) of 95.91%. This result allows us to consider that the correlation equation determined has a good representation of the experimental data [19], since the differences between the evaluated values and the predicted values through the established model are small and impartial, thus validating the results obtained with the tests.

The analysis and interpretation of the results allow us to consider that the correlation equation between the results evaluated with the Dynamic Cone Penetrometer (DCP) device with the results of the CBR laboratory tests, allows validating the evaluation of the in-situ CBR of the subbase courses built with material from the Vicho quarry, for the construction of road pavements in the city of Cusco.

A comparison of the curves corresponding to the equations published in the technical literature, from Eq. (2) to Eq. (16), with Eq. (17) determined in the present investigation is shown in Fig. 5. Graphically, it can be seen that the curve of Eq. (17) is similar to the other curves in terms of the slopes (from -2 for Eq. (13) to -0.71 for Eq. (4)) and their intersections with the ordinate axis (from 2.81 for Eq. (5) to 1.76907 for Eq. (13)) excepting Eq. 14; however, each of the equations provides different CBR values for a given DCP index value, because each of them has been determined with distinct materials and under different conditions. This can also be seen in Eq. (12) proposed for all soils except for CL soils, Eq. (4), and Eq. (6) for coarse soils, the CBR values that they provide are different because they are different equations. Therefore, it would be advisable to determine specific correlation equations for the quarry materials used in constructing pavements in the city of Cusco, so that the values correlated values will be much more accurate.

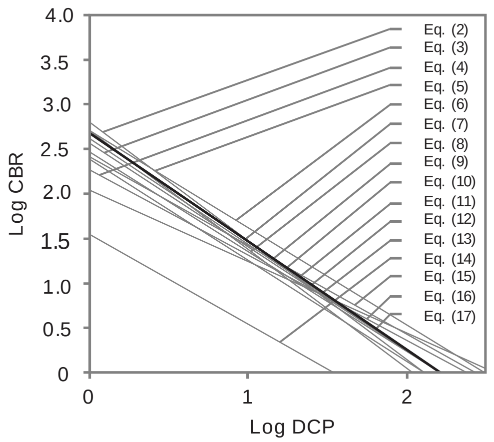

Fig.5 Comparison of the correlation curves published in the technical literature with the determined correlation curve.

The results obtained also allow us to consider that it is convenient to establish different equations that correlate CBR test results with the DCP index, for different soils that are used in the construction of pavements, considering local conditions.

5. CONCLUSIONS

The Dynamic Cone Penetrometer (DCP) test will allow the evaluation of the in-situ CBR of the soil material from the Vicho quarry during the compaction process of the subbase course of pavements in road works, with practical, economical, and reliable procedures; considering that the experimental results were validated based on an adequate correlation equation between the CBR of the soil evaluated in laboratory and the DCP Index measured with the Dynamic Cone Penetrometer (DCP) device on the same compacted specimens.

According to the physical properties evaluated, the Vicho quarry soil is classified as A-1-a(0) according to the AASHTO soil classification system, and the modified Proctor compaction test results are $\gamma_{d(max)}$= 21.87 KN/m^3 and w_{opt}= 7.10%.

The correlation between the results of the CBR test in the laboratory with the results of the test with the Dynamic Cone Penetrometer (DCP) device was established, through the equation Log(CBR)=2.6838-1.2189xLog(DCP), with a coefficient of determination R^2= 95.91%. Therefore, based on the results of this investigation, the correlation equation obtained allows the indirect determination of the CBR based on the DCP index to be validated as a reliable alternative, for subbase soils of the Vicho quarry; considering that the equation was determined specifically for the vicho quarry soil.

Although exist different equations published in the technical literature for similar soils and even for all soils except clays, these provide different CBR values, so the correlation equations for local materials with an adequate coefficient of determination are more representative.

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